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Investigating the Spark

"There's a term in French that describes falling in love at first sight: *coup de foudre,*" said Yoav Yair. "Literally translated, it means 'bolt of lightning.'" Yair is the dean of the School of Sustainability at the Interdisciplinary Center Herzliya in Israel and *Eos*'s Science Adviser for AGU's Atmospheric and Space Electricity section. "This is how I felt about atmospheric electricity when I started my master's degree at Tel Aviv University back in the 1980s: instant fascination, deep curiosity, and a desire to know more."

I was excited when Yair suggested that we cover lightning in our May issue of *Eos*. As a magazine editor, I certainly think you can't beat the photography, but more than that, I was intrigued by the number of questions that remain about this phenomenon nearly all of us have grown up experiencing, watching from our windows as storms roll in. "Lightning is indeed beautiful, dangerous, and multifaceted, and it hides a lot and reveals a lot. And although it has been known to humanity for millennia—feared and worshiped—we still don't fully understand it," explained Yair.

Chris Schultz of NASA's Short-term Prediction Research and Transition Center assures me we are living in a "second golden age" of lightning observations. In "Lightning Research Flashes Forward" (p. 28), meteorologist Ashley Ravenscraft explains how she uses data recently made available to the National Weather Service from the Geostationary Lightning Mapper on board the GOES-R satellite (p. 5) that show the rate of lightning strikes in an area. She uses these data—sometimes these data alone, when necessary—as a proxy to predict tornadoes and issue warnings to the nearby Huntsville, Ala., community. Like so many meteorologists, she got into the field to save lives, and with this new information, she's giving her neighbors sometimes as long as 45 minutes to get to safety.

"In recent decades, we have made tremendous progress and devised sophisticated ways to decipher lightning and its associated impacts on the atmosphere," said Yair, "here on Earth and also on other planets." In "Planetary Lightning: Same Physics, Distant Worlds" (p. 22), we take a trip through the solar system to investigate why lightning is pervasive on Jupiter, how Neptune and Uranus are similar in so many ways except in generating lightning, and, in this case and so many others, why Venus is just so weird.

Finally, where are all these lightning data when you need them? On page 18, learn about WALDO—the Worldwide Archive of Low-frequency Data and Observations—in "Returning Lightning Data to the Cloud." Morris Cohen, professor of electrical engineering at Georgia Institute of Technology (and president-elect of AGU's Atmospheric and Space Electricity section), and a colleague manage this database of radio measurements meant to facilitate research not only in lightning but also in space weather, terrestrial gamma rays, and gravity waves, among other phenomena.

"As our society becomes more technological, urban, [and] densely populated, and as our climate is changing, we need to know what lightning will be like in the future," said Yair. We hope this issue gives you some idea of how lightning affects us, as well as of the interdisciplinary nature of the exciting science questions it presents.

Heather Goss, Editor in Chief

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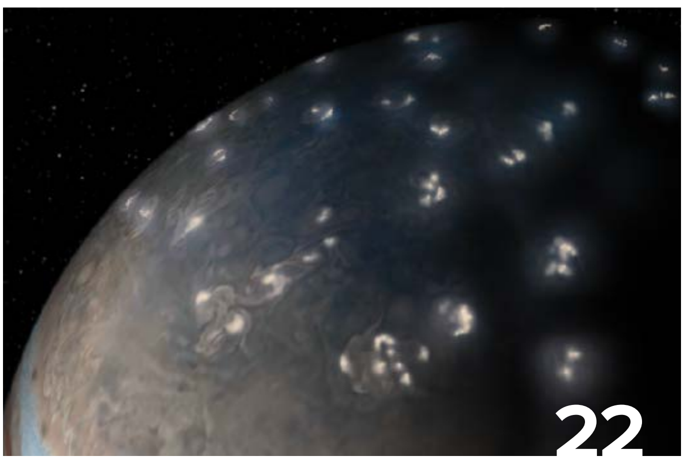
CONTENT



Features

On the Cover

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Columns

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Speleothem Documents Belgium's Historic Climate

Researchers analyze speleothems in Belgium's Han-sur-Lesse cave system. Credit: Sophie Verheyden

Deep in the south of Belgium, near the winding Lesse River, lies a cave rich with history and geologic wonders. The Han-sur-Lesse cave system has long fascinated visitors, with its well-defined calcium carbonate formations (speleothems) marveled at for centuries.

Recently, scientists from various Belgian institutions studied one of the cave's fastest growing stalagmites, Proserpine, to learn more about the evolution of the region's climate. By analyzing such data as stable isotopes and trace elements, the researchers found clear evidence of increasingly dry conditions and anthropogenic activity over the past 4 centuries.

Tiny Clues from the Past

Proserpine is formed by water dripping from bedrock above the cave. Once the drip water lands on the surface of the stalagmite, it releases carbon dioxide and precipitates into a mixture of calcium carbonate and any other minerals that hitched a ride on the way down through the limestone above. With a flat, 2-square-meter face growing at roughly half a millimeter per year, this special stalagmite displays clearly distinct layers with seasonal variability, making it a perfect proxy to study past climate.

In a recent paper published in *Climate of the Past*, researchers analyzed three distinct sections of Proserpine, labeling them P16, P17, and P20, according to the centuries they represent (bit.ly/stalagmite-seasons). Because the stalagmite's layers show a distinct seasonal variability in chemical composition, the researchers were able to make several conclusions about how Belgian climate and land use have changed seasonally over many centuries.

"Caves and speleothems are rather local phenomena, but they can record patterns of regional climate quite accurately," said Niels de Winter, a postdoctoral researcher at Vrije Universiteit Brussel and one of the authors on the study. When added to paleoclimate data from such proxies as tree rings, ice cores, and peat bog records, speleothems add a great deal to the bigger picture of climate history. Their samples cover a much longer period of time than tree ring data, as well as a broader range of environments than ice cores or peat bog records.

De Winter and his colleagues used laser spectroscopy to detect trace elements, among the most important data found within speleothems. Some trace elements, like lead, appeared in significantly higher amounts in more recent samples, hinting at anthropogenic pollution.

Trace elements also revealed more subtle properties about the cave and the region's past climate. For example, elevated levels of magnesium, barium, and strontium suggest higher rates of prior calcite precipitation in the modern drip waters. Prior calcite precipitation occurs when drier conditions and hotter temperatures cause water to percolate more slowly through the bedrock, giving the water more time to precipitate calcite and pick up trace elements before entering the cave.

Another, more obvious sign that the Belgian climate has gotten drier over time can be seen in the stalagmite layers themselves. Thicker layers are found in the Little Ice Age samples because rainfall levels and drip water precipitation on Proserpine were higher.

Digging Deeper

One of the study's most intriguing discoveries was the stark contrast in trace elements between the P16 and P17 samples. This marked shift suggests a change in vegetation cover, possibly introduced by late-17th-century farmers—but no historical records were found to independently confirm this hypothesis. What's certain is that something abruptly affected the drip water's path through the ground during this period.

In the words of the researchers, the change itself "can serve as a valuable palaeoclimate proxy." Many speleothem studies take place over decadal to millennial scales, making these abrupt changes harder to resolve and place in context. To get around this hurdle, the researchers suggest sampling well-expressed seasonal speleothem layers at "strategic places" and superimposing them over longer timescales. However, not all speleothems have well-expressed layers.

According to Sophie Verheyden, a postdoctoral researcher at the Royal Belgian Institute of Natural Sciences in Brussels and a researcher on the study, another way to measure seasonality is by detecting invisible layers in speleothems that reveal themselves through ultraviolet light, a phenomenon known as luminescence. Other methods, such as measuring wiggles in amounts of phosphorus, can be used as well.

Speleothems add a great deal to the bigger picture of climate history.

Just like telescope engineers, scientists will continue to upgrade their paleoclimate techniques to peer deeper into the past. "This research is very difficult because there are a lot of things that can happen to the rainwater before it reaches the stalagmite. Understanding all these processes requires a mixed understanding of biological, geological, hydrological, and chemical processes," de Winter emphasized.

Ian Fairchild, professor emeritus at the University of Birmingham in the United Kingdom and a longtime speleothem expert, said, "This looks to be a very well-executed study that makes excellent use of preserved high-resolution information." And although he admitted that many speleothems can't be studied in such detail, he noted that when they are, "a powerful understanding can be revealed."

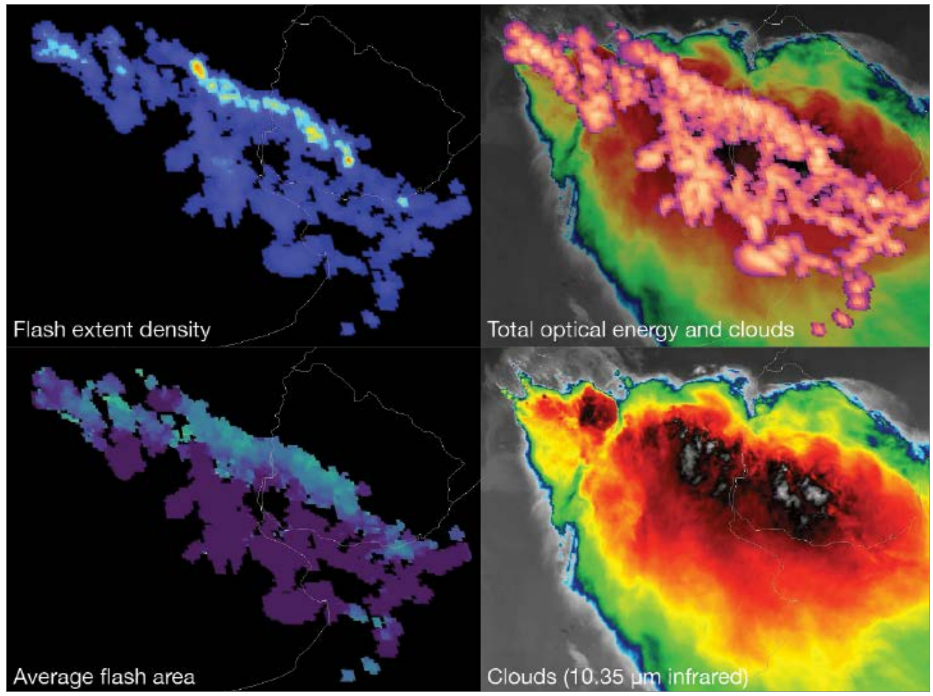
By **Christian Fogerty** (@ChristianFoger1), Science Writer

Mapping Lightning Strikes from Space

If lightning strikes anywhere in the Western Hemisphere, odds are it has already been detected and mapped by satellite-bound cameras orbiting some 35,000 kilometers above Earth.

Lightning flashes are more typically mapped from ground-based networks using radio frequencies to generate precise data on the order of meters (see "Lightning Research Flashes Forward," p. 28). However, ground-based systems have a limited line of sight. The view from a satellite does not, for example, need to "account for things like tree lines or city skylines or even just general dissipation over distance," said Michael Peterson, an atmospheric scientist at Los Alamos National Laboratory in New Mexico.

The idea of using a satellite to detect lightning has been around since at least the 1980s, but with the launch of the National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellite–R Series (GOES-R) weather satellites starting in 2016, researchers and forecasters have attained unprecedented amounts of lightning data from the Geostationary Lightning Mapper (GLM) instruments attached to the satellites.



Five minutes of lightning from the Geostationary Lightning Mapper show small areas of high lightning flash rates (maximum of about 100 per minute) and a few very large flashes that cover thousands of square kilometers. Credit: NOAA/NESDIS/Scott Rudlosky

An interdisciplinary team of researchers now has developed a technique that can map out the lightning flashes GLM detects across the entire Western Hemisphere in real time.

"It's not only a matter of being able to see more, but being able to see things completely," said Peterson, who was not involved in the study.

The new technique was reported in the *Journal of Geophysical Research: Atmospheres* (bit.ly/GLM-images) and has been adapted for use by the U.S. National Weather Service (NWS).

Seeing Lightning More Completely

The GLM is essentially a video camera in space that captures lightning flashes across the Western Hemisphere at 500 frames per second. "There's very little dead time. No matter how rare the lightning flash is, you're probably going to see it," Peterson said.

But that deluge of data comes with a downside. "You can't send all that video data down to the ground," said Eric Bruning, an atmospheric scientist at Texas Tech University in Lubbock and lead author on the study. Instead, the data are sent as pixels attached to geolocation information that clustered into lightning flashes. "For a lot of users, it's just really challenging to even know what to do with those data," he said.

The new technique reconstructs and spatially maps the lightning flashes while retaining the quantitative physical measurements made by the GLM. "In a way, it's just restoring the video nature of the camera," Bruning said.

Adapting the technique to work with the NWS systems required getting the product to work with NWS operational display systems, matching data formats, making it timely, and not allowing it to fail.

The researchers demonstrated that this space-based lightning mapping technique can distinguish the many tiny flashes of lightning within thunderstorm cores and the large lightning flashes that are part of mesoscale storm systems.

Myriad Applications

The technique's application for weather forecasters was readily apparent and rapidly developed over the course of a year to be used by NWS. The process required getting the product to work with NWS operational display systems, matching data formats, making it timely, and not allowing it to fail, Bruning said. In adapting the tool for practical applications, "you find all the bugs that you just ignore as a researcher in your code."

Using this technique, it would be possible to track the origin of so-called bolts from the blue that occur without rain, said Chris Schultz, a research meteorologist at NASA's Short-term Prediction Research and Transition Center in Huntsville, Ala., and coauthor on the study. Seeing the origin of the flash is important to anticipate future lightning and is not possible with traditional ground-based lightning data. This capability is important for public safety because "the majority of injuries and fatalities occur just before the rain has started or just after the rain has ended," Schultz said.

"Right now the main users are [at] the National Weather Service, and that's mainly because the instrument is brand-new to the public," said Schultz. He expects that as the technology evolves and gets into the public's hands, it will become more widely used, like radar is now.

"It is certainly useful to be used in real time, but it's not as useful as it could be," Peterson said. One major caveat with the technique is that it relies on the data provided by NOAA and assumes their veracity. "Unfortunately, the algorithm is not perfect."

Because of the complexity of the data, large flashes of lightning are automatically split into multiple flashes, explained Peterson. He recently published a new processing system to stitch these smaller flashes back together. "Now, this isn't a huge deal in terms of overall statistics. We're talking 4% to 8% of all lightning depending on what storm you're looking at."

Still, the latest study adds a powerful new tool for scientists and forecasters studying lightning. The technique, which is available as open-source software, also grants "the ability to use lightning to monitor the climate and also to even study storm processes in places where we don't have the rich radar network that we have in the U.S.," Bruning said.

"I think it's important to keep that global perspective in mind," he added.

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

Earth's Skies Transmitted Signs of Life During Lunar Eclipse

During a total lunar eclipse, the Moon travels first through the umbral (orange) and then the penumbral (red) shadow of the Earth, becoming progressively darker and redder before returning to normal. This is a composite of a sequence of images of the 21 January 2019 total lunar eclipse as seen in Austria. Credit: H. Raab, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Last year's so-called super blood wolf moon gave astronomers the chance to measure the spectrum of Earth's atmosphere as if it were a transiting exoplanet, a feat that is possible only during a total lunar eclipse.

"It's a very fascinating thought to imagine that the spectrum of Earth is always broadcast to the outside," said Matthias Mallonn, a postdoctoral researcher at Leibniz Institute for Astrophysics Potsdam in Germany. Mallonn and other researchers on the project typically hunt for faint spectral signals from the atmospheres of distant worlds, but the lunar eclipse let them look at Earth instead.

During the 21 January 2019 total lunar eclipse, the researchers used one of the largest visible-light telescopes on Earth to measure the spectrum of sunlight that had passed through the top of Earth's atmosphere. That light bore signals from molecular oxygen and water vapor and also sodium, potassium, and calcium. This is the first time this method has been used to spot those three elements in Earth's atmosphere.

"Exoplanets are truly alien worlds and typically have very different properties from the solar system planets," said Eliza Kempton, an assistant professor of astronomy at the University of Maryland in College Park who was not involved with this research. "We must first establish what the Earth and other solar system planets look like 'as exoplanets' to benchmark our understanding of the far more exotic extrasolar planets."

Lunar Eclipse Mimics a Transit

One way that astronomers can measure the chemical composition of exoplanet atmospheres is called transmission spectroscopy, which captures starlight that has passed through a planet's atmosphere. The atmosphere imprints a chemical signature on the starlight that can reveal major components like water, methane, or even metal oxides. So far, most of these measurements have been done for large, gaseous planets that orbit close to their stars.

Future telescopes will allow similar measurements of Earth-sized planets in the hab-

> **We must first establish what the Earth and other solar system planets look like 'as exoplanets' to benchmark our understanding of the far more exotic extrasolar planets.**

itable zones of their host stars, and the researchers wanted first to test this out on Earth. Fortunately, the positions of the Sun, Earth, and Moon during a total lunar eclipse mirror the geometric setup needed for this: the Sun as the distant star, the Earth as the exoplanet, and the Moon as the far-off observer, Mallonn explained.

However, there is no telescope on the Moon waiting to capture the transmitted light. Instead, the team measured that light after it reflected from Tycho Crater. That light then entered our atmosphere and was observed by the Large Binocular Telescope (LBT) over a roughly 4-hour period. After accounting for the spectra of sunlight, the lunar surface, and contamination from traveling to the telescope on the ground, the team was left with the signal as it appeared when the light passed through Earth's atmosphere.

Earth's transmission spectrum showed strong signals from molecular oxygen and from water, both important biosignatures. Sodium, calcium, and potassium also appeared in Earth's transmission spectrum, and all three elements have been detected in the atmospheres of hot Jupiter exoplanets. These results were published in *Astronomy and Astrophysics* (bit.ly/eclipse-Earth-transit).

"The entire exercise was not to learn something new about the Earth's atmosphere," Mallonn said, "but to prove the technique and check out how well we can actually get to the biosignature features, the molecules that might be indicative of life."

"Studies such as this one, which observe solar system planets as if they were exoplanets—i.e., using the same types of observational techniques and/or observing geometry—are vital for our understanding of exoplanet atmospheres," Kempton said.

Awaiting Future Telescopes

Mallonn acknowledged that a lunar eclipse isn't a perfect analogue to what astronomers could expect to see from a transiting exoplanet. During a total lunar eclipse, an observer on the Moon would see the entire Sun blocked by the Earth, but a transiting exoplanet blocks only a small fraction of its host star. The atmospheric signal from such an exoplanet would be much weaker than what the team observed for Earth, he said.

At the moment, "if we were in the situation where we found an Earth-sized planet around a Sun-like star, the LBT could hardly do anything about it," he said. "We would have to wait another 10 years for the next generation of ground-based telescopes with much larger mirror sizes and much larger apertures." Some of those telescopes, such as the European Extremely Large Telescope and the Thirty Meter Telescope, are currently in development and are expected to play a crucial role in detecting signs of life on exoplanets, Mallonn said.

Moreover, molecular oxygen and water aren't the most convincing of biosignatures. Methane, ozone, and a host of gases are more suggestive of life. However, the most persuasive biosignatures produce signals at longer infrared wavelengths that are difficult to measure beneath Earth's atmosphere. The atmosphere absorbs much of that light in what's called a telluric spectrum.

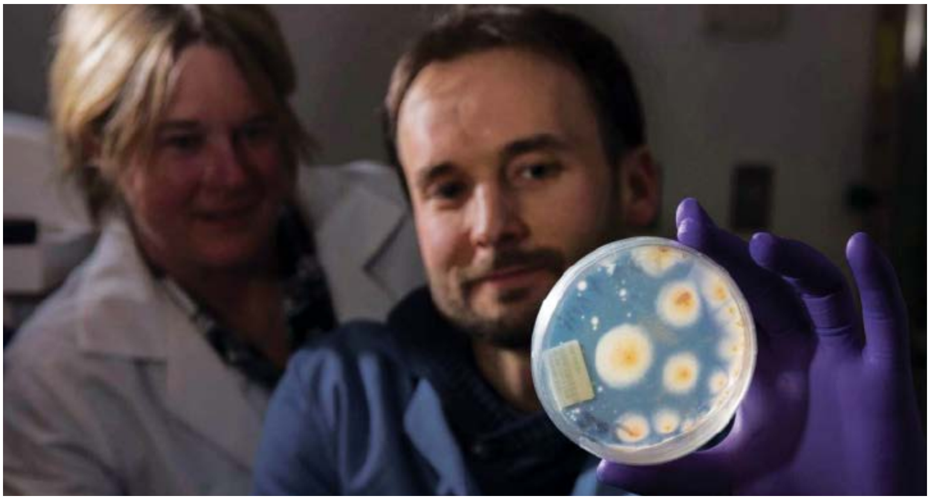
"In the infrared, the space telescopes have the strong advantage of not being affected by the telluric component of the spectrum," Mallonn said. The James Webb Space Telescope is expected to fill that role.

"It's rather simple to see that there's life on Earth," he said. "If another civilization living out there takes a spectrum of the Earth, then [it'll] actually see by our own biosignature molecules that there is life…and I just hope that in another 30 years or whenever, we might be able to do a similar observation of another planet."

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

Opposite: Josep Castells/Unsplash

Microbes Discovered Hanging Out in the Ocean's Crust



Microbiologist Ginny Edgcomb (left) and Gaëtan Burgaud cultured fungal colonies from rock samples deep within the seafloor. Credit: Tom Kleindinst/WHOI

These [communities] can basically be hanging out for millions of years in a very quiescent state."

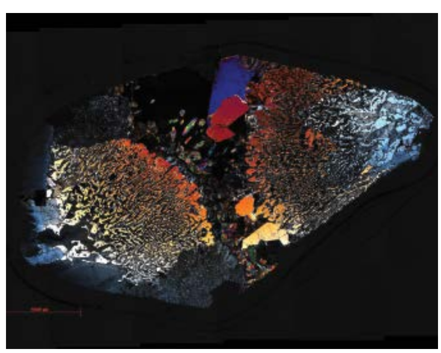
Scientists have found evidence of active microbial communities living in the oceanic crust hundreds of meters beneath the seafloor, proving that life can persevere under even the most extreme and remote conditions.

Rock cores drilled from an undersea mountain in the Indian Ocean revealed that bacteria, fungi, and single-celled organisms called archaea live in cracks and fissures in the dense rock of the ocean's lower crust. The scientists discovered that the rock samples contained biosignatures of life, including DNA and lipid biomarkers, and messenger RNA extractions showed that some of the cells were actively dividing.

Beneath the soft sediments of the seafloor sit layers of basaltic and gabbro rocks that make up the oceanic crust. Scientists know that life exists in seafloor sediments, but only one previous study in the Atlantic Ocean probed the oceanic crust for signs of life (bit.ly/crust-life). In the latest research, scientists recovered rock from 750 meters into the lower crust and performed a host of laboratory tests in search of microbial activity.

"These [communities] can basically be hanging out for millions of years in a very quiescent state," study author and associate scientist Virginia Edgcomb, from Woods Hole Oceanographic Institution, said. "I'm sure even the active microbes are carrying on at a very slow rate relative to those near the surface, but nevertheless, they're buzzing along."

