Eos

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Five Remaining Martian Mysteries

Crowdsourced Science Pulls Off a Daring WWII Data Rescue

New Depths to North America's Deepest Lake

THE SOUNDS OF SCIENCE

Noisy data aren't always a bad thing.

AGU
ADVANCING EARTH AND SPACE SCIENCES

The Sound of Science

The pejorative term “noisy data” indicates meaningless or distorted information. And we admit, some Earth and space science data can be noisy at times.

But auditory and sonified data can be melodious, harmonious, and just plain weird.

I mean, “Earth is Noisy. Why Should Its Data Be Silent?” ask Leif Karlstrom, Ben Holtzman, Anna Barth, Josh Crozier, and Arthur Paté on page 18. Kīlauea is one of the most well studied volcanoes in the world, but fresh insights about the magma system below its summit bubbled to the surface with innovative auditory displays and sonification of decade-long data sets, the scientist-authors write. “Sonification as a tool for representing Earth science data is in its infancy,” they conclude, but their “Listener’s Guide to Kīlauea” is a first step in the methodology finding its stride.

Earth is not the only noisy place in the universe, as Damond Benningfield notes in “The 21st Century’s Music of the Spheres” on page 26. Audification and sonification of space science data are supporting the development of new audiences and collaborations between scientists, artists, and engineers. The processes are also helping blind and visually impaired astronomers contribute more broadly and deeply to the discipline.

And sometimes, of course, noisy data are just noisy. In “Oceanic Cacophony,” Alka Tripathy-Lang explores how anthropogenic sound has added another layer to an already buzzing underwater soundscape (p. 34). Sounds from human activity such as multibeam sonar, shipping, and oil and gas exploration are redefining both the science of hydroacoustics and the biological communities that rely on sound to literally and metaphorically navigate their world.

From whale songs to black holes to lava lakes, auditory data are expanding the scope of Earth and space sciences. Listen up!

Caryl-Sue Micalizio, Editor in Chief

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Janice Lachance, Interim Executive Director/CEO

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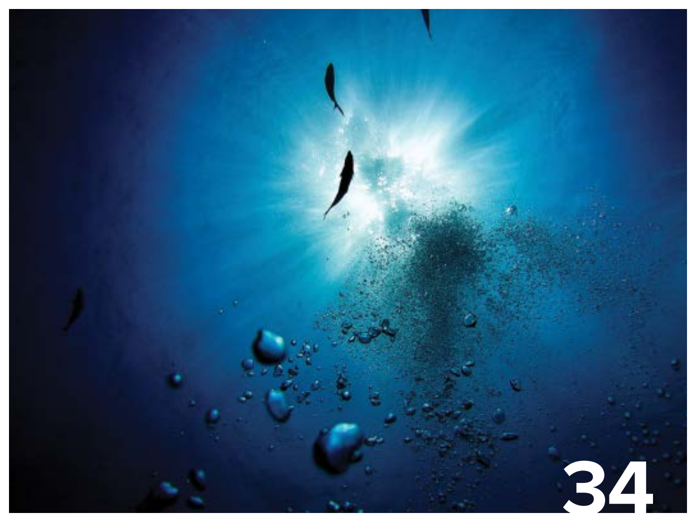

Features

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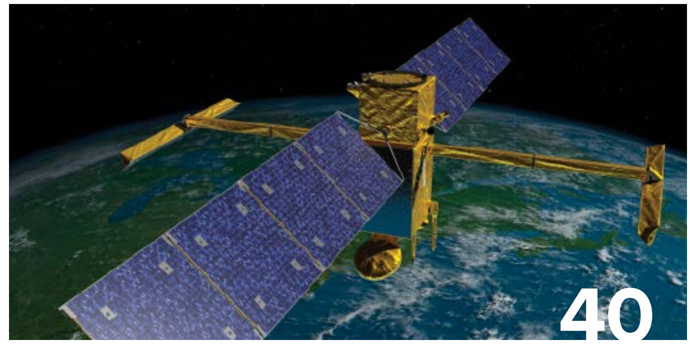
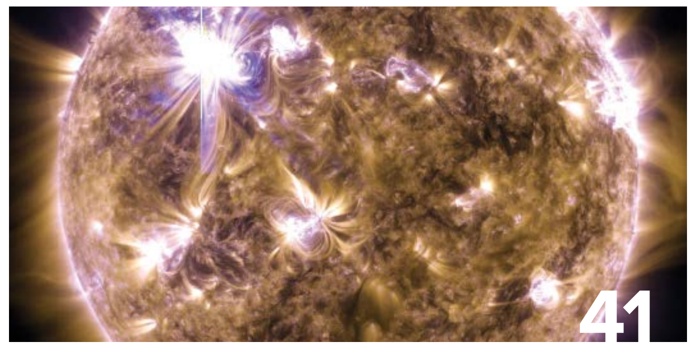




Columns


THANK YOU SCIENCE!

River Recovery from Drought Can Take Years

Since about 2020, North America has been in a drought that has caused water shortages, threatened crop yields, and killed wildlife. After a wet 2022–2023 winter, drought conditions have improved. But that doesn't mean water supply woes are over.

Even after rain returns to dried-out areas, the impact of precipitation drought (also known as meteorological drought) persists in rivers for months or even years. In new research published in the *Journal of Hydrology,* scientists report that the lag time between the return of regular rain and the recovery of a river to its normal conditions can be years (bit.ly/baseflow-recovery). Climate change is worsening drought severity, which puts rivers at further risk of prolonged recovery, the authors write.

"This is really important for understanding how meteorological drought impacts reverberate through the water cycle," said Olivia Miller, a hydrologist at