The latest research, published in the journal *Nature,* suggests that survival in the deep biosphere depends on underground fluid flow (bit.ly/fluid-flow). As seawater entrains deep in the crust, it travels through cracks in the rock, some microfine and others as large as, or even larger than, spaghetti noodles. The fluid likely carries organic matter from the ocean, said Edgcomb, and the team found signs of life clustered around these nutrient highways.



A thin section of the rock core shows distinct minerals (colored) and a small cavity through which fluid may have flowed, delivering organic matter that fuels subsurface microorganisms. Credit: Frieder Klein/WHOI

Many of the microorganisms match those observed in other extreme environments, like hydrothermal vents, said Edgcomb. But unlike what she expected, the underground life relied on both fixing chemicals for energy and co-opting organic matter floating in the fluid. Messenger RNA analysis revealed that the microbes can recycle amino acids or lipids of dead (or even living) matter. Steven D'Hondt, a professor at the University of Rhode Island who was not involved with the research, said this "runs counter to standard assumptions about subseafloor crustal life."

"The readiness of that community to consume organic matter suggests that it is metabolically linked to the broader world (e.g., the ocean) via ocean circulation," D'Hondt said.

It's unclear whether these results can apply to other areas of the ocean's lower crust. The research team extracted cores from the undersea mountain Atlantis Bank where the lower crust is exposed at the ocean bottom, which is unusual—normally, thousands of meters of sediment would cover it. The site gave the research team unprecedented access to the lower crust, but future research must confirm whether life is possible with upper crust and bottom sediments still intact.

The latest study shows that "life finds a way," said Jennifer Biddle, an associate professor at the University of Delaware who did not take part in the study. Earth's lower oceanic crust could be an analogue of how life might survive on other planets, Biddle added.

Edgcomb cautions that the biomass in the study was extremely low: The cells are just "barely eking out a living," she said. Still, "the lower ocean crust is one of the last frontiers of the exploration for life on Earth," Edgcomb said. "We have a better understanding that the lower crust does indeed host viable and, in some cases, active microbial cells."

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

Researchers Quantify a Seeded Snowpack

Denys Nevozhai

Skiers are in their element the moment temperatures start to fall—gear out, tire chains at the ready, and eager for the first snowflakes to float down from the sky.

Snow season is a popular time in the western United States, but winter precipitation does more than create a playground for outdoor enthusiasts. Winter snowpacks provide much-needed water for arid and populated Western states, and in a warming climate, these snowpacks are at risk.

For almost 100 years, scientists have been working on a way to seed clouds, forcing them to drop their floating moisture. Seeding works, but scientists have found it difficult to quantify just how much precipitation is a result of cloud-seeding events.

In a new study, scientists were able to measure the amount of snow generated from cloud seeding over an area in western Idaho.

This work is an important step in understanding how effective cloud seeding might produce much-needed water in the arid and mountainous West.

Coaxing Precipitation from Clouds

Seeding clouds in mountainous regions, or orographic cloud seeding, has the potential to increase water storage in dry areas. During orographic seeding, silver iodide (AgI) is released from an airplane or flares. Tiny, supercooled water droplets in the atmosphere crystallize around the AgI droplets, eventually merging and becoming heavy enough to fall out of the sky.

But the efficacy of artificially coaxing water out of the sky has been a mystery. “Despite cloud seeding being conducted for almost a hundred years, we had difficulties quantifying how much water we can get out of these clouds,” said Katja Friedrich, an atmospheric scientist at the University of Colorado Boulder and lead author of the paper in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/seeding-snowfall).

Friedrich said the biggest problem is distinguishing natural precipitation from that generated from cloud seeding. In the past, scientists statistically compared the results of a cloud-seeding event to precipitation on a nonseeding day.

Measuring Snowfall

Friedrich said her team’s monitoring method allowed them to see unambiguous evidence that significant precipitation was generated from cloud seeding.

The team traveled to Idaho’s Payette River basin to measure precipitation resulting from three cloud-seeding events. Weather radar tracked the generation and intensity of precipitation while gauges on the ground measured snowfall during three hour-long seeding sessions.

Seeding clouds in mountainous regions has the potential for increasing water storage in dry areas.

Snow ranging from 0.05 to 0.3 millimeter fell to the ground after the seeding events. “In total, we generated water that’s equivalent to 282 Olympic-sized swimming pools,” said Friedrich.

In addition to the measurements of snow, Friedrich noted that her team learned how the distributions of snow changed on the basis of atmospheric conditions. For example, on the third day of seeding, high winds and turbulent conditions caused precipitation to spread out over a large area.

“I think what is interesting about this study is that they were able to take a very still-pressing question, which is whether or not cloud seeding is an effective way of increasing precipitation, and apply cloud research tools to try to effectively answer that question,” said Gannet Hallar, director of the Storm Peak Laboratory at the Desert Research Institute in Steamboat Springs, Colo. She was not part of the new study.

Hallar said although the study was an impressive and carefully designed investigation, “the limitation is that these are only case studies.” She added that there are still unanswered questions about how spatial and temporal variables in the atmosphere affect precipitation from cloud seeding.

“It’s one thing to increase precipitation at a given point; it’s another thing to increase precipitation over a basin scale,” said Hallar. She noted that expanding the cloud-seeding research to another orographic area would be a logical next step in understanding how to create targeted precipitation. “There’s still quite a bit of research to be done,” she said.

Friedrich agreed with Hallar and said there are a lot of unanswered questions.

The team’s next steps include more scientific analyses of their data, including understanding the water year with and without cloud seeding and how much of the water would get stored in stream and reservoir systems.

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

The Ecological Costs of Removing California's Offshore Oil Rigs

Dozens of drilling platforms (like Ellen and Elly, off the coast of Long Beach) are being decommissioned in California. Credit: Bureau of Safety and Environmental Enforcement

Life finds a toehold just about anywhere, and the hulking edifices of offshore oil- and gas-drilling platforms are no exception. But these structures, many of which are decades old, are starting to be decommissioned.

Researchers have now calculated the ecological impact of losing these human-made habitats. Over 95% of fish biomass around a platform would be lost if it were removed completely, the team found. Another option—severing platforms at a water depth of 26 meters and removing only the uppermost part of the structure—would deplete only about 10% of fish biomass, they concluded.

Ghost Ships off California

Twenty-seven oil- and gas-drilling platforms dot the coastline of California, most of them in the Santa Barbara Channel. They were built from the 1960s through 1980s, and they're showing their age—several are in the early stages of decommissioning. (The Los Angeles Times called one of those platforms, Holly, a "ghost ship.")

There's ongoing discussion about what to do with these structures as they're decommissioned, said Erin Meyer-Gutbrod, a marine ecologist at the University of California, Santa Barbara. "That's going to mean plugging and abandoning the wells. And then conversations will start about what to do with the infrastructure, whether to remove everything or leave some of it in place for an artificial reef."

Donna Schroeder used this small submersible to collect data for the study. Credit: Bureau of Ocean Energy Management

A "rigs to reefs" approach—turning decommissioned structures into habitats for marine creatures—has been applied extensively in the Gulf of Mexico. Such artificial reefs have been shown to be extremely productive fish habitats.

The scientists calculated that removing the platforms in their entirety would result in 83%–99% losses in fish biomass.

Three Scenarios

For 24 of California's oil- and gas-drilling platforms, Meyer-Gutbrod and her colleagues analyzed the ecological impacts of three decommissioning scenarios: leaving the platform in place, removing the portion of the platform in water shallower than 26 meters, and removing the entire platform. The team relied on observations collected by divers, crewed submersibles, and bottom trawl surveys between 1995 and 2013.

Donna Schroeder, a marine ecologist at the Bureau of Ocean Energy Management in Camarillo, Calif., was instrumental in collecting some of those data. She rode to the seafloor aboard the *Delta*, a petite submersible painted bright yellow. "You had to [lie] down horizontally in the front of the submersible and look out the portholes," said Schroeder. Dives could last for several hours, so drinking a lot of liquids beforehand was ill-advised, she said. "There's not much privacy and not many options."

Schroeder and other researchers manually counted fish around the platforms. They used estimates of the animals' sizes and spatial density to calculate the amount of fish biomass present near different parts of each platform.

An oil platform close to Catalina Island, California, supports a healthy reef habitat. Credit: Adam Obaza, NOAA Fisheries West Coast, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

Meyer-Gutbrod and her collaborators found that blacksmith were common in the upper water column. Rockfish inhabited the lower reaches of most platforms, and assorted small fish darted among piles of mussel shells that littered the platforms' bases. Mussels cling to oil- and gas-drilling platforms but can be dislodged by waves or intentional cleaning efforts, said Meyer-Gutbrod. "They rain down and pile up into a big mound of shells beneath the platform." That creates new habitat, she said. "The spaces amongst the mussels make good hidey holes for the smallest fish."

Biomass Losses

The scientists calculated that removing the platforms in their entirety would result in 83%–99% losses in fish biomass. But cutting off just the top portion of the platforms—leaving structures below a water depth of 26 meters intact—would deplete, on average, just 10% of fish biomass. That significant difference makes sense, said Meyer-Gutbrod, because there's "all of this added habitat" from a platform's A-frame-shaped underwater structure.

"This work is on point," said Claire Paris-Limouzy, a biological oceanographer at the University of Miami's Rosenstiel School of Marine and Atmospheric Science in Virginia Key, Fla., not involved in the research. The findings make sense, she said, because the submerged portion of a platform attracts new fish. "It's a completely different community," said Paris-Limouzy, so removing that habitat is bound to decimate fish populations.

These results were presented in February at Ocean Sciences Meeting 2020 (bit.ly/oil-rigs). They were also shared at a public forum in Long Beach, Calif., in January. It's important to disseminate these findings to the public, said Meyer-Gutbrod, because many of the platforms—and the marine habitats they sustain—lie very close to the shore. "We can see Holly right from the beach that we walk to from our house."

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

Could Wildfire Ash Feed the Ocean's Tiniest Life-Forms?

NASA's Terra satellite caught images of smoke clouds from the Thomas Fire on 16 December 2017. Credit: NASA/Goddard Space Flight Center Earth Science Data and Information System (ESDIS) project

The Thomas Fire was the biggest wildfire California had ever experienced at the time. It burned over 280,000 acres and destroyed more than a thousand structures in the final month of 2017. It painted the sky orange and brown, streaking across NASA's satellite images of the state's central and southern coast.

Tanika Ladd, a graduate student at the University of California, Santa Barbara, was on campus as the fires raged. "We were walking around town, and everyone was wearing masks because all this ash was falling," she said.

Ladd wondered how the ash might mingle with marine life offshore. So after a colleague collected fallen ash from the fire off car windows, she took the samples to the lab to find out. The tests suggest that nutrients leeched from the ash could spur phytoplankton growth, particularly during times of the year when the ocean is short on nutrients. The preliminary research is another step in uncovering wildfire's evolving fingerprint on Earth's landscape.

An Inhospitable Ocean

Despite how *Planet Earth, The Blue Planet,* and other documentaries depict the ocean, most of its surface is a barren, nutrient-poor wasteland.

Tiny floating organisms, called phytoplankton, rarely have the nutrients they need to grow in much of the ocean, and they take nutrients from wherever they can find them, even from atmospheric sources. Past studies on volcanoes have revealed how eruptions pumping iron-rich ash into the atmosphere could feed phytoplankton downwind, and dust drifting off the Sahara has long been recognized as a "sandy fertilizer" for ocean plants.

Much less attention has been paid to the impact of wildfire ash. In the case of Australia's recent bushfires, which burned an area roughly the size of the state of South Carolina and killed at least 34 people, experts didn't know how the ash accumulating along beaches affected marine life. And as wildfires in some places accelerate from drought, climate change, and forest management practices, this question may become more pressing.

The tests suggest that nutrients leeched from the ash could spur phytoplankton growth, particularly during times of the year when the ocean is short on nutrients.

Charred Fertilizer

Ladd and her colleagues devised an experiment to test how plankton communities bobbing in the Santa Barbara channel's coastal waters would respond to an influx of ash-leeched chemicals. They mixed the ash with seawater, collected offshore in the channel (where ash clouds blew during the Thomas Fire), to create a yellowish mixture in the lab. After straining out the floating bits, researchers enriched tanks full of naturally occurring marine phytoplankton communities and let them grow outside in natural light conditions. At four different times over a week, they measured biomass and nutrients in the water. They repeated the experiment during each season.

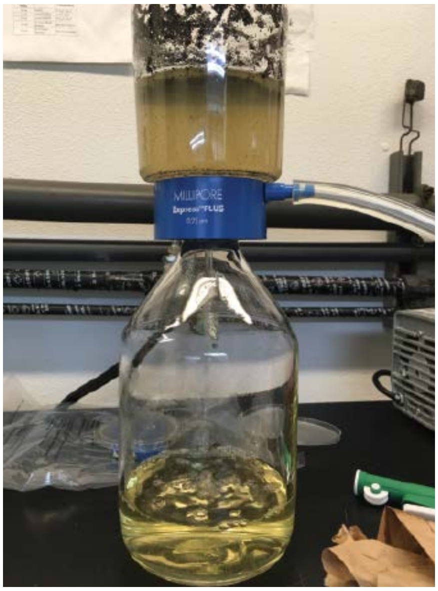
In the experiments, the phytoplankton greedily sucked up the available organic and inorganic nitrogen coming off the ash in the form of nitrite, nitrate, and ammonium. Nitrogen is a major component needed for cells, but as Ladd explained, fire season, at least in the Santa Barbara Channel where she did the study, is a time when there are generally fewer nutrients in the system.

The additional nitrogen helped phytoplankton communities grow more than the controls during summer, fall, and winter, a trend Ladd could see by measuring the total biomass in the samples over time. During summer, fall, and winter, the ash-fueled phytoplankton had more than double the biomass than the controls. Plankton in the spring, on the other hand, showed less of an effect. The ocean has a huge influx of nutrients in the spring from ocean upwelling, so any seeding from the ash didn't have as great an impact.

The ash didn't leech phosphorus, which the ocean is often depleted of, but Ladd said the exact chemicals leeched from the ash will change by location. "My findings might be slightly different than [those of] someone else who does something with the Australian wildfires," she said.

Questions Adrift

Ladd noted that the study is one of the first to link wildfire ash and marine systems, but many unknowns remain, such as the amount of ash deposited and what happens to it when it settles on the ocean. "If this is happening, then that atmospheric component of ash is



Researchers siphoned out the ash from the seawater after letting it soak for 1 hour. Credit: Tanika Ladd

likely a more important nutrient source for coastal systems," she said.

Sasha Wagner, an assistant professor at Rensselaer Polytechnic Institute in Troy, N.Y., who did not contribute to the work, said ash deposition is an important source of nutrients in surface water for freshwater streams and lakes after a fire. "The fact that they were able to capture these samples and start asking these questions, I think, is really important to kind of push this kind of research forward."

Nick Ward, a research scientist at Pacific Northwest National Laboratory in Sequim, Wash., who was not involved with the research, said he's curious to know how wildfires might contribute to excess nutrients in the marine environment. With large fires in places like the Amazon, ash deposition "could have a global impact if it's changing productivity or shifting communities," he said.

Ladd plans to analyze the DNA of plankton from the experiment to see whether the ash gave certain species an advantage over others. In a preliminary analysis using microscopes, Ladd found that the ash did not seem to change the abundance of one particular type of phytoplankton, but further analysis is needed. Ladd presented the work in February at Ocean Sciences Meeting 2020 (bit.ly/ash-phytoplankton).

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

Coastal Wetlands Save $1.8 Million per Year for Each Square Kilometer

Mangroves in Florida's Biscayne National Park near Miami. Credit: Yinan Che, Public Domain

Mangrove forests, marshes, and seagrass beds protect inland areas from storm surges and strong winds. Over long periods, coastal wetlands like these build up sediment that mitigates sea level rise and local land subsidence.

A new analysis of property damage from Atlantic and Gulf of Mexico coastal storms has shown that counties with larger wetlands suffered lower property damage costs than did counties with smaller wetlands.

"Starting in 1996, the U.S. government started to produce damage estimates for each tropical cyclone in a consistent manner," explained coauthor Richard Carson, an economist at the University of California, San Diego (UCSD) in La Jolla. Before that, the data were collected only for hurricanes, which hindered past attempts to put a price on the marginal value, or price per unit, of wetlands, he said.

With the complete data set, the researchers examined all 88 tropical cyclones and hurricanes that affected the United States starting in 1996. That time period includes Hurricanes Katrina and Sandy.

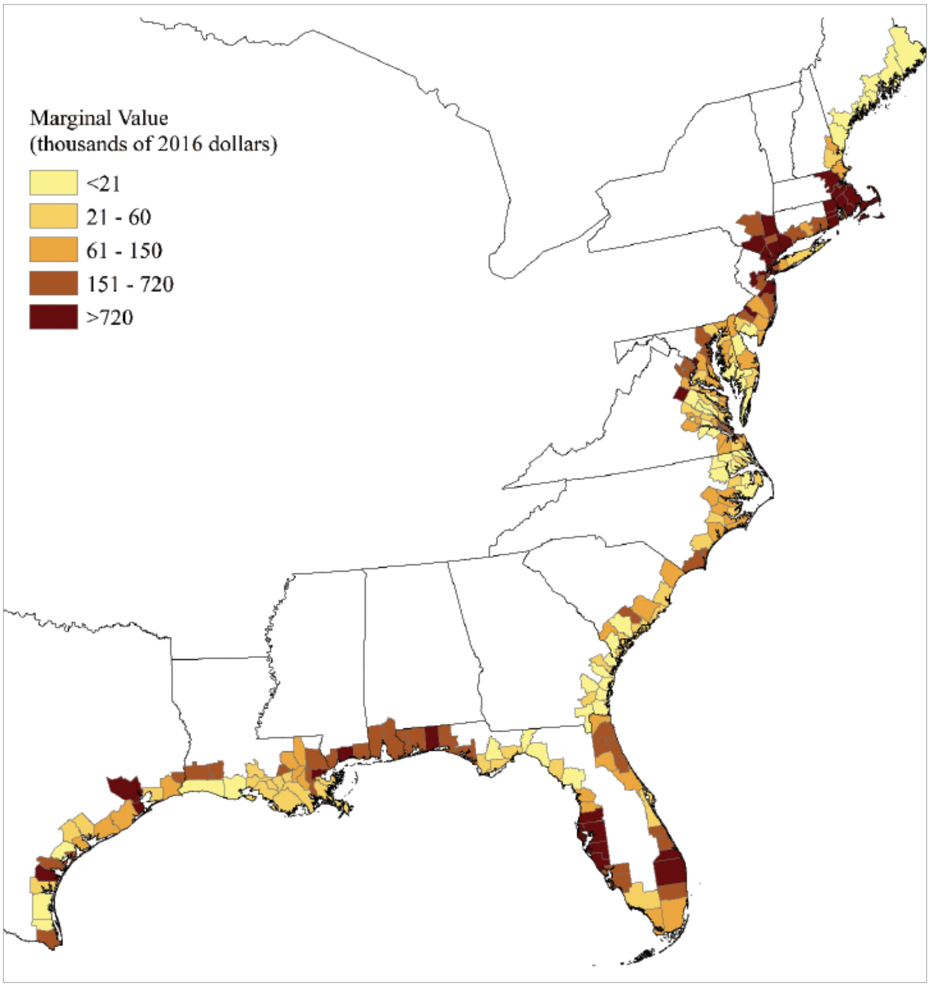
A Protective and Economic Boon

In addition to property damage data for tropical cyclones of all strengths, "our data set has considerably more spatial resolution," Carson said, "which is a result of large amounts of information on storm tracks, property location, and wetland location all being digitized for use in a geographical information system basis."

First author Fanglin Sun, formerly at UCSD and now an economist at Amazon, added that "areas subject to flood risk in a county are more accurately estimated, based on local elevation data and detailed information on individual storm trajectories" and wind speeds throughout affected areas.

The finer level of detail for the storm data let the researchers finally begin connecting wetland coverage and storm damage on a county-by-county basis, Carson said. "A storm track moving a couple of kilometers one direction or the other allows the amount of wetland protection to vary within the same county."

In terms of property damage, Sun and Carson found that a square kilometer of wetlands



Wetlands along the Atlantic and Gulf of Mexico coasts of the United States have a higher marginal value (dark colors) in densely populated urban counties but are worth relatively more in counties with weaker building codes. Credit: Sun, F., and R. T. Carson (2020), Coastal wetlands reduce property damage during tropical cyclones, Proc. Natl. Acad. Sci., 201915169, https://doi.org/10.1073/pnas.1915169117.

saved an average of $1.8 million per year. Over the next 30 years, an average unit of wetlands could save $36 million in storm damage.

Some wetlands were valued at less than $800 per year per square kilometer and some at nearly $100 million. That marginal value depended on many factors, including a county's property values, existing wetland coverage, coastline shape, elevation, building codes, and chance of actually experiencing damaging winds. And each of those variables fluctuated over the 20 years the team studied.

Over the next 30 years, an average unit of wetlands could save $36 million in storm damage.

Overall, the highest-valued wetlands were in urban counties with large populations and the lowest-valued were in rural areas with small populations. However, wetlands provided a greater relative savings against weaker cyclones and in counties with less stringent building codes—areas that might not expect or plan for a tropical storm.

The team found no significant difference in the marginal value of saltwater versus freshwater wetlands or mangroves versus marshes. "Forested wetlands tend to be better at reducing wind speed and marshes tend to be better at absorbing water," Carson said, "so the specific nature of the storm when it hits an area is likely to matter. [But] our results suggest that, on average, there is no difference."

"The value coastal wetlands provide for storm protection is substantial and should be taken into account as policy makers debate the Clean Water Act."

The team published these results in *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/wetlands-damage).

Wetlands at Risk

Most areas that have experienced storm-related property damage in the past 20 years have also lost wetland coverage, the researchers found. They calculated that Floridians would have been spared $480 million in property damage from Hurricane Irma alone had the state's wetland coverage not shrunk by 2.8% in the decade prior.

Moreover, recent changes to the Clean Water Act have made the remaining coastal wetlands more vulnerable (see bit.ly/Eos-Clean-Water-Act).

"The federal government, with respect to the U.S. Clean Water Act, took the position that the previous wetland studies were not reliable enough for use in assessing the benefits and cost of protecting wetlands," Carson said.

"The value coastal wetlands provide for storm protection is substantial and should be taken into account as policy makers debate the Clean Water Act," Sun said. "It's also worth noting," she added, "that storm protection for property is just one of many ecological services that wetlands provide. We hope our study will spur future research quantifying these other services as well."

With tropical storms and hurricanes expected to happen more often because of climate change, the team wrote, wetlands will be more economically valuable than ever.

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

Sustainable Agriculture Reflected in Cuba's Water Quality

Scientists gather water quality measurements in central Cuba. Credit: Joshua Brown

Beginning in 1990, Cuban agricultural technology did an about-face as small-scale, organic practices proliferated after the fall of the Soviet Union. And now, just 3 decades later, the country's river chemistry reflects these sustainable practices, an international team of researchers showed.

Cuban river water has very high levels of cations and anions released by rock weathering, a natural process, and relatively low levels of nutrients linked to fertilizer runoff. That's good news for preventing harmful algal blooms in Cuba's coral reefs, which represent a significant source of tourist-driven income for the Caribbean's largest and most populous nation, the researchers suggest.

Have Minivan, Will Travel

In August 2018, Paul Bierman, a geologist at the University of Vermont in Burlington, and his colleagues convened in central Cuba. The group included scientists and technicians from American and Cuban institutions.

Biologists, geologists, and physicists rubbed shoulders during the fieldwork, said team member Alejandro García Moya, an Earth scientist at the Centro de Estudios Ambientales de Cienfuegos in Cuba. "We had the opportunity as scientists to share our experience and knowledge with people from different research and science perspectives."

The team traveled in two yellow minivans and visited 25 rivers across central Cuba. They typically went to two or three field sites per day. At each site, the scientists made measurements of the river water's dissolved oxygen, temperature, pH, and conductivity. They also took water and sediment samples, photographed the area, and recorded the region's geographical coordinates using GPS.

Bierman and his colleagues shipped coolers containing the water and sediment samples to several laboratories in the United States. There were plenty of logistics involved, he said. "You can't export material from Cuba without a very thick stack of paperwork that's been signed, stamped, and approved." But the process is worth it, said Bierman, because scientists based in the United States are eager to work with Cuban samples. "We've gotten an awful lot of science done."

Weathering at the Surface

The researchers found that rivers in central Cuba contained high loads of dissolved solids produced by chemical weathering of rocks. Using precipitation and runoff estimates, Bierman and his colleagues calculated that on average, roughly 160 tons of rock per square kilometer of land were being transported downriver each year because of chemical weathering. "That's how much mass is being removed," said Bierman. That rate is comparable to the rates of other tropical environments and is in the top 25% of rates globally, the team concluded.

Furthermore, the dissolved solids tended to be correlated with the surrounding rock type, the scientists showed. That relationship is somewhat surprising, the team suggests, because it implies that river water is in direct contact with weatherable rock. (In tropical climates like Cuba's, chemical weathering should occur far below the surface.) One explanation, Bierman and his colleagues propose, is that tectonic uplift in Cuba—the island is located at the boundary of the North American and Caribbean plates—provides a constant supply of fresh rock that is continually incised by rivers and dissolved by groundwater.

Mind the Blooms

The researchers also showed that Cuban waters tended to contain relatively low levels of fertilizer-associated nutrients such as nitrates and phosphates. "The nitrate and phosphate loads coming off of Cuba are a lot lower than what's draining down the Mississippi River," said Bierman. That makes sense, he said, because area-normalized fertilizer usage in Cuba is roughly half that of the United States. "We put on a lot more fertilizer than the Cubans."

These results were published in *GSA Today* (bit.ly/Cuban-agriculture).

Cuba is far from a self-sustaining nation—it still imports roughly 70% of the food its citizens need—but its agricultural practices are a step in the right direction ecologically, said Bierman. They're helping to stave off the adverse effects of fertilizer runoff, for starters. When nutrients like nitrogen accumulate in the water, they can trigger harmful algal blooms, which can produce toxins and literally choke out other forms of life. In the Gulf of Mexico, for example, there's a large low-oxygen dead zone caused by such eutrophication.

Nitrogen runoff is a big problem for many coral reefs worldwide, but Cuba's ecosystem seems to have avoided a similar fate, said Daria Siciliano, a marine ecologist at the University of San Francisco not involved in the research. These results are "very valuable" because they provide an upstream explanation for the health of Cuba's coral reefs, she said.

Bierman and his U.S.-based colleagues plan to return to Cuba in August to sample rivers in other parts of the country. It's a "challenge and a huge opportunity" to work in a place so understudied by American researchers, said Bierman. He's looking forward to continuing to strengthen collaborations with Cuba-based scientists. "The bridges we've built for science have gone far ahead of what's going on politically between our two governments."

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

Don't @ Me: What Happened When Climate Skeptics Misused My Work

When my first peer-reviewed scientific paper was published in *Geophysical Research Letters* in February 2019, I felt that I had passed a significant graduate school milestone, and I celebrated the way many early-career researchers do: I told my parents and had drinks with my coauthors. A few months later, a colleague let me know that she had cited my paper—another milestone—and for the first time I navigated to the "attention score" page attached to my article. There I found my friend's citation as well as another, more sinister surprise.

My article's attention score, an indicator of interest in a paper, was in the top 5% of all research tracked by Altmetric, largely because of a plethora of Twitter posts. Initially curious, I quickly became mortified as I scrolled through the page and found that something was wrong. Accounts with thousands of followers were using my article to substantiate their arguments that climate change is a hoax perpetrated by the scientific establishment.

How Did This Happen?

The energy budget at Earth's surface consists of several components: Incoming shortwave radiation from the Sun (mostly visible and ultraviolet light) and longwave (infrared) radiation emitted downward by clouds, water vapor, and other greenhouse gases in Earth's atmosphere are balanced largely by longwave radiation emitted upward by the surface and by evaporation of liquid water from Earth's oceans. The paper in question, which I coauthored with two colleagues, concerned the longwave radiation emitted by the atmosphere toward Earth's surface (see bit.ly/longwave-radiation).

The amount of downward longwave radiation that reaches Earth's surface is controlled by clouds, greenhouse gas concentrations, temperatures in the atmosphere, and how these all vary with height. This height dependence means that not all parts of the atmosphere are equally important to the longwave radiation incident at Earth's surface. Nearly all the water vapor in the atmosphere is located within a few kilometers of the surface; under this thick layer of water vapor, the surface is radiatively isolated from all but the lowest layer of the atmosphere. The temperature throughout this lower atmospheric layer is tightly coupled to that of Earth's surface by turbulence that mixes air extremely efficiently. Any increase in the surface temperature is communicated very quickly via turbulence to the lower atmosphere, where it is reflected back toward the surface in the form of enhanced downward longwave radiation that contributes to further surface warming. In other words, the system comprises a positive feedback loop.

By invoking this feedback, our work explained why, when climate models are forced with high atmospheric carbon dioxide concentrations, the increase in downward longwave radiation at the surface is much larger than the change one might expect from excess emissions alone.

Accounts with thousands of followers were using my article to substantiate their arguments that climate change is a hoax perpetrated by the scientific establishment.

In our abstract, my coauthors and I wrote that "surface downward longwave radiation is tightly coupled to surface temperature; therefore, it cannot be considered an independent component of the surface energy budget." The community that promoted our paper on Twitter mistakenly took that to mean that global temperature change cannot be caused by changes in the longwave portion of the planetary energy budget, thus furthering their argument that greenhouse gas concentrations do not contribute to climate warming.

Is this a logical interpretation? Absolutely not. A strong feedback between surface temperature and downwelling longwave radiation does not mean that carbon dioxide emissions have no impact on the longwave component of the planetary energy budget. In fact, just the opposite is true: The strong feedback means that greenhouse emissions can have a substantial effect on longwave radiation. Yet I found myself scrolling through pages of posts jeering at climate scientists and dismissing science as politically motivated propaganda. I felt sick to my stomach that my work had become part of messaging targeting legitimate climate science.

Unfamiliar Territory

For several days, I felt demoralized, embarrassed, and frustrated. Like many young climate scientists, I came to graduate school because I have a passion for science and because I want to use what I learn to help society mitigate and adapt to the dangerous impacts of climate change. Instead of contributing, however, my work had been incorporated into a discourse that demonizes both the scientific consensus on climate change and the scientists who publicly speak out to defend it.

Worse, it felt like there was nothing I could do. As an early-career scientist with no social media following and little institutional credibility, I felt completely unequipped to address this problem on my own. It seemed that my only options were to jump into the fray on Twitter or to do nothing, ignoring those who misrepresented my work and going back to doing my research.

Engaging with those who misrepresented my research on their turf could play into their hands, serving only to raise their online profiles. But doing nothing widens the disconnect between science and society that is at least partially responsible for the success of campaigns to misrepresent the climate consensus in the first place. If the climate science community does not actively fight against the deliberate misuse of credible science, we run the risk of being outpaced in the battle for public opinion that has an important front on social media.

Unsure of how best to proceed, I asked for help. I talked with my adviser and other faculty members in my department, and one thing became clear: I was far from alone in having my research hijacked. One mentor had her work on carbon dioxide fertilization of plants picked up by a far-right magazine in Australia that claimed her research demonstrated the positive effects of fossil fuel emissions. Another had her work on climate sensitivity misused in a report published by the Heartland Institute, a think tank that has disseminated climate misinformation to schools across America. Although these stories helped me to realize that I am not the only one who has had his or her work misrepresented, I still had no constructive avenue to respond to the community that had misrepresented my research.

Climate scientists know that a vocal minority in the United States is skeptical about—and often antagonistic toward—the global warming consensus. But until I experienced my own work being misused, I did not fully appreciate how this skepticism and antagonism are manufactured in the context of an explicitly politicized discourse. By taking slivers of published scientific research out of context, anybody who can parse an abstract can launch an ideological crusade—masquerading as thoughtful scientific criticism—against the scientific consensus.

These crusades are *always* political. Criticism of the global warming consensus is motivated by criticism of policies informed by that consensus. This motivation is why producing more thoughtful and accurate science does not silence skeptics or convince them of the overwhelming scientific agreement about the reality of global warming and its causes and effects, which leaves scientists and their institutions in unfamiliar territory. The paradigm of scientific progress gradually inching toward truth (or slowly ruling out falsehood) is not sufficient to counter the political dimensions of climate science misinformation campaigns. Acknowledging this insufficiency on personal and institutional levels is the first step in addressing the manufactured controversy over climate science that is happening outside academia.

I learned to anticipate how my science could potentially be distorted and to address these points explicitly in abstracts and in any public-facing components of my research.

Lessons Learned

I still feel guilty for not engaging those who misrepresented my work on Twitter; maybe I was wrong to abdicate responsibility for standing up for my science. Regardless, the experience taught me valuable lessons that will inform my response—and that may be of help to other scientists, early career or otherwise—when similar episodes occur.

One lesson I learned is to anticipate how my science could potentially be distorted and to address these points explicitly in abstracts and in any public-facing components of my research. If I could go back and rewrite the abstract of my group's paper, I would include a sentence that points out why a feedback between surface temperatures and downwelling longwave radiation does not preclude the existence of the greenhouse effect.

Journal editors can act as a second line of defense, directing authors to acknowledge and preemptively refute points in their papers that could be misrepresented. Such refutations will undoubtedly seem obvious to trained scientists, but they are still important. By explicitly refuting potential distortions in our publications, we acknowledge the presence of a controversy and help to address it on our own platforms that lend professional credibility to our statements. The clearer we are in our publications, the more difficult it is for skeptics to muddy the water, and the more difficult it becomes for politicians and corporations to disingenuously question consensus climate science.

Still, these steps do not address the significant public dialogue about science that now takes place on social media. The unprecedented dissemination of information (and misinformation) made possible by the Internet demands that scientists and their institutions evolve to meet the public's growing appetite for credible science while also acknowledging political implications of their work.

Social media training offered by universities and membership organizations like AGU is important for preparing those who want to use social media to communicate science to the general public. Even though online ecosystems can feel alarmingly hostile to informed debate, we must all do our part to ensure that our work is as difficult as possible to misrepresent. By addressing head-on the fact that our public-facing communications about research will be scrutinized by those with political axes to grind against climate science, we can reduce the bandwidth across which skeptics can misrepresent science on Twitter and other platforms; ultimately, this practice will diminish their credibility.

The political dimensions of climate change guarantee that climate science will continue to be misrepresented by those with ideological agendas. Climate scientists have a responsibility to untangle fact from fiction and to communicate with society clearly about the dangers of climate change. If we do not actively take on that role, others will fill the vacuum that our silence creates.

By **Lucas Vargas Zeppetello** (lvz7@uw.edu), University of Washington, Seattle

▶ Read the article at bit.ly/Eos-climate-skeptics

Opposite: iStock.com/Devrimb

RETURNING LIGHTNING DATA TO THE CLOUD

By Morris Cohen

SCIENTISTS ARE ASSEMBLING AN ONLINE DATABASE WITH DECADES OF LOW-FREQUENCY RADIO MEASUREMENTS COLLECTED WORLDWIDE TO FACILITATE MODERN RESEARCH ABOUT LIGHTNING, SPACE WEATHER, AND MORE.

This past December at AGU's Fall Meeting in San Francisco, I presented a poster with not a shred of new science on it. Yet it might turn out to be the highest-impact presentation I've made.

With the poster, several colleagues and I introduced WALDO to the world. WALDO, or the Worldwide Archive of Low-frequency Data and Observations, is a large—and growing—trove of low-frequency (0.5 to 50 kilohertz) radio data collected over decades at sites around the world. Mark Golkowski of the University of Colorado Denver (CU Denver) and I jointly manage the database.

Such data have all kinds of uses in geophysics, including in lightning detection and characterization, remote sensing of ionospheric and magnetospheric phenomena, and detection of solar flares, gamma ray flashes, and gravity waves. Until recently, however, the data on WALDO have been amassed and stored mainly on tens of thousands of DVDs—and thus have been largely inaccessible to anyone interested in using them.

Data collected using the antenna array of the High-frequency Active Auroral Research Program in Alaska are included in the new Worldwide Archive of Low-frequency Data and Observations (WALDO) database, along with data from numerous other sites. Credit: Secoy, A., CC BY-SA 4.0 (bit.ly/ccbysa4-0)

WE HAVE DEVELOPED AN ONLINE INTERFACE THAT ALLOWS EASY ACCESS TO THE DATA. THROUGH THE WEBSITE, USERS CAN VIEW AUTOMATICALLY GENERATED QUICK-LOOK PLOTS TO MAKE IT EASY TO FIND OUT WHAT'S AVAILABLE.

A very low frequency radio antenna sits atop a glacier in 2006 (top) near Palmer Station on the Antarctic Peninsula (bottom). Credit: Morris Cohen (top); Christopher Michel (bottom), CC BY 2.0 (bit.ly/ccby2-0)

Our goal with WALDO is to transfer and organize these historical data, augmented with ongoing data collection, into a single, standardized cloud-based repository so that scientists today and in the future can access them and put them to use in studies of lightning, the ionosphere, the magnetosphere, space weather, and more.

The Science of ELF/VLF

Each of the millions of lightning strokes per day on Earth releases an intense, roughly 1-millisecond-long pulse of extremely low frequency to very low frequency (ELF/VLF) radio energy known as a sferic. These sferics reflect from the lower ionosphere (60–90 kilometers altitude) and off the ground, allowing them to travel—and be detected—globally. A handful of VLF receivers scattered around the globe can geolocate most lightning flashes with incredible kilometer-level accuracy [*Said et al.*, 2010]. Sferic detection can also be used to characterize the electrical properties of the lower ionosphere between the source and a distant receiver.

Narrowband beacons used by the U.S. Navy, nominally for submarine communications, also transmit in the ELF/VLF frequency band, providing another means of ionospheric remote sensing. Although these messages are encrypted for security, the radio signals themselves are a useful ionospheric diagnostic that can be picked up anywhere on Earth. Changes in ionospheric conditions, namely, the electron density, manifest as changes to either the amplitude or the phase of received signals. In turn, the ionosphere can be used as a sensor to monitor all kinds of geophysical phenomena, including solar flares, electron precipitation from the magnetosphere, solar eclipses, lightning-related heating, cosmic gamma rays, gravity waves, and much more. Each of these phenomena disturbs VLF signals propagating under the ionosphere in different ways—affecting how quickly a disturbance begins and ends, for example—and these signatures allow them to be distinguished from one other. Some ionospheric disturbances are very reliable and repeatable, like the effect of the Sun rising and setting.

Some ELF/VLF energy also escapes into the magnetosphere (as lightning-generated plasma waves called whistlers), where it can interact with trapped energetic electrons in Earth's radiation belt and trigger precipitation of electrons into the atmosphere. ELF/VLF waves are also generated and accelerated in the magnetosphere (as waves called chorus and hiss) as a result of wave-particle interactions and thus play a role in the dynamics of space weather at Earth. Studying ELF/VLF radio waves allows us both to study and better understand these processes and to piece together mysteries of what happens during space weather events and geomagnetic storms.

These uses of ELF/VLF data, reviewed by, for example, *Barr et al.* [2000], *Inan et al.* [2010], and *Silber and Price* [2017], have been developed since the late 1800s, when natural ELF/VLF signals could be heard coupling into long telegraph lines. But a number of other applications outside the traditional uses of ELF/VLF data have also popped up recently. For example, detection of objects inside metal boxes using ELF/VLF waves [*Harid et al.*, 2019] could be used to discover a cache of guns hidden inside a shipping container.

In partnership with a cybersecurity research group at the Georgia Institute of Technology (Georgia Tech), colleagues and I are also using ELF/VLF data to boost the security of the power grid against cyberattacks, such as the major attack in Ukraine in December 2015 in which hackers disabled multiple electrical substations. ELF/VLF data detected by radio receivers can be used to monitor power grid signals for irregularities. These data are also littered with sferics from lightning flashes around the world, which arrive at receivers at quasi-random times as lightning occurs. Nature thus provides an effective and detectable random number generator that because lightning flashes cannot be predicted in advance, allows us to validate the integrity of other data detected by the receivers [*Shekari et al.*, 2019].

Developing WALDO

The WALDO database—currently about 200 terabytes and growing daily—already contains or will soon contain data that could enrich studies of all of the above phenomena and applications. Much of the data were collected by Stanford University ELF/VLF receivers and, more recently, by new sites deployed by Georgia Tech and CU Denver.

WALDO also includes ELF/VLF recordings from experiments carried out as part of the High-frequency Active Auroral Research Program (HAARP) in Alaska [*Cohen and Golkowski*, 2013], which has been running experiments to study the high-latitude ionosphere since the mid-

1990s. It includes many years of data from Palmer Station on the Antarctic Peninsula. And it will eventually include a lot of data from the famous Siple Station ELF experiment, which ran from 1973 to 1988 to study the amplification and triggering of ELF signals in the magnetosphere using a 42-kilometer antenna in Antarctica. By the end of the year, we anticipate having 500–1,000 terabytes of data available.

The effort to compile these disparate data sets into a single database began in fall 2018, when the space at Stanford University where these data were physically stored—on roughly 80,000 DVDs and CDs and on one badly corrupted server—had to be cleared. The disks, some of which were damaged after decades of storage, were packed and shipped to either Georgia Tech or CU Denver, where DVD-reading robots that can rip a stack of 300 disks at a time are used to move the data onto hard drives. Meanwhile, John DeSilva at Stanford has slowly extracted the contents of the old server and placed those data into temporary cloud storage for us to retrieve.

After retrieval, the data are passed through a digital sorting scheme that updates the formatting so it is all consistent and then places the data into sorted folders. We have developed an online interface (http://waldo.world) that allows easy access to the data, which can also be shared with anyone with a Google account upon request. Through the website, users can view automatically generated quick-look plots to make it easy to find out what's available, for example, maps of receiver sites from which data from a given day are available, annual calendars showing data availability, and summary charts of the data on a day-by-day basis.

The Value of Dusty Data

The work of preserving data is hard and time-consuming but also rewarding. We have seen evidence of this in many fields. Historical and long-term data sets have been critical in studies of climate and ecosystems, for example, shedding light not only on past conditions but also on the present and future. And thanks to preservation efforts, we are fortunate to have sunspot data extending back more than 400 years—data that underlie critical early discoveries of space weather dynamics.

As a junior at Stanford in January 2002, I approached one of my professors, Umran Inan, and asked whether I could get involved in research. I suspect he wasn't anticipating much from a student who had just gotten a C in his class. Days later I found myself in a dusty, nearly abandoned warehouse near the Stanford Dish, rummaging through 15-year-old Betamax and Ampex magnetic tapes filled with ELF/VLF radio data. The tapes were still stuffed in their original cardboard boxes and were lined up on shelves stacked 5 meters high in several rows, each probably 30 meters long. Why was I there?

In 1994, bursts of high-energy gamma rays called terrestrial gamma ray flashes (TGFs) were discovered serendipitously from space [*Fishman et al.*, 1994]. It appeared that TGFs originated with lightning, but that was pretty much all we knew about them. ELF/VLF data can be used to characterize the lightning that caused the phenomenon, but scientists had only two examples in hand of TGFs that could be directly linked with lightning via ELF/VLF data. My job was to find more examples hidden in the data on all those tapes.

As I coughed away the cobwebs, I thought about all the trouble people had gone through to keep these Betamax tapes (long an obsolete format even by then) flowing. The data I was looking through were recorded at Palmer Station, Antarctica, by a receiver mounted on a shifting glacier that was carefully watched by a full-time science technician and serviced every year by a student in the group. With each boat trip from the station, the tapes were shipped out in large boxes, then stacked and stored in this rodent-infested space—all funded by American taxpayer dollars via the National Science Foundation. And this sort of data collection had been going on for decades at sites all over the world maintained by this research group.

Living Data Sets

"Was it worth it?" I thought while slogging away in that warehouse. The answer, as I came to find out, is an unequivocal yes (and not just because these data led to my first peer-reviewed research papers and helped me get my foot in the door of research). I learned that geophysical data sets are living and that their intellectual value shifts as our scientific priorities do.

When the measurements recorded on those Betamax tapes were obtained, no one envisioned eventually needing them to study TGFs; the measurements were originally collected for other reasons. It would have been easy to throw the data away before they proved useful for studying TGFs—or even after that too. Following the use of Betamax tapes, we shifted to recording digital data on CDs, then on DVDs, then on external hard drives, then onto a large data server—and now we're moving them into the cloud. At every step, we had to drag all the accumulated data from old media into the present day. But because these data haven't been discarded, they are still available today for studying numerous natural phenomena and processes.

It's fair to ask whether it's worth it given the expense and effort. I think it is. You never know how these data might be used. I would have never expected geophysical lightning data to make an impact in the cybersecurity world, for example. Today we are seeing high-performance computing and machine learning reveal new insights from old data, and interdisciplinary projects often find surprising uses for historical data sets. In the not-too-distant future, I suspect someone will think of a new way to look at ELF/VLF data collected a decade ago. But will the data still be available?

We owe it to future scientists—and to U.S. taxpayers, who have funded much of this work—to ensure that they are available. Since announcing WALDO in December, we've gotten several inquiries and notifications from people using the database. Our hope is that by preserving these data in WALDO, we will open doors for surprising and unexpected discoveries.

References

Barr, R., D. Llanwyn Jones, and C. J. Rodger (2000), ELF and VLF radio waves, *J. Atmos. Sol. Terr. Phys., 62,* 1,689–1,718, https://doi.org/10.1016/S1364-6826(00)00121-8.

Cohen, M. B., and M. Golkowski (2013), 100 days of ELF/VLF generation via HF heating with HAARP, *J. Geophys. Res. Space Phys., 118,* 6,597–6,607, https://doi.org/10.1002/jgra.50558.

Fishman, G., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science, 264,* 1,313–1,316, https://doi.org/10.1126/science.264.5163.1313.

Harid, V., et al. (2019), Magnetic field penetration into a metal enclosure using an ELF/VLF loop antenna, *IEEE Trans. Electromagn. Compatibility,* https://doi.org/10.1109/TEMC.2019.2952560.

Inan, U. S., S. A. Cummer, and R. A. Marshall (2010), A survey of ELF and VLF research on lightning–ionosphere interactions and causative discharges, *J. Geophys. Res., 115,* A00E36, https://doi.org/10.1029/2009JA014775.

Said, R. K., U. S. Inan, and K. L. Cummins (2010), Long-range lightning geolocation using a VLF radio atmospheric waveform bank, *J. Geophys. Res., 115,* D23108, https://doi.org/10.1029/2010JD013863.

Shekari, T., et al. (2019), RFDIDS: Radio frequency–based distributed intrusion detection system for the power grid, in *Network and Distributed Systems Security (NDSS) Symposium 2019,* Internet Soc., Reston, Va., https://doi.org/10.14722/ndss.2019.23462.

Silber, I., and C. Price (2017), On the use of VLF narrowband measurements to study the lower ionosphere and the mesosphere–lower thermosphere, *Surv. Geophys., 38,* 407–441, https://doi.org/10.1007/s10712-016-9396-9.

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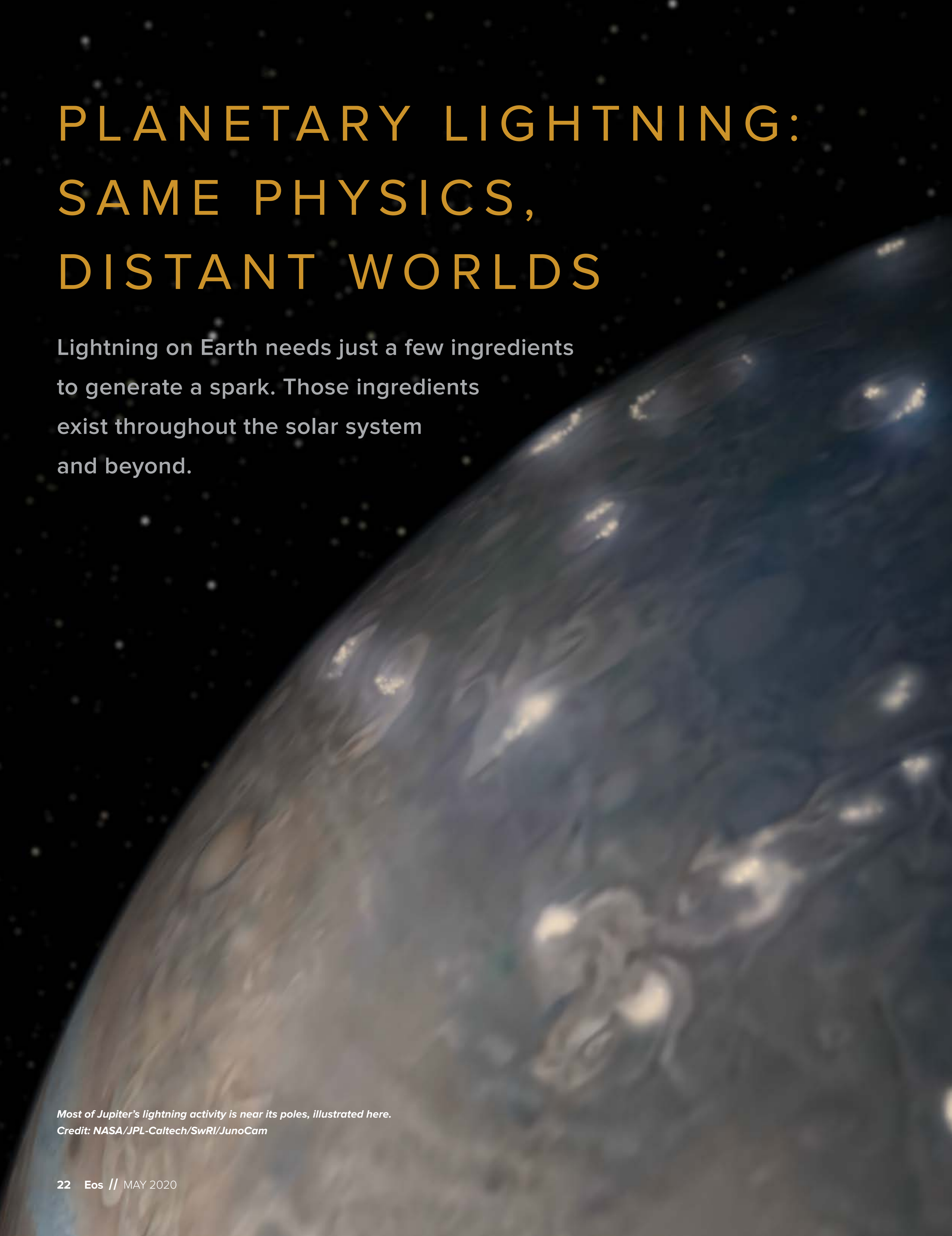
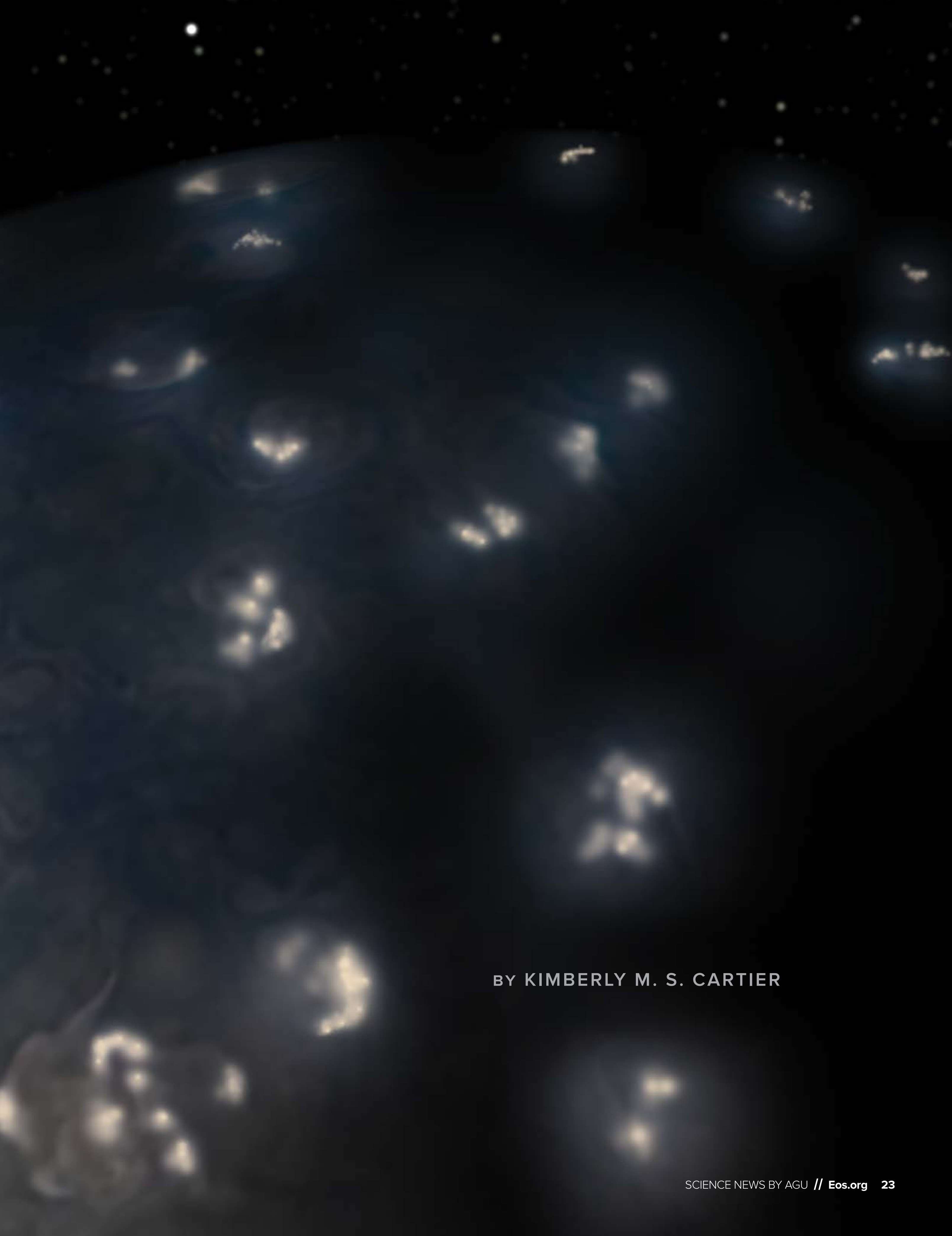
PLANETARY LIGHTNING: SAME PHYSICS, DISTANT WORLDS

Lightning on Earth needs just a few ingredients to generate a spark. Those ingredients exist throughout the solar system and beyond.



Most of Jupiter's lightning activity is near its poles, illustrated here. Credit: NASA/JPL-Caltech/SwRI/JunoCam



BY KIMBERLY M. S. CARTIER

What do you think of when you imagine lightning?

If you picture a zigzagging bolt of electricity striking the ground from a rolling thundercloud, you're right. If you picture elves, sprites, spiders, jets, or volcanoes, you're also correct.

You're also right if you picture any of those phenomena on another planet.

In 1979, NASA's Voyager 1 spacecraft flew past Jupiter and saw flashes of light larger than the United States illuminating areas of the planet's nighttime sky. Accompanying those flashes were extremely low frequency radio signals, called whistlers. On Jupiter, as on Earth, those two signs taken together unequivocally point to lightning.

Since that first Voyager 1 detection of planetary lightning, scientists have found proof of lightning and other lightning-related transient luminous events elsewhere in the solar system. In our solar system and beyond, planetary lightning goes beyond the simple scheme of the "haves" and the "have-nots." There are plenty of "maybes" and "why nots" too.

A Recipe for Lightning

Generating lightning requires a few key ingredients, explained Karen Aplin, an associate professor of space science and technology at the University of Bristol in the United Kingdom: "Lightning's like a spark, which happens because positive and negative charges become separated. When the charges are big enough, the air breaks down," she said. Lightning is the manifestation of that electrical breakdown.

Earth's thunderstorms have those key ingredients, and above thunderstorm clouds, different methods of discharging electricity can create sprites, elves, and blue jets.

But thunderstorms aren't the only environment that creates the conditions needed for lightning. "Volcanic lightning is really common in explosive eruptions. It's not a rare, unusual phenomenon," explained Alexa Van Eaton, a volcanologist at the U.S. Geological Survey's Cascades Volcano Observatory in Vancouver, Wash. "It happens during most intermediate or larger explosions, and it gets started in a simple way."

"You can expect that if it's an ash-producing eruption, it is capable of making lightning."

"As the magma rises to the surface," she said, "it can become really frothy and bubbly and break itself apart. The water bubbles expand and blow themselves up. That breakage process is highly electrifying. Once those tiny rock particles—volcanic ash—are shooting up into the atmosphere at high speed, they're colliding, exchanging electrons, and creating a charge right at the base of the volcanic plume. Then once the plume rises high enough to freeze, the ice particles help to generate even more lightning" by separating more charge.

"You can expect that if it's an ash-producing eruption, it is capable of making lightning," said Sonja Behnke, a scientist who researches volcanic lightning at Los Alamos National Laboratory in New Mexico. "It's very common, and even if it doesn't produce lightning, the ash plume might still be charged."

The ingredients for lightning—polarized gas molecules, atmospheric movement, and the possibility of electrical breakdown—exist to some degree on any world with an atmosphere. Scientists have found that this so-called planetary lightning creates signals similar to those that Earth lightning makes.

Lightning superheats the surrounding atmosphere into a plasma and creates a visible flash of light. It emits electromagnetic pulses at high, low, and broadband radio frequencies. Lightning can also create audible pressure pulses—thunder—and magnetic pulses, but these two signals are more difficult to detect even when in a close orbit around a planet.

Volcanic lightning, which might also exist on other worlds, puts out a unique signal during the explosion of ash: thousands of tiny sparks. "Unfortunately, you have to be pretty near the volcano to detect them," Behnke said. "But they are a signature that could be exploited... because thunderstorms don't make a whole swarm of these itty-bitty discharges that lasts tens of seconds. It's a very distinct signature."

The Haves: Jupiter, Saturn, and Uranus

On Jupiter, scientists observed lightning storms almost anywhere and anytime they looked, said Yoav Yair, dean of the School of Sustainability at the Interdisciplinary Center Herzliya in Israel and a scientist whose research focuses on atmospheric electricity. Yair is also a Science Adviser for *Eos.*

Jovian lightning has been observed for 4 decades in visible, low-frequency radio, and high-frequency radio wavelengths by visiting spacecraft and atmospheric probes. After studying thousands of lightning events, scientists now know that most of Jupiter's lightning occurs above midlatitudes and near its poles (where there are large convective storms) and can occur at a rate similar to that of Earth lightning. Data also reveal that a flash of Jovian lightning has 10 times the total electromagnetic energy of a terrestrial lightning flash.

Saturn, too, has lightning. During its Saturn flyby in 1980, Voyager 1 detected lightning-generated radio pulses, initially suspected to come from the rings but later found to be from the atmosphere. But it wasn't until a few years into the Cassini mission that optical flashes of lightning became visible. The lightning storms, or Saturn electrostatic discharges, are intermittent but can last for months at a time.

Most of the lightning observed by Cassini occurred right before or after Saturn's equinox in 2009, suggesting that it was triggered by a seasonal change in the weather. Saturn has also produced some of the most spectacular planetary lightning seen to date, including the "Dragon Storm" of 2005 and, in 2013, the largest and most energetic storm ever recorded in the solar system.

Is there lightning on Uranus? "The answer is quite certainly yes," affirmed Philippe Zarka. Zarka is an astrophysicist and a senior scientist at Observatoire de Paris, Centre National de la Recherche Scientifique, Université Paris Sciences et Lettres.

Lightning-related signals "were detected with Voyager 2 during the Uranus flyby," he said. "We found radio spikes very, very similar to the ones at Saturn. Also we observed a different frequency range covered on the dayside and nightside of the planet. So it's quite clear that it's lightning."

Voyager 2, the only mission to visit Uranus, didn't see visible flashes of lightning, and Aplin said it's not likely we ever will. "People think that the lightning was quite deep in the atmosphere," she said. "If there were [optical] flashes, we wouldn't have seen them anyway because they're too deep to be detected. There are many layers of cloud above the layers of cloud that would have had lightning in them."

Planetary scientists have used radio telescopes on Earth to study lightning on Jupiter and Saturn. Observations of Uranus, too, might be possible. "If you do some back-of-the-envelope calculations," Aplin said, "it looks like the signal might just about be detectable from Uranus lightning, based on the sort of strength that we estimate it is."

The Have-Nots: Mercury, Moon, Titan, and Pluto

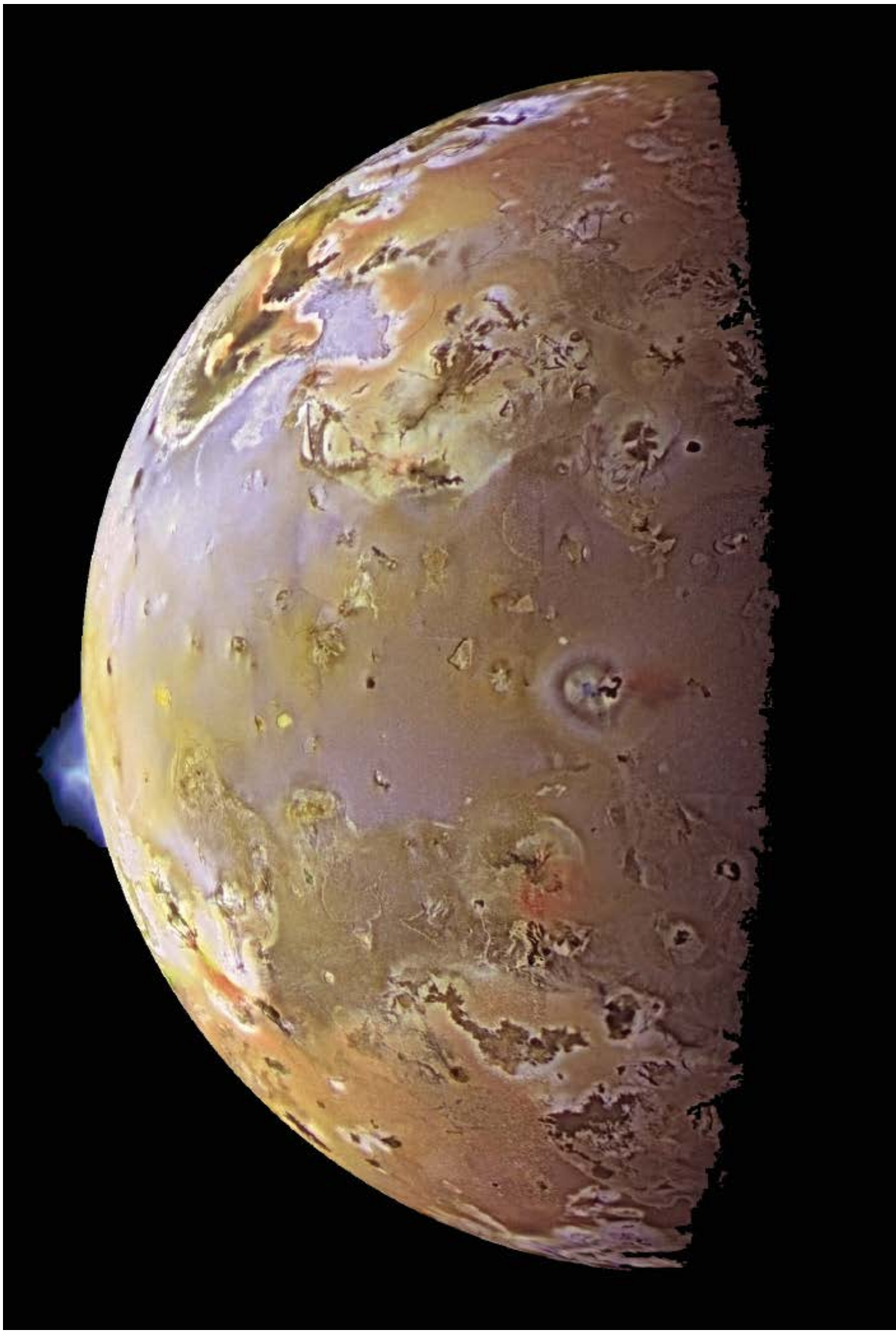
Anyplace in the solar system that does not have a convective atmosphere or similar process cannot have atmospheric lightning. That rules out Mercury, the Moon, and other airless bodies like asteroids for atmospheric or volcanic lightning. Despite this, solar wind can impart charge onto a dusty surface, including the Moon's, which can present an electric discharge hazard to equipment and astronauts alike.

Unlike the Moon, Saturn's moon Titan does have a thick atmosphere. But "methane clouds on Titan are not that good for producing electricity," Yair said. The clouds are made of an organic substance (methane), he explained, which is poorly electrified. As a result, the clouds tend to be less capable of building up a charge strong enough to produce lightning.

No lightning was observed on Titan before the Huygens probe landed in 2005, and the team had calculated a less than 1% chance that the moon's hydrocarbon-rich atmosphere and surface could generate or discharge enough electricity to create lightning.

However, organic molecules, like those that make up wildfire ash on Earth, can still create lightning when lofted to high altitudes because of ice formation in upper levels of the clouds, Van Eaton explained. And Titan's atmosphere does have trace amounts of water.

Huygens was equipped with lightning safety measures but didn't experience any lightning. Furthermore, Cassini saw no evidence of lightning on Titan during its 10-year mission. "If lightning occurs at all—and it may not—then it likely occurs in rainstorms," said Ralph Lorenz, a planetary scientist at the Johns Hopkins University Applied Physics Laboratory in Laurel, Md.



Jupiter's small moon Io, seen in this image from NASA's Galileo spacecraft, could generate lightning in its volcanic plumes. Credit: NASA/JPL/University of Arizona

Lorenz and the rest of the team behind NASA's upcoming Dragonfly mission to Titan are nonetheless exercising caution. "Rainstorms do not occur at the latitude and season of Dragonfly's nominal mission. We are, however, taking, like aircraft on Earth, precautions against electrostatic discharge, just in case that occurs when sand blows around."

There's no conclusive proof yet that Venus can generate atmospheric lightning, but this artist's illustration shows what it might look like from the surface. Credit: ESA/J. Whatmore

Last on the list of worlds that likely don't have lightning is Pluto. Although Pluto has layers of atmospheric haze, Yair explained, that haze is composed of nonconductive hydrocarbons like those surrounding Titan and is much too thin to produce or conduct electricity.

The Maybes: Venus and Neptune

Although Neptune is similar to Uranus in many ways, lightning might not be one of them. "In 1989 during the [Voyager 2] flyby of Neptune," Zarka said, "we recorded data similar to the data recorded at Saturn and Uranus. We analyzed the data in a similar way.... The analysis showed just five events similar to lightning. To give a comparison, at Saturn we saw something like 10,000 or so. At Uranus, it was 140."

"With five [events], we cannot say it was detected, because they may be spurious," he said. "It may be some electrostatic discharge on the spacecraft. So we cannot seriously claim that we detected, lightning on Neptune." There's no reason to suspect that Neptune wouldn't have lightning, Zarka said, but maybe the flyby occurred during a lull in lightning activity. Or lightning simply might be more sporadic than on Uranus because of a slightly different atmospheric composition and vertical convection.

> "We cannot seriously claim that we detected lightning on Neptune."

Neptune, like Uranus, likely makes lightning below thick upper clouds that would block any visible flashes, Aplin said. Radio measurements from Earth are out, too. "The energy we estimate for the lightning is lower for Neptune, and because it's further away, that means the signal would be so weak you couldn't detect it," she said. Resolving this puzzle, however, will likely require an orbital mission to the ice giant.

On Venus, there has been some evidence of lightning, but the matter is still very much up for debate. "Venus is quite controversial," Aplin said. "I think the best evidence at the moment [suggests] there's probably not lightning at Venus. But if there is, it's a bit weird, and we don't quite understand it. It's not behaving in ways that we expect."

In the 1970s, the Soviet Venera 11–14 missions detected whistlers and other radio emissions, as did the Pioneer Venus Orbiter in 1980, the Galileo spacecraft in 1991, and the Venus Express mission in 2007. On the other hand, NASA's Cassini mission flew by Venus in 1998 and 1999, and Japan's Venus Climate Orbiter Akatsuki has been orbiting Venus since 2015. Both were equipped with an instrument designed for detecting lightning, and neither craft has found any.

Maybe Venusian lightning is rare and localized, Zarka said, or maybe Venus's atmosphere just can't create lightning at all. "At Venus, there is a very, very strong horizontal superrotation of the atmosphere," he said. "That could prevent vertical convection." Too, Venus's clouds aren't rolling thunderstorms like on Earth, Jupiter, and Saturn, Aplin said. "On Venus, it's not like that at all. There's no known mechanism by which the lightning could be generated. That's not saying it's not there but just saying it's different to the simplest interpretation."

What data would resolve this debate? "Ideally, you'd like a radio detection and an optical detection at the same time," Aplin said, "because people can argue about one or the other, but if you have them both at the same time, then it's not really controversial."

Lorenz agreed and added that "if radio emissions characteristic of lightning could be repeatedly associated with [a] specific formation mechanism—e.g., the geographical location of a known volcano—or with specific atmospheric conditions identified by other means like cloud updrafts or fronts, then that would be a compelling indication of a lightning-like phenomenon."

The Why Nots: Mars, Io, and Exoplanets

And then there are the worlds where we have not detected convincing evidence of lightning but have no reason to think lightning couldn't exist there.

Mars's atmosphere is generally considered too thin and dry to create lightning storms. But more frequent phenomena like dust devils and dust storms might create something like large-scale static electricity. Just like volcanic lightning, dust particles colliding with one another will build up some charge and then the storm or vortex could separate the charge like a convective cell, Zarka explained. This type of static charging could also create lightning at Jupiter's moon Io, which regularly spews volcanic debris into space, according to Yair.

What it comes down to is that if there's a way to create lightning, there's probably somewhere in the solar system that does it. And that holds true for worlds beyond the solar system, too.

"It's just standard atmospheric physics," Zarka said. "Lightning is quite common. There's really no reason not to have lightning at exoplanets."

It's not likely that astronomers will be able to detect exolightning anytime soon, Zarka said. "The answer is no, absolutely no," he said. Typical radio signals from lightning are much weaker than background noise from a planetary magnetosphere. To be seen from so far away, the lightning would have to be billions or trillions of times stronger than terrestrial lightning. That's just not realistic, Zarka explained.

Making Use of Lightning?

Lightning—whether atmospheric, volcanic, or otherwise—can be a powerful tool for understanding the complexities of distant worlds, especially on planets we have not explored or cannot explore in situ.

The rate, duration, and frequencies of radio pulses as well as the optical flash duration can distinguish between lightning sources. The spatial distribution can tell scientists whether lightning is associated with thunderclouds, hurricanes, or a specific geographic feature like a volcano. How lightning strikes vary over time can also reveal daily or seasonal weather patterns.

Moreover, "people are so sure that lightning's about convection that if they see lightning, they just know it's convection," Aplin said. And lightning can spark unique chemical reactions that might not otherwise happen, some of which might be important for developing life.

But back home on Earth, lightning has been gaining ground as a way to detect eruptions of remote volcanoes and assess their hazards to aviation, shipping, agriculture, and people.

"Lightning is becoming very useful for scientists to track volcanic ash clouds," Van Eaton said. "And we want to make better and better instruments and improve our scientific understanding so that lightning is not just beautiful but is also really valuable for keeping people out of harm's way."

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LIGHTNING RESEARCH FLASHES FORWARD

A GREATER UNDERSTANDING OF LIGHTNING MECHANISMS IS SPURRING THE DEVELOPMENT OF MORE ACCURATE WEATHER FORECASTING, INCREASED PUBLIC HEALTH PRECAUTIONS, AND A MORE SOPHISTICATED UNDERSTANDING OF LIGHTNING ITSELF.

BY HEATHER GOSS

Lighting generated during a tornadic storm in Oklahoma.
Credit: Media Drum World/Alamy Stock Photo

Ashley Ravenscraft had a decision to make. Over the past several hours as a storm rolled through northern Alabama on 11 January, her team at the National Weather Service (NWS) office in Huntsville had already issued two tornado warnings.

Ravenscraft, a meteorologist, had issued the warnings using the Three Ingredients Method, which uses radar inputs to estimate the likelihood a linear storm will shift into a vortex. Then the azimuth motor went down on the radar closest to the storm—a technician had been sent to repair it, but it would be a least an hour before he would arrive and be able to get it back online. The remaining radar stations were far enough from the storm that they were capturing only data above several thousand meters in altitude—too high to make accurate judgments on storm rotation close to the ground.

But Ravenscraft was getting consistent data about one piece of the storm that would become key: lightning.

The NWS had brought a new application online in 2018—Ravenscraft was using it for only the second time. Her color-coded screen was showing 1-minute flash extent density data, or the rate at which lightning was flashing in the area. It was pulling in real-time data from the Geostationary Lightning Mapper (GLM), a near-infrared instrument aboard the GOES-R satellite. As the frequency of flashes increases, the colors on the map move from cool to warm.

A month earlier, on 16 December 2019, Ravenscraft had been on radar for her first big storm and had GLM data up on her screen. As the storm line approached the Huntsville region through northern Mississippi, "I was watching the nature of the lightning jumps [the flash extent density data]—how high it got, how quick it got," she said. "I knew that they were putting out tornado warnings, and I knew how the radar looked, so I thought, 'If we start to see these lightning jumps, and we see these updrafts grow, especially combined with the surge in the line we can see on radar, then there's a good chance we're going to end up with a tornado.'"

When the storm reached her coverage area, eight reported tornadoes touched down. Ravenscraft successfully predicted and sent out a warning for each one.

But there was one additional warning she issued that night, for residents in Lincoln County, Tennessee. The lightning jump had been lower than the others she had seen, but combined with what she saw on radar, she made the call. That night, no tornado was reported in that location. A few weeks later, however, her team was looking over the data and became so convinced that something had to have happened there that a colleague drove out to inspect the scene for himself. Ravenscraft had been right: A line of uprooted trees and an eyewitness account from a neighbor confirmed that a small twister had touched down. "From that event," she said, "we realized how significant the GLM data was."

Now Ravenscraft was studying the January storm on her monitors, with very limited radar data, and the current tornado warning was just about to expire, which meant residents would believe it was safe to leave shelter. "I started to notice that every minute, the [lightning flash] rate was going up.... I said, this is not good. Obviously the updraft was strengthening." Then the GLM data spiked.

Ravenscraft issued the alert. The action began a cascade of notifications in the area: Weather radios blared the alarm, local media were instantly notified, automated scripts went out on all the regional NWS social media pages, and within about 10 seconds, anyone with a mobile app that pulled NWS data and was within cell range was alerted to take—or, in this case, stay in—shelter.

Almost immediately, an EF2 tornado touched down and slammed into an elementary school, causing significant damage—thankfully, it was a Saturday. "GLM was the decision-maker," Ravenscraft said. "If we had only radar, we may not have decided to issue that warning."

REACHING THE PERFECT STORM OF LIGHTNING DETECTION

GLM is the most recent lightning detection instrument to go online in what is still a relatively young field. In the early 1980s, detection sensors were popping up in regions around the United States. In 1989, they were consolidated into the National Lightning Detection Network (NLDN). Today a little more than 100 low-frequency sensors are distributed across the continental United States under the operation of Vaisala, a company that performs industrial and environmental observations and makes them available to clients like the NWS.

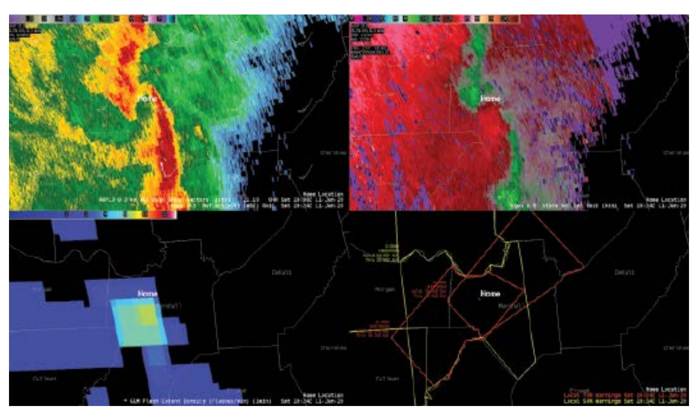
About 15 years ago, Ryan Said was in the electrical engineering doctoral program at Stanford University. His research group was taking very powerful sensors that had been used for studying the ionosphere and repurposing them into exceptionally sensitive lightning detectors. Whereas the NLDN sensors can detect lightning around 800 kilometers away, these sensors can pick up lightning emissions up to 10,000 kilometers away. About halfway through development, Vaisala got wind of the project and invested in it—one of the head engineers at the company became Said's dissertation adviser. That network, called the Global Lightning Dataset 360, or GLD360, was launched in 2009. Said wrote the sensor software and location algorithms for it and has been at Vaisala as a senior scientist and systems engineer since 2012.

Between NLDN and GLD360, explained Said, "we can detect these radio signatures from lightning happening anywhere on Earth." (And he really does mean anywhere. Last June, GLD360 detected the closest flashes to the North Pole ever observed.) When a sensor detects a radio impulse from a flash, the GPS-synchronized data are sent to a central hub and processed into lightning location data. Clients who subscribe to the data get a near-real-time feed that includes the time of each detected stroke within a flash to within a microsecond, the location to within 200 meters in the United States (2–3 kilometers for the GLD360), the peak current, and the polarity of the lightning flash.

Many of the people who use this information, like Ravenscraft and her colleagues at NWS, use streams from several environmental monitoring networks simultaneously. "They take that real-time feed and then overlay it on their AWIPS [Advanced Weather Interactive Processing System] software," explained Said, "which is sort of a Swiss Army knife tool that can overlay satellite and radar and lightning data for meteorological information on the same display."

The major benefit of the NLDN—which detects radio emissions in the very low frequency and low-frequency ranges—is its precise location pinpointing. GLM observations, meanwhile, capture the flashes from above, making one of its major benefits the ability to see the horizontal extent of a storm and to detect the majority of intracloud flashes—flashes that don't make ground contact but tend to indicate stronger updrafts as they occur in greater numbers (NLDN sensors can detect only about half of all intracloud flashes). In other words, NLDN tells you, among other things, precisely where powerful strokes may be causing damage, and GLM tells you how far away that storm is still churning.

One of the experiments Said and his team are pursuing is using these complementary data sets to study lightning-triggered wildfires. The numbers here themselves are wild: Lightning causes around 16% of wildfires, but those fires burn 56% of the acreage burned by all wildfires, making it a priority for many in the forest services to track these triggering events [*Balch et al.*, 2017].



A screen capture of data viewed by the National Weather Service office at Huntsville on 11 January 2020 as a severe storm rolled through northern Alabama. With the radar closest to the storm down, the meteorologist on call that night used lightning rate information from the Geostationary Lightning Mapper (GLM; lower left) to issue tornado warnings. The screens, clockwise from upper left, show bulk shear vectors and reflectivity; storm relative velocity; warnings issued for severe storms (yellow) and tornadoes (red); and GLM flash extent density data. Credit: NASA SPoRT

Top: Lightning protection equipment, provided by the African Centres for Lightning and Electromagnetics Network, is installed at the Shone School in Uganda. The school now serves as a model where students, teachers, and parents from other school districts learn about lightning safety. Bottom: A community member digs a trench around the Palabak school in Uganda. The trench will hold a cable attached to conductors running up the building to a lightning rod on the roof. When lightning hits the school, the electricity will be channeled down into the trench to dissipate. Credit: ACLENet

It's not as simple as monitoring lightning data during storms. Wildfires are often caused by continuing currents—that's when a lightning flash establishes a conductive channel to the ground, but instead of concluding in a fast-return stroke, a weaker sustained electrical current continues on the ground for 10–100 times longer than the stroke. "An analogy I often give is a hot poker," explained Said. "If you just touch something quickly, it might not do much damage, but if you hold it for awhile it can heat up." If you heat up a patch of underbrush long enough, it catches fire.

The GLM can see this type of sustained flash—from 10 to several hundred milliseconds long—but can resolve its location only to around 64 square kilometers. Vaisala is testing software that takes these broad GLM data points and combines them with NLDN data to narrow down the location to 200 meters. That's information that emergency management personnel could use to investigate potentially smoldering locations before they catch fire.

WHAT LIGHTNING TELLS YOU AT A GLANCE

Going one step further, one group is trying to take these data and create automated wildfire detection algorithms. Chris Schultz is a research meteorologist at NASA's Short-term Prediction Research and Transition Center, or SPoRT, in Huntsville. He recently led a team that looked at how long an area might smolder before catching fire after it has been struck by lightning. In a paper published last year, the team found that half of causal flashes occurred the same day as the fire, but the rest were tracked largely between 2 and 5 days before the fire was spotted—one fire in New Mexico didn't catch until 12 days after the causal lightning strike [*Schultz et al.,* 2019].

"The end goal is to develop an algorithm where you have all the inputs of precipitation, storm type, and land surface and soil moisture that forecasters look for as assessment of the fire danger," said Schultz, "and then as thunderstorms roll through, you can evaluate the likelihood of a fire" from a lightning strike, even if it doesn't ignite for a week.

SPoRT is tasked with developing all sorts of tools that can help forecasters and anyone charged with public safety to handle the ever changing weather. Later this year, the National Oceanic and Atmospheric Administration will be rolling out the Time Since Last Flash tool, an operational version of a concept that SPoRT created that uses GLM data. The tool automatically changes colors on a digital map from red to yellow to, finally, green, when lightning was last detected 30 minutes ago. It's a simple application that could be used by football game managers or lifeguards to easily and accurately know when people can safely come back outside.

Other applications are those that meteorologists like Ravenscraft use, such as the colors that indicate a spike in lightning rates. "The hardest thing to measure in atmospheric sciences is vertical motion," said Schultz, so forecasters use lightning as a proxy for that motion.

"We've gotten to this point where forecasters are comfortable taking their radar data, taking their lightning data, taking their satellite data and understanding the formation of that storm and its impact for the next 30–40 minutes," said Schultz. And applications like the ones SPoRT provides to meteorologists allow them to make faster and more confident predictions and get people to safety. "That's what gives me that warm, fuzzy feeling, when forecasters are able to utilize the things we've been working on."

MODERN LIGHTNING SAFETY IN THE UNITED STATES

Last year, the NLDN recorded 20 million lightning flashes that hit the ground in the United States. But as modern, grounded buildings were erected, metal-topped cars proliferated, and the percentage of people working outside went down, fatalities from lightning have gone from around 400 annually in the early 20th century to 27 for the past decade.

Maybe you've called your kids in from the yard because you know "When thunder roars, go indoors." Or perhaps you know the 30-30 rule: When the time between lightning and thunder is less than 30 seconds, it's not safe to be outside; when 30 minutes have passed since the last strike, it's safe to go back outside (the rule behind Schultz's Time Since Last Flash concept).

If so, you can thank Ron Holle, Mary Ann Cooper, and a group of colleagues determined to educate the public on lightning safety. The group met to discuss these ideas in 1998 at the American Meteorological Society conference. The timing (30 seconds, 30 minutes) was based on data they were collecting from the NLDN. Then Holle and Cooper, today known as the preeminent lightning safety experts in the world, went on a media blitz, giving thousands of interviews to local and national reporters to spread these simple messages [*Cooper and Holle,* 2012].

Even with this progress, Holle, who is now a consultant for Vaisala, argues that there's a long way to go—in developed countries like the United States, that means vulnerability regarding our infrastructure.

“A lot of the power companies are not using lightning data,” Holle said, noting that 50 years ago it may not have been a huge issue if a transformer blew and power went out for an evening, but today even a few seconds of outage can cause major problems. Nevertheless, Holle said, the list of companies—utilities, airports, major sports facilities—that could still benefit is significant. “It’s a bit frustrating to know that we’re sitting on the data that really could help people.”

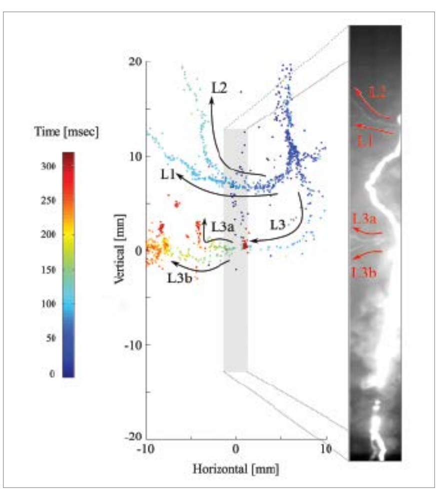
LIGHTNING SAFETY IS AN ENTIRELY DIFFERENT ISSUE IN DEVELOPING COUNTRIES. WHEN THUNDER ROARS, GO INDOORS? “NOT IF YOU HAVE A THATCHED ROOF.”

THE CURRENT THAT KILLS CAN COME FROM BELOW

Lightning safety is an entirely different issue in developing countries. When thunder roars, go indoors? “Not if you have a thatched roof,” said Cooper.

In June 2011, 18 children were killed and 38 were injured when lightning struck Runyanya Primary School in Uganda. The tragedy moved Richard Tushemereirwe, an adviser on science and technology to the president of Uganda, to found the African Centres for Lightning and Electromagnetics Network, or ACLENet. The organization collects injury data, educates communities on lightning dangers, and raises funds to protect schools and other buildings with lightning safety devices.

The first thing Tushemereirwe did was recruit Cooper to run the organization. (She brought on Holle, who serves on the board.) Cooper is a medical doctor and one of the first experts in modern emergency medicine. She quite literally wrote the book on it—helping to design the first protocols and accreditation standards for the doctors who treat you in the emergency room today. While Cooper was in school, a family friend suffered a high-voltage industrial accident; several years later, it inspired her to give a lecture on electrical injuries at which an attendee asked about lightning injuries. She discovered that there was almost nothing published on the topic. She decided to do it herself, searching back through a century of literature for the few documented cases and eventually developing a handful of correlations on locations and types of burns and their impact on mortality.



This figure shows the time development of a lightning flash as observed by the Lightning Mapping Array (left) compared to an image from a high-speed camera. The arrows show the direction of propagation of the observed lightning channels, with blue indicating earliest in time and red, the latest. The gray shaded area shows the field of view of the camera. Credit: Kotovosky et al., 2018 (https://doi.org/10.1029/2018JD029506)

There are five electrical mechanisms through which lightning can kill or injure a person. Only a small percentage of victims are killed or injured by a direct lightning strike. An equally small number are hit through conduction, or contact injury, such as touching a faucet when lightning strikes it. Sideflashes, the electrical current that strikes outward once lightning has hit something nearby, like a tree, kill or injure 15%–20%.

Another 15%–20% of victims suffer through a terrifying mechanism called an upward streamer. “As a thunderstorm is coming through the area—it doesn’t even need to be over top of you—this intense, huge electrical field starts, inducing opposite charges in whatever’s underneath it, whether it’s a TV tower or a tree or a person or a cow,” said Cooper. “It turns out that sometimes that opposite charge can be strong enough that an upward streamer will actually start up from the skull of that person or tower.” Sometimes a lightning flash will attach to that upward streaming charge, but it doesn’t have to—the charge itself can be strong enough to kill you. Cooper herself wrote the first medical report on the mechanism after studying the case of a man who was killed during a lightning storm but presented none of the usual high-voltage burns and neither his nearby crew members nor the electrical equipment he was working on suffered any damage [*Cooper*, 2002].

But it’s the final mechanism that’s responsible for half of all deaths and injuries through lightning: ground current. That is largely the challenge in Africa, where many buildings still have dirt floors, and schools are collections of unsafe buildings in close proximity. In the United States, it’s extremely rare for more than one person to be killed by a single strike; in Africa, it’s not uncommon for groups of 10 or more people to be killed while sitting together in a room—often children attending class.

Cooper and her team presented their data on the high incidence of lightning deaths of African schoolchildren at an international conference in 2014, urging the attendees to focus on safety in schools. The presentation fostered a partnership with German lightning protection company DEHN, and together they developed a system that was first installed at Runyanya in 2016.

The system starts with a simple lightning rod. “There’s nothing that’s superior to the old-fashioned Ben Franklin lightning rod,” said Cooper. The building is then retrofitted with wires or metal fittings, and the system ends in a ground ring.

In Runyanya, community members were greatly involved with the project, using their farming tools to dig a trench about half a meter deep around each building to bury cables, said Holle. “When the lightning hits the building, it comes down the conductors and goes directly into the ground, into this long loop around the building, and dissipates.” It took about 3 days to retrofit all six Runyanya buildings plus a local church.

ACLENet has now protected six schools around Uganda and is currently negotiating some plans with the government to increase and better fund these efforts, including developing workshops on lightning safety building codes for engineers in Africa.

BIG QUESTIONS REMAIN ON THE BIG SPARK

A better understanding of the mechanisms of lightning itself can better support prediction and mitigation efforts on the ground, researchers say.

Vaisala engineers install a precision lightning sensor using a solar panel for power in Australia. The sensitive antennas under the white dome detect powerful radio bursts from lightning. The electronics in the enclosure digitize, process, and transmit these signals to a central server in real-time. Credit: Vaisala

"Lightning is just a big spark," said Bill Rison, a research professor at Langmuir Laboratory for Atmospheric Research at the New Mexico Institute of Mining and Technology in Socorro. "You can measure sparks quite well in the laboratory." But when researchers compared lab conditions to measurements taken by balloons or aircraft inside storms, he said, "you find that the electric field in the thunderstorm is about an order of magnitude smaller than it would take to generate a spark in the laboratory."

In 1996, Rison was flying with his colleagues back from AGU's Fall Meeting in San Francisco when they had a bit of an epiphany. They had been working with NASA on a novel very high frequency (VHF) detection system at Kennedy Space Center in Florida that could map lightning flashes in 3-D. But the cost was exorbitant—about $1 million for each of 10 stations. The key to this kind of instrument is highly accurate timing, and highly accurate GPS technology was just becoming available.

Rison and his team used this new technology to design the GPS-based 3-D instruments that make up the Lightning Mapping Array (LMA). The instruments cost only about 5% of the original NASA stations' price tag, which meant Rison's New Mexico Tech team could deploy them all over [*Rison et al.,* 1999]. Today there are about 15 of these arrays around the world, and the data they produce are "supercool," said Vaisala's Ryan Said. "There are some things we can't measure," referring to the NLDN. Unlike radio detectors, VHF instruments can measure all the very small electrical discharges that a flash produces to create that detailed 3-D structure. "It's remarkable," said Said. "The amount of intuition we have from this research into lightning flashes is ridiculous."

Lately, Rison's team has been working in collaboration with the University of Utah, which runs a cosmic ray observatory. Thunderstorms can produce gamma rays, as NASA discovered in the early 1990s, and the Utah team was seeing these terrestrial gamma rays in its data. They contacted the New Mexico team, which went out and installed an LMA in the area, "so now we could actually see characteristics of lightning that were producing the terrestrial gamma ray flashes," said Rison [e.g., *Abbasi et al.,* 2018].

In 2017, researchers in Japan used instruments outside a nuclear power plant to detect what are called relativistic runaway electron avalanches produced by the strong electrical fields in a storm [*Enoto et al.,* 2017]. "Lightning is actually a slow nuclear reactor," said Rison; his team is working on a new paper from the Utah observations that will offer "more details with exactly what processes of lightning generate the terrestrial gamma ray flashes."

A SECOND GOLDEN AGE

When Chris Schultz looks around at the field of lightning study today, he sees immense progress. "We have a lot of new instrumentation that's come online in the last 2 years, so we're trying to integrate all that new information and build a better picture of how that lightning is forming and how it begins in the cloud," he said.

When Ashley Ravenscraft looked back at the stats for the eight tornadoes that touched down in northern Alabama in December 2019, she found that "we were giving 30–45 minutes of lead time" through lightning-based tornado warnings that told local residents to get to safety. "It tears me up that we had two fatalities, but to not have more is a step in the right direction."

As researchers build that better picture—through the NLDN and GLD360, through optical images obtained by the GLM in low Earth orbit, through 3-D lightning mappers—the practical applications for how we protect our communities from dangers of lightning proliferate. Schultz concluded, "We're in the second golden age of lightning measurement."

REFERENCES

Abbasi, R. U., et al. (2018), Gamma ray showers observed at ground level in coincidence with downward lightning leaders, *J. Geophys. Res. Atmos., 123,* 6,864–6,879, https://doi.org/10.1029/2017JD027931.

Balch, J. K., et al. (2017), Human-started wildfires expand the fire niche across the United States, *Proc. Natl. Acad. Sci. U. S. A., 114*(11), 2,946–2,951, https://doi.org/10.1073/pnas.1617394114.

Cooper, M. A. (2002), A fifth mechanism of lightning injury, *Am. Emerg. Med., 9,* 172–174, https://doi.org/10.1197/aemj.9.2.172.

Cooper, M. A., and R. L. Holle (2012), Lightning safety campaigns—USA experience, in *2012 International Conference on Lightning Protection (ICLP),* pp. 1–7, Inst. of Electr. and Electron. Eng., Piscataway, N.J., https://doi.org/10.1109/ICLP.2012.6344289.

Enoto, T., et al. (2017), Photonuclear reactions triggered by lightning discharge, *Nature, 551,* 481–484, https://doi.org/10.1038/nature24630.

Rison, W., et al. (1999), A GPS-based three-dimensional lightning mapping system: Initial observations in central New Mexico, *Geophys. Res. Lett., 26,* 3,573–3,576, https://doi.org/10.1029/1999GL010856.

Schultz, C. J., et al. (2019), Spatial, temporal and electrical characteristics of lightning in reported lightning-initiated wildfire events, *Fire, 2*(2), 18, https://doi.org/10.3390/fire2020018.

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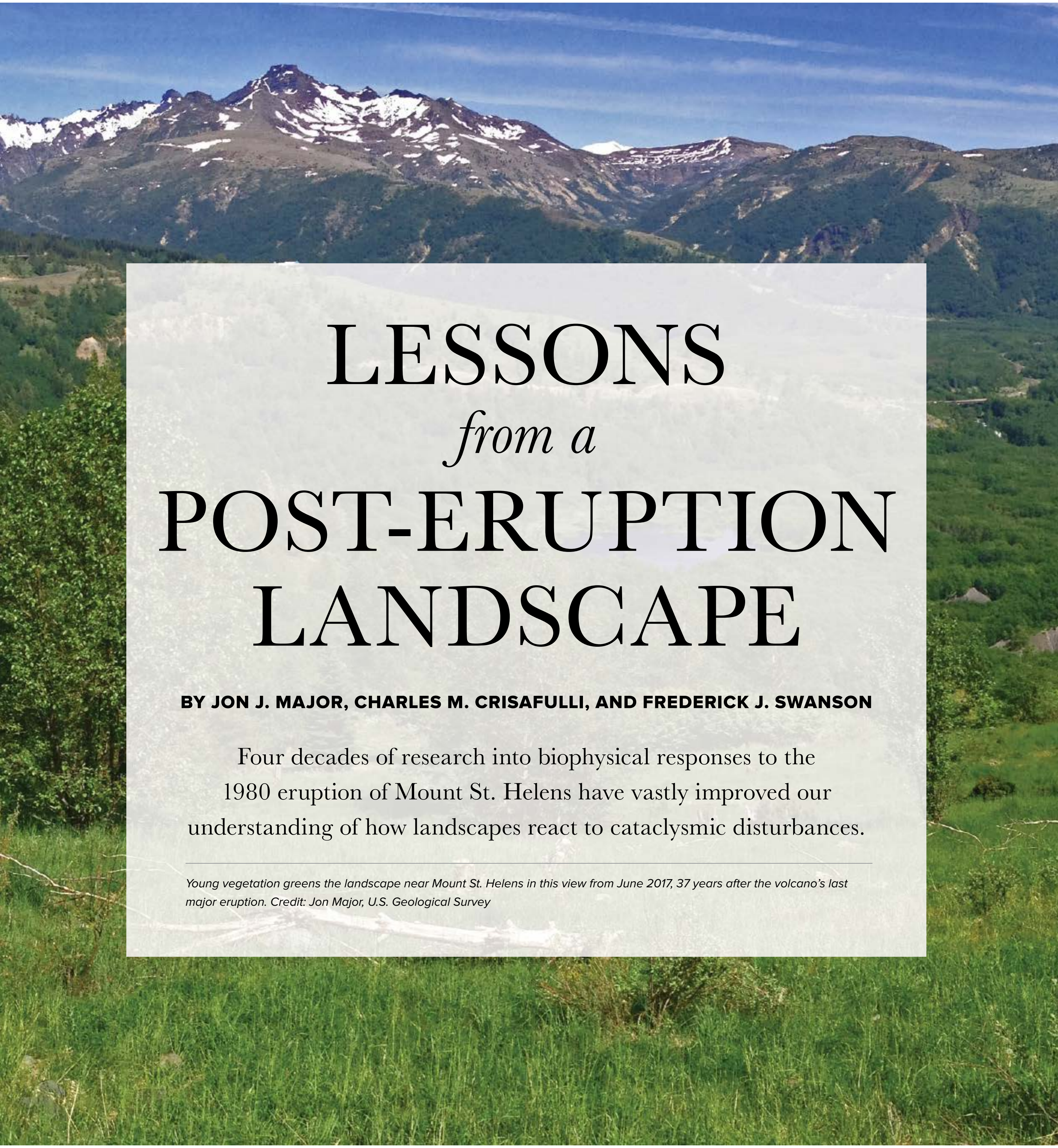

LESSONS *from a* POST-ERUPTION LANDSCAPE

BY JON J. MAJOR, CHARLES M. CRISAFULLI, AND FREDERICK J. SWANSON

Four decades of research into biophysical responses to the 1980 eruption of Mount St. Helens have vastly improved our understanding of how landscapes react to cataclysmic disturbances.

Young vegetation greens the landscape near Mount St. Helens in this view from June 2017, 37 years after the volcano's last major eruption. Credit: Jon Major, U.S. Geological Survey

FROM MARCH TO MAY 1980, magma rose high into Mount St. Helens (MSH), swelling and—as it turned out—destabilizing its north flank. Scientists knew the volcano had been highly active at times over the past 40,000 years, but the mountain, located amid the Cascade Range in southwestern Washington, had been mostly quiet since the mid-19th century. The collapse of the north flank on 18 May shattered that quiet, triggering a cascade of events that left resounding impressions not only on those who witnessed and studied them but also on the surrounding landscape [*Lipman and Mullineaux,* 1981; *Waitt,* 2015].

The eruption of MSH also provided unparalleled opportunities for advancing several disciplines [e.g., *Shore et al.,* 1986; *Newhall,* 2000; *Franklin and MacMahon,* 2000]. Among these was an intensification of research investigating biophysical impacts of eruptions and subsequent responses [e.g., *Dale et al.,* 2005; *Pierson and Major,* 2014; *Crisafulli and Dale,* 2018]. Long-term research on the biophysical responses at MSH has provided important new insights, challenged long-standing ideas, and provided many societal benefits.

Long-term research on the biophysical responses at Mount St. Helens has provided important new insights, challenged long-standing ideas, and provided many societal benefits.

The fortieth anniversary of the eruption this year offers a timely opportunity to reflect on these insights and influences. This long-term vantage is important because sustained, place-based studies following landscape disturbances are rare; because the MSH eruption spurred the greatest depth and breadth of multidisciplinary studies of biophysical responses to landscape disturbance; and because these responses created some of the most significant societal challenges to emerge after the eruption. We summarize key biophysical disturbances and responses, highlight salient insights, and suggest actions that can extend the usefulness of these insights to volcanically vulnerable communities worldwide.

SMOTHERED, BATTERED, AND SINGED

The flank collapse at MSH on the morning of 18 May initiated several catastrophic events over the next several minutes (Figure 1). The resulting colossal landslide smothered 60 square kilometers of river valley to a mean depth of 45 meters, obstructed tributaries to the North Fork Toutle River, or NFTR (consequently impounding two permanent and several ephemeral lakes), and blocked the outlet of Spirit Lake at the foot of the volcano. An associated energy blast from the eruption unleashed a scorching cloud of rocky debris known as a pyroclastic density current (hereinafter called the blast PDC) that swept over 600 square kilometers of rugged mountain terrain, removing, toppling, and singeing tracts of forest. Parts of that cloud also sped down the volcano's snowclad east and west flanks, triggering meltwater flash floods that swept up sediment to become large, swift volcanic mudflows (lahars) that traveled many tens of kilometers downstream.

A vigorous vertical eruption plume soon followed these events, raining shards of volcanic debris (tephra fall) downwind and producing pumice-rich pyroclastic flows that settled atop the landslide deposit. Hours after the landslide emplacement, parts of the newly deposited material liquefied, forming muddy slurries that coalesced into the massive NFTR lahar that reached distant communities and choked navigation on the Columbia River more than 100 kilometers downstream from the volcano.

These eruption processes battered forest, meadow, riparian, riverine, lake, and lakeshore environments. Erosion, burial, heat, blunt force, and abrasion produced a mosaic of landscape disturbances that extended tens of kilometers from the volcano. The magnitude of disturbances ranged widely, from the near-total removal of all vestiges of plants and animals in areas nearest the volcano to terrain dusted with only a thin layer of tephra. This patchwork of disturbances created an exceptional natural experiment for assessing physical and biological responses to spatially variable impacts.

THE BACKDROP FOR BIOPHYSICAL RESEARCH

Biophysical research at MSH following the eruption was influenced by prevailing ideas in 1980 of how landscapes and ecosystems change in response to large disturbances, by the state of the new landscape, and by management of public lands at the volcano. In 1980, U.S. scientists had little direct experience with explosive volcanism or biophysical responses to eruptions. Lahars were a known volcanic process, but scientists poorly understood how they evolved downstream and how landscapes responded to other hydrogeomorphic impacts, such as riverine responses to vast injections of sediment or modifications to basin hydrology caused by expansive changes in forest cover, tephra deposition, and channel disruption. Meanwhile, conventional ecological wisdom held that most organisms would likely perish where intense volcanic forces affected the landscape. It was also thought that recovery of decimated areas would be regulated by their distance from neighboring, unaffected areas, from which hardy pioneering species could migrate and reestablish conditions favorable for later successional species [*Franklin and MacMahon,* 2000].

The 1980 eruption upended the normal hydrogeomorphic functioning of much of the landscape. Loss of hillside vegetation and deposition of impermeable silty tephra promoted rapid surface water and sediment runoff; immense amounts of material introduced to stream channels disrupted major river corridors; landslide debris tenuously dammed existing and developing lakes; and lahar deposits compromised navigation and flood protection capacity in distant communities by raising channel beds. These conditions created intense concerns over public safety related to flood and sediment hazards and afforded needs and opportunities for subsequent studies.

Prior to the MSH eruption, ecologists had commonly studied organism responses years to centuries after an eruption and typically had studied single groups of organisms affected by single volcanic processes or deposits. After the eruption, the mosaic of different volcanic deposits and widely varying impacts to numerous organisms across multiple environments afforded ecologists opportunities to make significant strides in understanding linkages among disturbance, survival, and succession.

Research efforts at MSH have influenced, and have been affected by, political and institutional processes that determined human engagement with this new landscape. In 1982, Congress created the 445-square-kilometer Mount St. Helens National Volcanic Monument (NVM), identifying science, education, and recreation as the primary objectives of land management. The U.S. Forest Service was charged with "allowing geologic forces and ecological succession to continue substantially unimpeded," except as necessary to ensure public safety. Meeting this charge has entailed striking a delicate balance among competing interests, including public desire for full access, minimization of access to certain areas to protect ecological research values, and the NVM's responsibility to manage geologic hazards to ensure protection of public safety and the environment. It's a challenge complicated by changing landscape conditions, evolving social values, and emerging scientific knowledge.

A LANDSCAPE RESHAPED

Geomorphic responses to the landscape disturbances far outweighed hydrological responses. The nature, magnitude, and duration of geomorphic responses around MSH varied substantially and reflect the types and severities of different eruption processes. Stormflows from basins

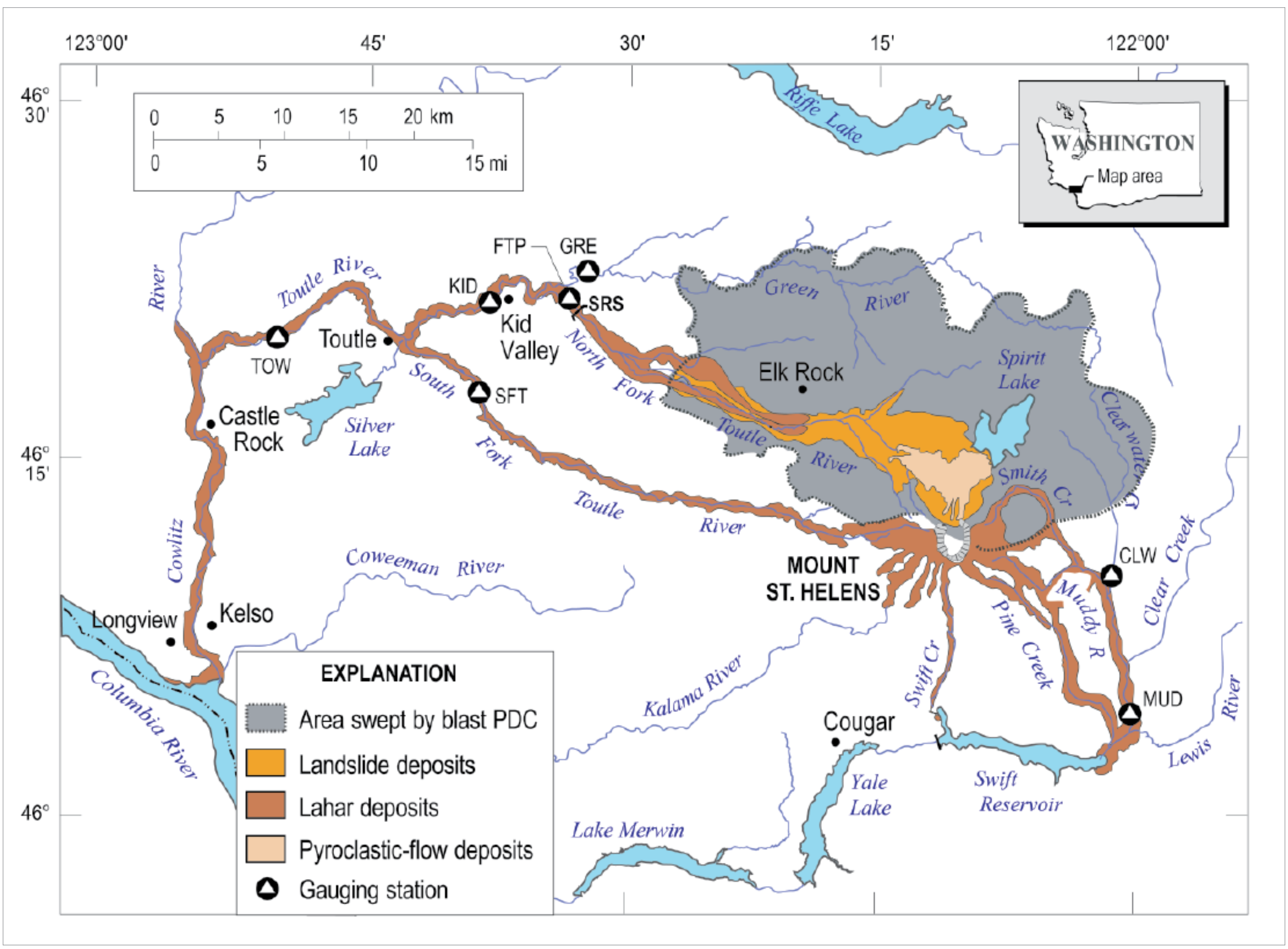

Fig. 1. Map showing the distribution of different deposits following the 1980 Mount St. Helens eruption. (The distribution of tephra fall is not shown). Locations of U.S. Geological Survey (USGS) stream and sediment gauges (e.g., TOW; see Figure 2 for other names and abbreviations) are also shown. Abbreviations are SRS, sediment-retention structure; PDC, pyroclastic density current.

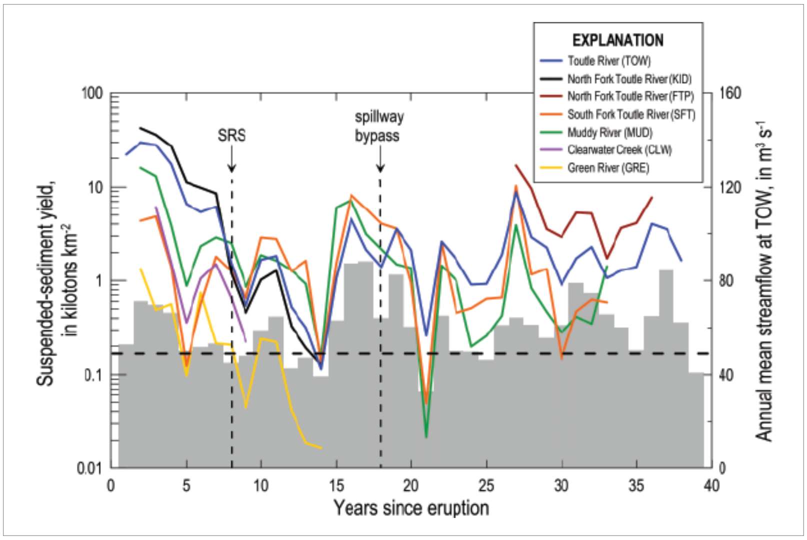

Fig. 2. Suspended sediment yields (in kilotons per square kilometer) as measured by USGS sediment gauging stations (see Figure 1 for station locations) along various waterways near Mount St. Helens. The horizontal dashed line depicts the median value of suspended sediment yields measured at several western Cascade Range rivers (exclusive of rivers near Mount St. Helens), which is used as a proxy for typical pre-1980 sediment yield at Mount St. Helens. The gray histogram represents annual mean streamflow (in cubic meters per second) along the Toutle River measured at stream gauge TOW, highlighting the broadly similar trends between sediment and water runoff, especially after 1990. SRS indicates the onset of sediment trapping by the U.S. Army Corps of Engineers' sediment-retention structure; "spillway bypass" indicates when sediment began passing over the SRS spillway and its trapping efficiency declined substantially.

that were heavily affected by the eruption, however, increased by a few percent to a few tens of percent compared with pre-eruption flows for roughly 5–10 years [*Major and Mark,* 2006].

The most substantial geomorphic response occurred in the NFTR basin, which was affected by all the eruption processes; this response continues today because the basin's upper valley was smothered in thick deposits. In the NFTR basin, water runoff, small lake breakouts, and water pumped from Spirit Lake (to lower the lake level from 1982 to 1985 until an outlet was constructed) efficiently carved the landslide and pyroclastic flow deposits, leading to exceptional erosion of new channels (tens of meters of incision and hundreds of meters of widening) and driving extreme levels of sediment delivery (Figure 2). Although that extraordinary sediment yield declined rapidly as channels widened and beds coarsened, it remains elevated decades later because of ongoing, low-magnitude lateral erosion of the deep channels [*Major et al.,* 2018].

In comparison, in basins affected solely by the blast PDC and tephra fall, stream channel responses were minor and hillside erosion decreased swiftly owing to mechanically driven (versus vegetation-driven) increases in infiltration and the complex topography created by downed trees [*Collins and Dunne,* 2019]. In those basins, such as the Green River and Clearwater Creek basins, elevated sediment delivery was brief and returned to background levels within about 5 years (Figure 2). After 40 years, more than 80% of all MSH eruption-deposited sediment remains in place—and much of that might remain permanently—but problematic sediment delivery from the NFTR basin will likely persist for decades to come.

Hydrogeomorphic responses to volcanic disturbances can result in socioeconomic consequences more damaging than the direct impacts of eruptions themselves [*Pierson and Major,* 2014]. The great flush of sediment into waterways around MSH, to date more than 400 million tons, has compounded eruption impacts, greatly prolonging navigation problems and flood hazards to vulnerable communities, for example. This forced the U.S. Army Corps of Engineers (ACOE) to conduct extensive, but unsustainable, channel dredging [*Willingham,* 2005]. In 1989, ACOE completed a 56-meter-tall, 800-meter-long sediment-retention dam to minimize sediment reaching the Cowlitz and Columbia Rivers (Figure 1). But persistent erosion and sediment delivery have proved to be a formidable foe; by 1998, sediment behind the dam reached the spillway level, prompting further efforts to curtail sediment delivery downstream [*Sclafani et al.,* 2018]. To date, ACOE has spent more than $435 million mitigating eruption and post-eruption impacts on the Cowlitz and elsewhere, and no immediate end is in sight.

Insights from hydrogeomorphic studies at MSH have had wide influence. They have sharpened global understanding of post-eruption landscape functioning by elucidating the nature and pace of landscape responses, and they have informed flood management planning and policies locally by quantifying magnitudes and durations of sediment delivery and by identifying sources of sediment erosion and sinks of deposition. These studies have also helped hone interpretations of hydrogeomorphic responses to other types of disturbances, such as wildfires (which in some ways mimic those following tephra falls) and abrupt injections of channel sediment following large-dam removals and mining.

LEGACIES LIVE ON

After the eruption, ecologists quickly discovered that biological legacies (surviving plants and animals) from pre-eruption ecosystems persisted and were widely distributed; even some of the most heavily affected landscapes were not as sterile as initially assumed. The seasonal timing of the eruption and its time of day played important roles in determining which plants and animals lived or died; many organisms in subalpine lakes and on hillsides, protected beneath snow or ice, were spared the brunt of eruptive forces, for example, and nocturnal animals were in their dens. Those protections resulted in numerous patches of surviving organisms embedded within a vast expanse of disturbed land (Figure 3).

Researchers found that the types, amounts, and distributions of biological legacies were the most important factors affecting rates of ecological recovery [*Dale et al.,* 2005; *Crisafulli and Dale,* 2018]. But ecological recovery also involved colonizing organisms. Forests and aquatic systems surrounding the disturbed landscape were largely intact and supported plants and animals that served as source populations for post-eruption recovery [*Crisafulli and Dale,* 2018]. These populations were particularly important for the recovery of species that experienced complete mortality in the blast PDC zone, such as many large mammals and birds.

Certain species, called keystone species, were exceptionally important in the recovery process. For example, lupines and alders flourished in the nutrient-impoverished volcanic substrates because of their ability to partner with root-borne, nitrogen-fixing bacteria. These pioneer species facilitated colonization of many other plants and animals by ameliorating inhospitable nutrient conditions and initiating soil development. Other species, such as the northern pocket gopher, facilitated recovery by mixing inert tephra with buried nutrient-rich soil, thus improving conditions for plant growth. American beavers modified streamflow and plant communities through herbivory and dam building, which created habitats with high biodiversity.

Abiotic factors were also important to ecological recovery. The unconsolidated texture of eruption deposits allowed animals to excavate burrows. Surviving plants penetrated thin (50 centimeters or less) deposits by sprouting new shoots upward, and roots of seedlings penetrated downward into nutrient-rich pre-eruption soils. The mild, wet maritime climate at MSH further facilitated ecological response.

Lessons from long-term ecological research at MSH have advanced fundamental understanding of how individual species and biological communities respond to large, intense disturbances. Locally, this work has assisted management of NVM lands. More broadly, it has allowed ecologists to address a fundamental question in ecology: How do biological communities arise from a seemingly barren slate? The importance of biological legacies in promoting recovery emerged as an epiphany, one that has informed research at other volcanoes [*Crisafulli et al.,* 2015] and at sites experiencing intense wildfires and windstorms. The work has also prompted fresh perspectives on management of forest landscapes in the United States and abroad, such as using variable-retention harvesting, rather than clear-cutting, to preserve forest structures and processes [*Franklin and Donato,* 2020].

FEEDBACKS BETWEEN LIFE AND LAND

Geomorphic and ecologic responses at MSH have evolved jointly and interacted in important ways. For example, on hillsides affected by the blast PDC, concentrated surface runoff eroded tephra, which exposed surviving seeds and rootstocks in pre-eruption soil and allowed them to flourish (Figure 4). Trees and shrubs are now widespread in some basins and have established enough cover, root mass, and strength to help anchor hillside tephra deposits, which minimizes additional erosion by runoff and landslides.

A similar example is seen along river corridors, where a certain degree of geomorphic stability has been needed before riparian vegetation could effectively be established. As that riparian vegetation has matured and gained stronger footholds, it has increased geomorphic stability. Furthermore, the combination of increased geomorphic stability and expanding riparian vegetation has helped establish animal communities. Areas where channel banks and floodplains remain unstable support little vegetation and few animals.

A CALL TO ACTION

Results from 4 decades of hydrogeomorphic and ecological research at MSH affirm the value of long-term monitoring and research at disturbed landscapes, as well as of the establishment of collaborative research communities. This multidisciplinary research continues to inform not only basic science but also societally important endeavors to understand and manage disturbed landscapes. These endeavors include efforts to manage flooding and sediment delivery in waterways affected by the eruption—especially as mitigation measures have

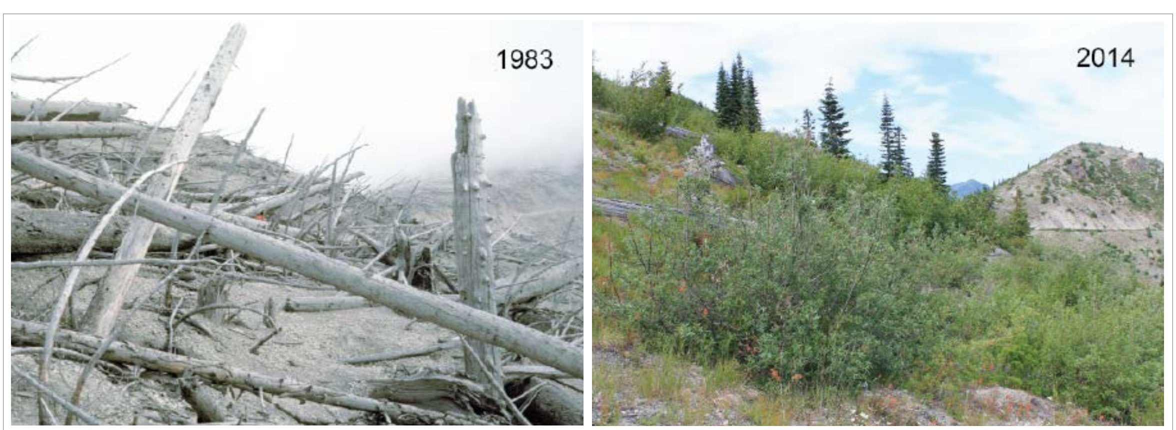

Fig. 3. Two views showing the development of plant communities between 1983 and 2014 at a site along upper Smith Creek (see Figure 1), an area affected by the blast pyroclastic density current and tephra fall. The site was snow-free at the time of the eruption. The ecological response reflects the influences of individual survivors as well as of colonizing plants arriving from distant source populations. Credit: C. M. Crisafulli, U.S. Forest Service

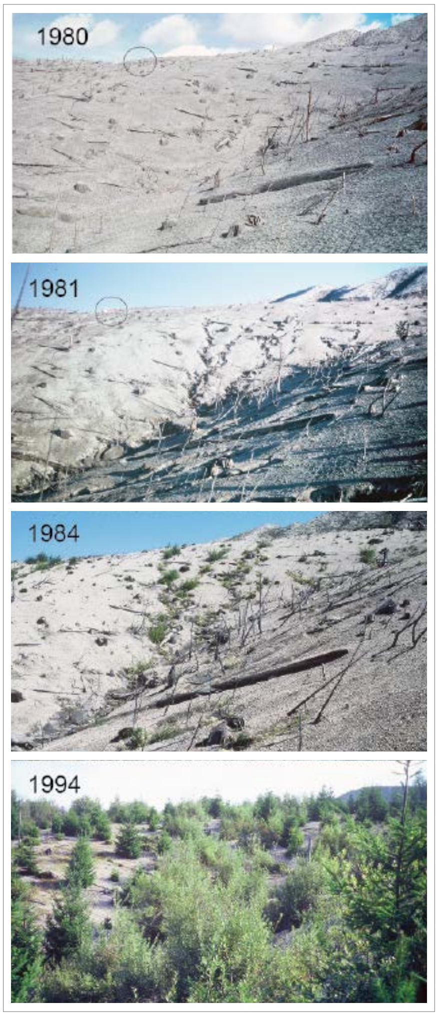

Fig. 4. Sequence of images showing geomorphic and vegetation change at a site in upper Smith Creek valley that received 50 centimeters of blast PDC and tephra fall deposits. Vegetation initially sprouted from surviving rootstocks in pre-eruption soils that, after the eruption, were re-exposed in the floors of gullies eroded through the new deposits. By 1994, trees were established on the hillside between the gullies and both surviving and colonizing species anchor the sediments. Helicopter circled for scale in the top two images. Credit: F. J. Swanson, U.S. Forest Service

failed or become less effective with age—and to manage native and invasive species on NVM lands. The research has also provided important, factual information about the eruption that is shared with the public at local visitor centers and through global media.

As populations living near volcanoes increase, more can be done to impart lessons learned from biophysical research at MSH. We propose five steps for the volcano science community to take that would extend the reach of these lessons:

1. Improve public awareness in communities vulnerable to volcanic hazards of the biophysical responses to eruptions. Scientists can fold discussions of these responses into other volcano hazard awareness efforts, such as workshops and public presentations.

2. Include instruction about biophysical impacts and responses to eruptions in academic courses focused on natural hazards to pass on the knowledge gained to future generations of students and scientists.

3. Include post-eruption sedimentation hazards in volcano hazards assessments to more accurately portray the full range and duration of hazards associated with volcanism.

4. Develop an international volcano ecology and hydrology network—either informally or formally through scientific societies—to connect ecologists, hydrologists, and geomorphologists; facilitate information sharing; and identify key issues that arise in post-eruption landscapes.

5. Foster collaborations among hydrologists, geomorphologists, and ecologists who can consult with local volcano observatories and provide training for local science agencies, civil authorities, and emergency managers. Training could address what to anticipate in the immediate and long-term aftermath of future eruptions, appropriate hazard assessment methods, possible options and approaches to mitigating posteruptive hydrogeomorphic hazards, and advice for restoring ecosystems to desired states. The U.S. Geological Survey's Volcano Disaster Assistance Program [*Lowenstern and Ramsey*, 2017], which is funded by the U.S. Agency for International Development, is one example of such a team; international scientific societies could facilitate others.

Following these steps can further advance the rich scientific understanding of the myriad and dynamic processes that occur in post-eruption landscapes, which studies at Mount St. Helens since 1980 have sharpened, and could help reveal how this understanding can best be applied for the benefit of public safety and the environment.

References

Collins, B. D., and T. Dunne (2019), Thirty years of tephra erosion following the 1980 eruption of Mount St. Helens, *Earth Surf. Processes Landforms, 44*(14), 2,780–2,793, https://doi.org/10.1002/esp.4707.

Crisafulli, C. M., and V. H. Dale (Eds.) (2018), *Ecological Responses at Mount St. Helens: Revisited 35 Years After the 1980 Eruption,* 336 pp., Springer, New York, https://doi.org/10.1007/978-1-4939-7451-1.

Crisafulli, C. M., et al. (2015), Volcano ecology: Disturbance characteristics and assembly of biological communities, in *The Encyclopedia of Volcanoes,* 2nd ed., edited by H. Sigurdsson et al., chap. 73, pp. 1,265–1,284, Elsevier, Amsterdam, https://doi.org/10.1016/C2015-0-00175-7.

Dale, V. H., F. J. Swanson, and C. M. Crisafulli (Eds.) (2005), *Ecological Responses to the 1980 Eruption of Mount St. Helens,* 342 pp., Springer, New York, https://doi.org/10.1007/0-387-28150-9.

Franklin, J. F., and D. C. Donato (2020), Variable retention harvesting in the Douglas-fir region, *Ecol. Processes, 9,* 8, https://doi.org/10.1186/s13717-019-0205-5.

Franklin, J. F., and J. A. MacMahon (2000), Messages from a mountain, *Science, 288*(5469), 1,183–1,184, https://doi.org/10.1126/science.288.5469.1183.

Lipman, P. W., and D. R. Mullineaux (Eds.) (1981), The 1980 eruptions of Mount St. Helens, Washington, *U.S. Geol. Surv. Prof. Pap., 1250,* 844 pp., https://doi.org/10.3133/pp1250.

Lowenstern, J. B., and D. W. Ramsey (2017), The Volcano Disaster Assistance Program—Helping to save lives worldwide for more than 30 years, *U.S. Geol. Surv. Fact Sheet, 2017-3071,* 6 pp., https://doi.org/10.3133/fs20173071.

Major, J. J., and L. E. Mark (2006), Peak flow responses to landscape disturbances caused by the cataclysmic 1980 eruption of Mount St. Helens, Washington, *Geol. Soc. Am. Bull., 118,* 938-958, https://doi.org/10.1130/B25914.1.

Major, J. J., A. R. Mosbrucker, and K. R. Spicer (2018), Sediment erosion and delivery from Toutle River basin after the 1980 eruption of Mount St. Helens: A 30-year perspective, in *Ecological Responses at Mount St. Helens: Revisited 35 Years After the 1980 Eruption,* edited by C. M. Crisafulli and V. H. Dale, pp. 19–44, Springer, New York, https://doi.org/10.1007/978-1-4939-7451-1_2.

Newhall, C. G. (2000), Mount St. Helens, master teacher, *Science, 288*(5469), 1,181–1,183, https://doi.org/10.1126/science.288.5469.1181.

Pierson, T. C., and J. J. Major (2014), Hydrogeomorphic effects of explosive volcanic eruptions on drainage basins, *Annu. Rev. Earth Planet. Sci., 42*(1), 469–507, https://doi.org/10.1146/annurev-earth-060313-054913.

Sclafani, P., C. Nygaard, and C. Thorne (2018), Applying geomorphological principles and engineering science to develop a phased sediment management plan for Mount St. Helens, Washington, *Earth Surf. Processes Landforms, 43*(5), 1,088–1,104, https://doi.org/10.1002/esp.4277.

Shore, J. H., E. L. Tatum, and W. M. Vollmer (1986), Evaluation of mental effects of disaster, Mount St. Helens eruption, *Am. J. Public Health, 76,* 76–83, https://doi.org/10.2105/AJPH.76.Suppl.76.

Waitt, R. (2015), *In the Path of Destruction: Eyewitness Chronicles of Mount St. Helens,* 416 pp., Wash. State Univ. Press, Pullman.

Willingham, W. F. (2005), The Army Corps of Engineers' short-term response to the eruption of Mount St. Helens, *Ore. Hist. Q., 106*(2), 174–203, https://www.jstor.org/stable/20615526.

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▶ **Read the article at bit.ly/Eos-Mt-St-Helens**

The Future Needs Science. The U.S. Elections Need You

With the 2020 U.S. election season well underway—not just for the presidency but also for many other national, state, and local positions—we haven't heard enough about the essential role that science plays in our society. Scientific research is a critical part of understanding how climate change will affect our lives, addressing and preparing for natural hazards like hurricanes and earthquakes, and supporting our economy—science, technology, engineering, and math (STEM) skills are needed for 67% of jobs in the United States today.

With the crucial role that science plays in society, scientists should be speaking up during elections to make sure that these issues are covered by the candidates and that their colleagues and anybody who cares about science are voting. Yet in 2018, only 34% of STEM students voted, a percentage lower than the voting rate for students of any other academic field.

To increase the representation of scientists at the polls and provide ways for scientists to speak up for science, AGU has launched the Science Votes the Future campaign. The campaign features tools to get your fellow scientists to polls and a 2020 Voter Pledge. We will make it easy to share scientific information with people running for office in your district, from talking points on key science issues to ideas for ways to engage with the candidates and your community. Science Votes the Future aims to help scientists engage in the election process, highlighting the need for candidates at all levels to include science as part of their platform.

Sign up and share our 2020 Voter Pledge to receive reminders about your state primaries. If you want to get more involved, we have information to get to your candidates about climate change, health, natural hazards, STEM education, and other science topics. In the months to come, we'll highlight how to volunteer with a campaign, attend district events, and get out the vote.

With this effort, AGU aims to increase the percentage of scientists and STEM students who vote in the 2020 elections. We hope to see a greater number of scientists engage with candidates and elected officials and to hear more candidates discuss the value and importance of science.

AGU would also like to hear from any of you who are inspired to act by Science Votes the Future—whether by voting, engaging with candidates, or encouraging your colleagues. Ultimately, we hope that this is just the beginning of a greater voice for scientists in the election process.

Visit Science Votes the Future and sign the voter pledge at sciencevotesthefuture.org. ■

STEM Supports 67% of U.S. Jobs

With the 2020 campaign a key focus in the United States, AGU joined nine U.S. scientific and engineering associations, university organizations, and industry organizations to analyze the critical role that the science, technology, engineering, and math (STEM) fields play in the U.S. economy.

Science organizations such as ours have long been working together to lead new generations down the path to careers in these fields, such as designing targeted informational programs that identify both traditional and alternative STEM careers and the critical skills students should learn to pursue each one. This new report, "STEM and the American Workforce," shows that not only are these jobs flourishing in our economy, but they are also attainable by an increasingly large percentage of the population (see bit.ly/STEM-workforce)

These are some of the key findings from the analysis conducted by FTI Consulting.

STEM Is the Economy's Engine

First and foremost, STEM powers the U.S. economy. STEM supports 67% of U.S. jobs and 69% of the nation's gross domestic product (GDP) are supported by STEM, with direct STEM jobs accounting for 33% of the economy. In addition, STEM is the primary U.S. economic driver and produces $2.3 trillion in federal tax revenue annually.

Federal support for science produces a tremendous return on investment. Science improves our ability to understand, adapt to, and even predict the impacts of natural hazards and climate change, and the federal investment benefits communities and taxpayers directly by protecting lives, property, and economic interests.

Highly Skilled STEM Careers Are One Third of U.S. Occupations

The analysis reviewed 819 occupations as defined by the Bureau of Labor Statistics and aggregated data using the Impact Analysis for Planning (IMPLAN) model. Of the 195.8 million jobs identified across these 819 occupations, 64 million, or 33%, were high-skilled STEM professions. Because the model used a conservative analysis, it's likely that the number of STEM-supported occupations is actually higher.

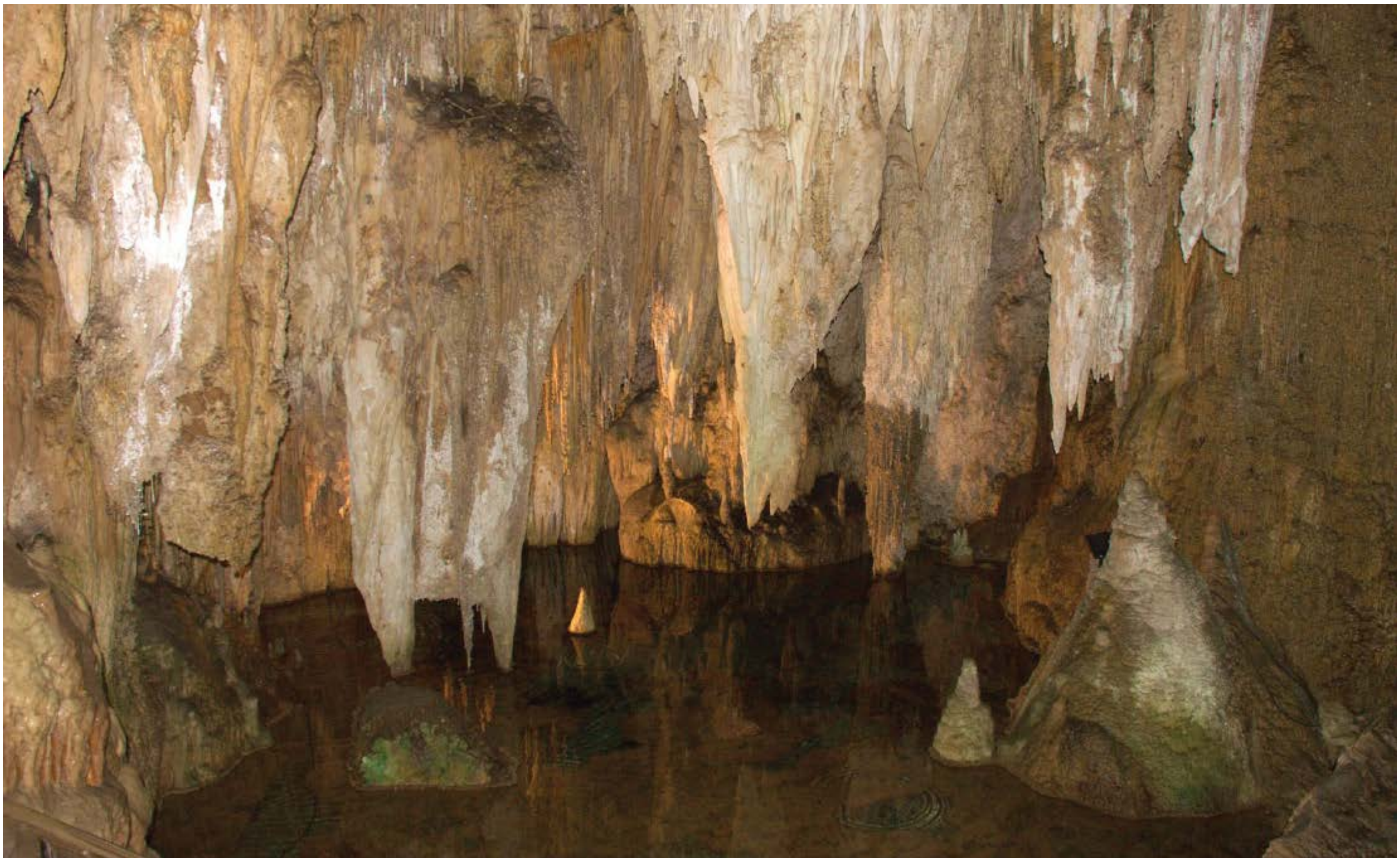
No College Required: Alternative STEM Fields Are Flourishing

The analysis also found that STEM jobs fall outside the bounds of common perceptions. For example, although people who study hurricanes or design satellites undoubtedly have STEM skills, there are many other STEM-based jobs that go unnoticed, such as air traffic controllers, crane operators, maintenance crews, and even tax preparers. In fact, 59% of Americans in STEM jobs in every segment of our economy do not hold bachelor's degrees.

This number demonstrates how attainable a career in the STEM workforce can be, the result of which can be a more diverse and inclusive STEM pipeline.

In the lead-up to the 2020 U.S. presidential elections, it's crucial that we continue our support of all researchers, STEM workers, and the global scientific enterprise. AGU encourages our members and the broader scientific community to engage candidates to make science a part of their campaigns and urge elected officials to champion science and its funding. ■

How to Read Atmospheric History Written in Flowstones



Isotopes deposited in formations like these in the Furong Cave complex near Chongqing, China, can shed light on climate history if they are read properly. Credit: Brookqi

As drops of water squeeze through fissures in limestone cave ceilings and drip one by one to the floor like a slow rain, each drop leaves behind dissolved minerals carried from Earth's surface above. And as these minerals solidify, they leave a record of the planet's climate.

Because cave mineral deposits called flowstones often preserve such detailed records, they offer unparalleled tools with which scientists can track Earth's climate history. Climate information is stored in the isotopic ratios of elements like oxygen deposited in the flowstones. But many factors can influence oxygen isotope ratios in precipitation and surface waters, so their interpretation is hotly debated.

In a new study, *Hu et al.* try to pin down how scientists can make the best use of these records. Focusing on caves in eastern China, they used a recently developed model to explore which contributing factors have the strongest effect on oxygen isotope ratios in cave formations.

Over long timescales, isotope ratios measured in Chinese caves correlate to the amount of solar radiation the area above receives each summer. Among other processes that affect this amount, the wobble of Earth's axis induces a cyclic fluctuation every 23,000 years. At times in this cycle when the Northern Hemisphere is closest to the Sun, the belt of heavy precipitation in East Asia's monsoon season moves faster and farther north. As it does, it draws less moisture from areas in the Pacific with high oxygen-18 to oxygen-16 ratios and more moisture from the Indian Ocean, where this ratio is lower. The air also has farther to travel and drops more rain on the way to eastern China, so the moisture becomes increasingly depleted of oxygen-18, and the ratio becomes more negative.

Thus, the researchers found that the isotope ratios scientists observe in caves over these long timescales are linked primarily to patterns of monsoon movement rather than to rainfall amounts at cave sites, the prevailing interpretation. And when they zoomed in on a seasonal timescale, they found that a similar interpretation of the isotope ratios in the caves held true.

The new study suggests that oxygen isotope records do provide key constraints on the water cycle in monsoon regions, but they do not offer the straightforward picture of monsoon intensity as assumed. More observations and more modeling are needed to further illuminate the complexities of isotope ratio data from cave formations and the timescales over which these data are most useful, as well as to discern influences on the ratios from other factors such as local atmospheric convection and cave processes. In the meantime, the new research reinforces the notion that conventional scientific understanding often needs to be challenged. (*Paleoceanography and Paleoclimatology,* https://doi.org/10.1029/2019PA003741, 2019) **—Elizabeth Thompson,** *Science Writer*

Investigating Rates of Microbial Methane Munching in the Ocean

Around the world, seafloor sediments harbor vast amounts of methane. When methane escapes into seawater, either by natural seepage or because of such human activities as the 2010 Deepwater Horizon oil spill, this potent greenhouse gas becomes food for certain microbes, limiting the amount that ultimately enters Earth's atmosphere.

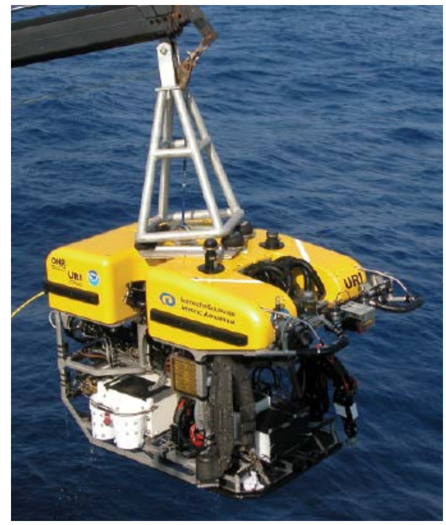
Now *Chan et al.* report new insights into the chemical dynamics involved in microbial consumption of methane released from two seafloor sites. In a companion paper, they also share new findings on how the total extent of microbial methane consumption can be tracked using changes in the ratios of methane molecules containing different isotopes of carbon.

In both studies, the researchers collected seawater from an active methane seepage site at Hudson Canyon off coastal New York while aboard the R/V *Endeavor*. They also sent the *Hercules,* a remotely operated vehicle, to gather seawater at a site 17 kilometers from the Deepwater Horizon wellhead in the Gulf of Mexico. In the laboratory, they incubated these samples in temperature-controlled containers, seeded some with extra methane, and monitored them for 80 days.

As reported in the first study, methane-munching microbes in the seawater consumed very little of the dissolved gas for several days or weeks. The microbial populations then suddenly increased, or bloomed, and quickly gobbled up the rest of the methane in just a few days, following a simple, linear consumption rate. This pattern held true across samples from different sites, though exact timing and rates varied.

The researchers also tracked changes in the ratios of different carbon isotopes in the methane, which microbes consume at different rates. From earlier research, they suspected that these rates would vary over the course of a microbial bloom. But in the companion study, they report that isotope ratio changes in the seawater samples followed a straightforward pattern during the bloom phase, suggesting that this pattern could serve as a simple proxy to track methane consumption in a bloom.

These two studies provide a deeper view of microbial methane oxidation, a process that is difficult to examine in the field yet is suspected of consuming tremendous amounts of the gas. The work helps refine scientific understanding of what happens when methane is released into seawater and could inform ongoing research into the aftermath of the Deepwater Horizon spill. (*Journal of Geophysical Research: Oceans,* https://doi.org/10.1029/2019JC015594 and https://doi.org/10.1029/2019JC015603, 2019) **—Sarah Stanley,** *Science Writer*



The remotely operated vehicle Hercules *collects seawater from a methane seepage site in the Gulf of Mexico. Credit: Brennanphillips*

Missing Lakes Under Antarctic Ice Sheets

Ragged and remote, Recovery Glacier drains nearly 1 million square kilometers of the East Antarctic Ice Sheet (EAIS), a massive system of glaciers that makes up about two thirds of the Antarctic continent. Past studies have suggested that there are a number of large lakes beneath the glacier, potentially contributing to its unusually fast westward flow along the Shackleton Range. Now, however, a new study suggests that many of these lakes do not exist.

Most previous studies that suggested that large lakes are present beneath Recovery Glacier were based on altimetry, a satellite-based method that measures a glacier's volume on the basis of its height. In the new study, however, *Humbert et al.* used a different technique, called radio echo sounding, to look for the lakes.

In radio echo sounding, an airplane broadcasts radio waves deep into ice and catches the signals as they bounce back, revealing a glacier's interior structure. Large, flat reflections from the base of the ice sheet typically indicate liquid water. In January 2014, the team carried out an extensive, airborne, radio echo survey of Recovery Glacier and its tributaries, flying a total of 22,700 kilometers along the glacier's path.

Although the researchers were able to accurately identify a few lakes beneath Recovery Glacier, they found no evidence of water at most of the sites where past studies have proposed large lakes. Computer models based on the new measurements suggest that the few large lakes that do exist beneath the ice sheet are not likely to be responsible for the glacier's high velocity, the team reports.

The findings could help scientists more accurately predict how loss of ice from Recovery Glacier will contribute to sea level rise as global temperatures warm. Although the EAIS, which Recovery drains, has traditionally been considered less vulnerable to warming oceans than the Western Antarctic Ice Sheet, recent research suggests that it, too, is losing billions of tons of ice per year. (*Journal of Geophysical Research: Earth Surface,* https://doi.org/10.1029/2017JF004591, 2018) **—Emily Underwood,** *Science Writer*

Santa Ana Winds and Wildfires Influence Air Pollution

Fine particulate matter ($PM_{2.5}$) in the air, defined as bits of debris and aerosols with diameters less than 2.5 micrometers, has negative impacts on human health, including contributing to cardiovascular and respiratory illnesses. This material is emitted into the skies from a variety of sources, such as combustion in automobile engines, coal-fired power plants, and wildfires. Once in the atmosphere, how $PM_{2.5}$ particles circulate depends greatly on local winds.

In Southern California, for example, where wildfires occur most often at the end of the dry season, Santa Ana winds can shift where fine particulate matter winds up. These northeasterly winds occur between September and May and result from dry air that warms over southwest facing coastal topography before flowing down from the mountains and offshore. In fall, when conditions are driest, the Santa Ana winds can be a major exacerbator of wildfires.

In a new study, *Aguilera et al.* compare local data on $PM_{2.5}$ concentrations against records of Santa Ana winds in Southern California. Their combined data set spans from 1999 to 2012 and reveals that the influence of Santa Ana winds on $PM_{2.5}$ concentrations depends on whether and where fires are burning.

In the absence of upwind wildfires, strong Santa Anas reduced $PM_{2.5}$ air pollution over Southern California by sweeping $PM_{2.5}$ out to sea. However, when wildfires were burning, the winds had the opposite effect, stoking the fires inland and transporting ash and other particulate debris from them to coastal cities.

In general, the Santa Ana winds decreased $PM_{2.5}$ particulates most in inland ZIP codes during years with fewer fires, whereas the biggest increases in $PM_{2.5}$ were observed in coastal ZIP codes in years with widespread wildfires.

Several large fires burn in Southern California in this satellite image taken on 22 October 2007. Researchers have found that the region's Santa Ana winds exacerbate fine-particulate air pollution in coastal cities when wildfires are burning. Credit: NASA Worldview

Projections of the dynamics of Santa Ana winds as well as of the changing precipitation regime in Southern California (i.e., with the wet season starting later) suggest that there could be more chances for consecutive Santa Ana wind days fanning wildfires and burning larger areas, which in turn would increase human exposure to fine particulates from wildfire smoke. (*GeoHealth*, https://doi.org/10.1029/2019GH000225, 2020) **—David Shultz,** *Science Writer*

New Study Shifts Paradigm of Coastal Sediment Modeling

Coastal habitats bear the brunt of global environmental change. Rising sea levels, intense shoreline development, and pollution all contribute to worldwide habitat losses on the order of 1%–7% per year. Cumulatively, nearly half of the world's wetlands, mangroves, and seagrass habitats have eroded away over the past several decades.

Coastal ecosystems serve as vital carbon sinks and storm buffers while also providing critical habitat for countless species, both rare and abundant. To protect and maintain both natural and developed shorelines, scientists and landscape planners need reliable models of how water, sediment, and vegetation interact in coastal environments.

For years, so-called sediment transport models relied on measurements of bed shear stress; however, recent studies indicate that these models underestimate the amount of material transported through plant-laden waterways. Specifically, the models do not account for the turbulence plants create in flowing water. In response to these shortcomings, *Yang and Nepf* propose a new framework for modeling sediment transport along vegetated shorelines and floodplains.

The authors developed an alternative method that relies on turbulent kinetic energy to predict the rate of sediment transport in vegetated zones. They conducted experiments in a 1-meter-wide × 10-meter-long flume that recirculated water and sediment while they varied the amounts of model plants and the water velocity in the flume.

Upon successfully developing a model for vegetated regions, the authors tested their work in conditions lacking vegetation, scenarios that the bed shear stress model typically captures well. The results of the follow-up experiments suggest that the turbulence models also successfully predict sediment movement in unvegetated channels; in some cases, the new model worked even better than the standard model.

When taken together, the results from both the vegetated and bare-channel experiments indicated that turbulence is a better universal predictor of sediment flow than bed shear stress. The findings represent a significant advance in the field of coastal hydrology and geomorphology. The newly developed model should improve predictions of sediment transport and retention in both vegetated and unvegetated regions while improving restoration and planning in coastal environments. (*Geophysical Research Letters*, https://doi.org/10.1029/2018GL079319, 2018) **—Aaron Sidder,** *Science Writer*

Solving the Global Nitrogen Imbalance

Wetlands like this restored fen in Ovando, Mont., can help mitigate nitrogen pollution by absorbing excess nutrients. Credit: U.S. Fish and Wildlife Service, CC BY 2.0 (bit.ly/ccby2-0)

Nitrogen, along with carbon, hydrogen, and oxygen, is one of the fundamental elements that make life on Earth possible. Nitrogen makes up nearly 80% of the air we breathe and is a key factor in food security, human and environmental health, climate change, and the economy. The problem with nitrogen today—at least with agricultural nitrogen in the form of fertilizers—is like many others: There is a geopolitical divide between haves and have-nots. And according to the researchers behind a new study, large-scale efforts are needed to address the environmental, economic, and social problems that surround the use, and misuse, of nitrogen around the world.

Agricultural nitrogen that doesn't enter crops contaminates the land, water, and air in many parts of the world, particularly in developed countries with ample access to fertilizers. Unused amounts represent wasted nutrients that do not contribute to farmers' yields but contribute to numerous health problems, as well as to ozone depletion, climate change, aquatic dead zones, water pollution, and other environmental problems.

In developing economies, though, farmers don't have enough nitrogen. Without fertilizer, exhausted soils cannot support the crops that local populations need, and food insecurity contributes to social unrest, economic stagnation, malnutrition, and famine.

In a new paper, *Houlton et al.* consider the problems of the global nitrogen imbalance as well as proposed solutions and present a five-pronged approach to maximize the positive effects of agricultural nitrogen on our planet.

First, we should build on the recent momentum of nitrogen efficiency gains in the United States, Europe, and China. With improved technology and farming practices, fertilizers can precisely meet the needs of growing plants. These efforts should extend to nitrogen in animal feed and waste as well. Incentive programs and more nitrogen-efficient crops can help farmers adopt better practices.

Second, nitrogen supplies should be distributed differently. Food-insecure areas, such as parts of sub-Saharan Africa and South America, would benefit from increased access to nitrogen fertilizers. These changes would require the cooperation of both national governments and private organizations and must account for farmers' local needs and customs.

Third, nitrogen pollution should be removed from the environment by both reducing nitrogen pollution at its sources and restoring wetlands and floodplains. These restored ecosystems can sponge excess nitrogen out of water, and they provide habitat that may increase biodiversity. In addition, wetland soils can further mitigate climate change by storing carbon.

Fourth, we should waste less food. A quarter of all food produced is never consumed, so the fertilizer used to grow this food is wasted. Better on-farm storage facilities and public awareness can help, as food waste occurs both on farms and at the consumer level.

Finally, we need a cultural shift to adopt diets with low nitrogen footprints. Farmers can breed and grow more nitrogen-efficient crop varieties, whereas consumers can opt to consume food with lower nitrogen footprints.

The researchers call on other scientists to model and explore the costs and benefits of these solutions. For example, quantitative modeling of how different practices might affect future climate change could spur governments to enact incentive programs, and research into which foods use nitrogen most efficiently would help consumers make more informed choices. (*Earth's Future,* https://doi.org/10.1029/2019EF001222, 2019) **—Elizabeth Thompson,** *Science Writer*

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POSITIONS AVAILABLE

Ocean Sciences

Modeling Ocean Biogeochemical Argo Observations Research at Princeton University

The Atmospheric and Oceanic Sciences Program at Princeton University in cooperation with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) seeks a postdoctoral research associate or more senior scientist to assess modes of variability in biogeochemical observations and assess the necessary scope of observations to constrain boundary conditions and underlying biogeochemical functioning towards improved predictability of living marine resources. The incumbent will leverage an existing ⅛ degree ocean biogeochemical eddying simulation along with a suite of coarse resolution ocean biogeochemical retrospective forecast experiments to a) assess daily variability in BGC ARGO observables, as well as the relationship to underlying biogeochemical interactions, in the California Current Large Marine Ecosystem (CCLME) b) conduct additional model simulations as needed, and c) inform GFDL Earth System Model (ESM) initialization for improved representation and understanding of the CCLME. The incumbent will also assess the large scale variability in water mass structure to contrast large scale drivers of shifting biogeochemical provinces, mesoscale dynamics, and drivers of physical and biogeochemical variability at the ocean weather scale. This multiscale assessment of the underlying variability and its drivers will inform not only interpretation of individual floats, but also serve as a framework to better characterize biogeochemical variability in boundary conditions for regional models, and evaluate the potential for seasonal to decadal scale predictability of hypoxia, ocean acidification, algal blooms and living marine resources. Personnel will join an active group at Princeton and GFDL studying the connections between biogeochemistry, ecosystems, and climate (https://www.gfdl.noaa.gov/marine-ecosystems/).

These are two-year positions (subject to renewal after the first year) based at GFDL in Princeton, New Jersey. Complete applications, including a cover letter, CV, publication list, a one to two-page statement of research interests and names of at least 3 references in order to solicit letters of recommen-

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dation, should be submitted online to https://www.princeton.edu/acad-positions/position/15601 by April 30, 2020 for full consideration, though evaluation will be ongoing.

Essential Qualifications: PhD is required. Candidates with quantitative, interdisciplinary knowledge from subsets of fields including climate dynamics, ocean and coastal biogeochemistry, marine ecosystem dynamics, and fisheries science and management are particularly encouraged to apply. Experience analyzing large data sets and/or model output is also critical, as is model development experience for those positions.

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The National Academy of Sciences, Engineering, and Medicine administers postdoctoral and senior research awards at participating federal laboratories and affiliated institutions at locations throughout the U.S and abroad.

We are actively seeking highly qualified candidates including recent doctoral recipients and senior researchers.

APPLICATION DEADLINE DATES (FOUR ANNUAL REVIEW CYCLES):
- February 1
- May 1
- August 1
- November 1

AWARDEE OPPORTUNITIES:
- Conduct independent research in an area compatible with the interests of the sponsoring laboratory
- Devote full-time effort to research and publication
- Access the excellent and often unique facilities of the federal research enterprise
- Collaborate with leading scientists and engineers at the sponsoring laboratories

AWARDEE BENEFITS:
- One-year award, renewable for up to three years
- Stipend ranging from $45,000 to $83,000; may be higher based on experience
- Health insurance (including dental and vision), relocation benefits, and professional travel allowance
- Applicants should contact prospective Research Adviser(s) at the lab(s) prior to the application deadline to discuss their research interests and funding opportunities.

DESIRED SKILLS AND EXPERIENCE:
Applicants should hold, or anticipate receiving, an earned doctorate in science or engineering. Awards are contingent upon completion of the doctoral degree. A limited number of opportunities in select fields are also available for graduate students. Degrees from universities abroad should be equivalent in training and research experience to a degree from a U.S. institution. All research opportunities are open to U.S. citizens; some are open to U.S. permanent residents and foreign nationals.

ABOUT THE EMPLOYER:
The National Academies of Sciences, Engineering, and Medicine's Fellowships Office has conducted the NRC Research Associateship Programs in cooperation with sponsoring federal laboratories and other research organizations approved for participation since 1954. Through national competitions, the Fellowships Office recommends and makes NRC Research Associateship awards to outstanding post-doctoral and senior scientists and engineers for tenure as guest researchers at participating laboratories.

DIRECTOR, EW BOSTON UNIVERSITY SUSTAINABILITY RESEARCH INSTITUTE FOCUSED ON ENERGY AND THE ENVIRONMENT

Boston University is embarking on a bold initiative to bring together over 100 faculty in nearly all of its 17 Schools and Colleges to enhance BU's ability to contribute pioneering research and leadership at the intersection of energy and the environment – one of the greatest interdisciplinary challenges of our time. The initiative focuses on the science, social science, communications, business/economic/financial, and policy dimensions of this complex, interwoven set of challenges.

Boston University is now seeking to create an overarching structure which will build on the success of the ***BU Institute for Sustainable Energy***, as well as the work of many other departments, projects, and existing programs at Boston University. The ***Institute for Sustainable Energy*** was founded in January 2016. Since its inception the Institute has experienced substantial growth in size, scope and impact and is gaining a national reputation for its research which spans nearly all of BU's schools and colleges. Faculty affiliated with the Institute currently work on topics such as smart grid technology, sustainable water management, sustainable urban systems, city climate strategies, green supply chains, electric vehicle adoption, carbon footprints and green bonds. The Institute played a crucial, leading role in the Boston Green Ribbon Commission's work on the City of Boston's Climate Action plan. The Institute has an extremely impressive external advisory board composed of industry and scientific leaders in the field and has embarked upon a significant fund-raising campaign.

The new Institute will build on the university's current initiatives and strengths in sustainability and climate change research and action and incorporate them into an umbrella organization grown out of the current Institute for Sustainable Energy. It will serve to unite our efforts in this area, as well as spawn related activities at the intersection of technology, society, business, and policy relating to energy and the environment. While continuing to direct the ongoing work of the ISE, the director will lead the final stages of planning as well as the transition and operation of the broader institute during the next academic year.

The **Director** who reports to the Vice President and Associate Provost for Research, reflecting the function of the Institute as a university-wide research center, takes primary responsibility for the strategic direction of the Institute and for all of its executive decisions. The Director of will continue the work of establishing the Institute as an internationally recognized Center of Excellence by:

1. Building on the Institute's success in fostering collaborative research that connects faculty across the University

2. Supporting the faculty in undertaking major research initiatives and cutting-edge research

3. Working with the faculty and the Deans to further develop those areas in which we have a reputation for excellence and the potential for carrying out ground-breaking work that would significantly expand our current impact.

Successful candidates will have a distinguished record of professional achievement as a scholar, teacher, and leader. Additionally, the successful candidates will have:
- Excellent scholarly credentials;
- Experience in a significant administrative role that includes budgetary oversight;
- The ability to articulate a compelling vision for the Institute;
- Demonstrated ability to work collaboratively with colleagues from different academic fields and with administrative units around the University; and
- A commitment to creating and sustaining a vibrant, diverse community of students, staff and faculty.

The Director of the Institute will hold a tenured appointment in one of the Schools or Colleges engaged in the initiative and must meet the criterion to be appointed as a full-professors. The Director will have a reduced teaching load in his or her College and will teach in their area of expertise at the undergraduate or graduate level. The appointment as Director is for a 5-year renewable term, beginning **Fall, 2020.**

Nominations and expressions of interest should be sent to: Gloria Waters, Vice President and Associate Provost for Research (Chair), **gwaters@bu.edu**, or ISEE Search Advisory Committee, c/o Office of the University Provost, Boston University, One Silber Way, 8th Floor, Boston, Massachusetts 02215. Prospective candidates should include a letter expressing interest and a current curriculum vitae. Candidates will be asked to provide references after preliminary review and screening. Nominations and applications will be accepted until a new Director is selected.

Boston University is committed to fostering a diverse University community within a supportive and respectful environment. We believe that the diversity of our faculty, students, and staff is essential to our success as a leading research university with a global reach, and that diversity is an integral component of institutional excellence. Boston University is an equal opportunity employer and gives consideration for employment to qualified applicants without regard to race, color, religion, sex, age, national origin, physical or mental disability, sexual orientation, gender identity, gender expression, genetic information, military service, or because of marital, parental, or veteran status or any other characteristic protected by law.

Greetings from the Wapta Icefield!

We completely lucked out on the weather window for our fieldwork here in the Canadian Rockies. The typically gray skies parted, and we have been treated to beautiful blue days since we arrived 5 days ago. We are spending the week skiing across the glacier carrying a ground-penetrating radar to measure ice thickness, to determine how much ice the glacier contains and how this mountainous area will look as the glacier continues to retreat in the coming decades. Spending time on a glacier presents some safety and logistical challenges—a lot of planning goes into any activity that needs to occur up there. Every morning we start with a group meeting to discuss the daily plan, organize the gear, and ensure a safe and productive day. Let's just say the views are better than the typical morning briefing!

Pictured here are (left to right) Steve Bertollo, Mark Ednie, and Eric Courtin.

—**Caroline Aubry Wake**, Ph.D. Candidate, University of Saskatchewan, Saskatoon, Canada

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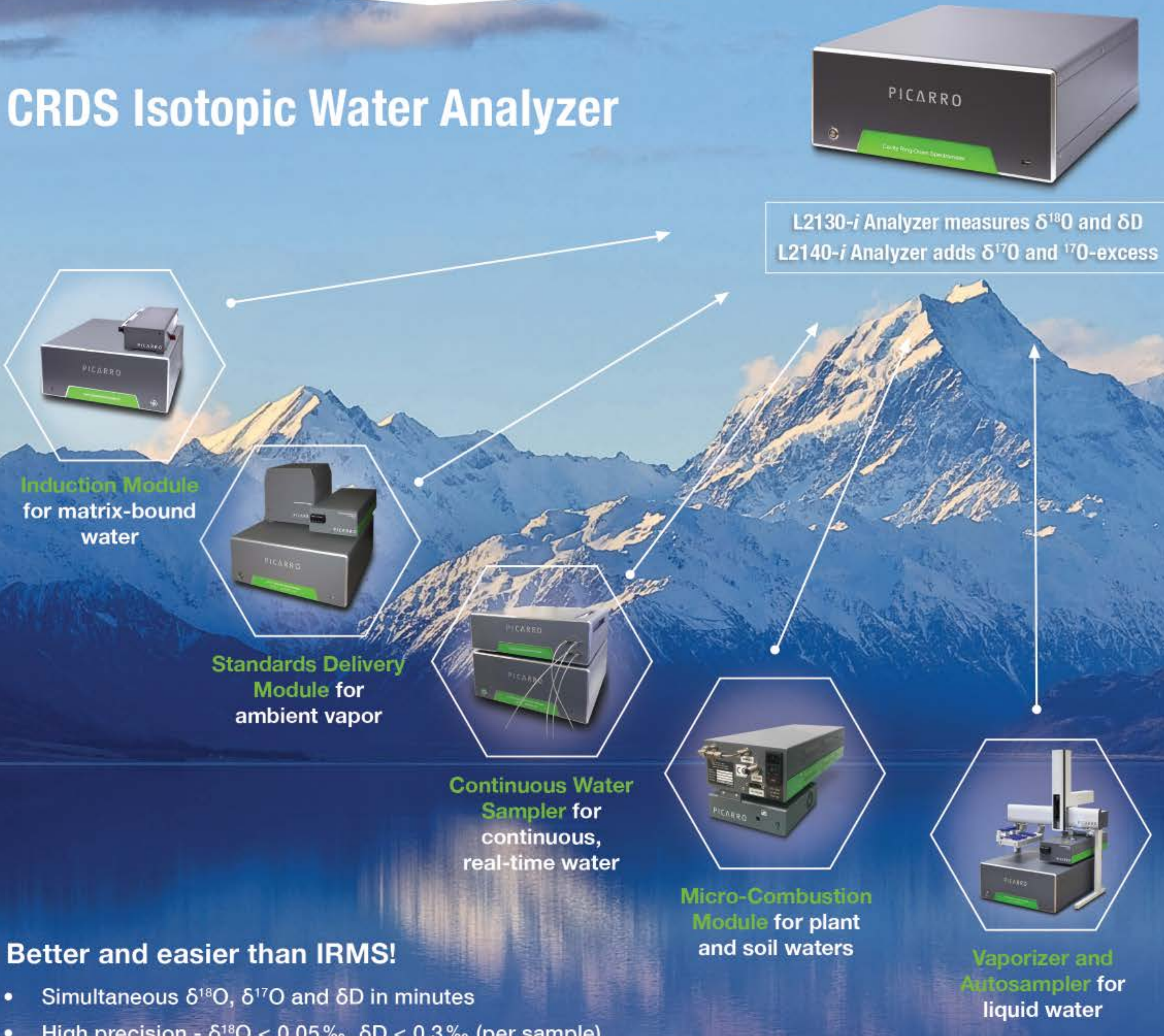

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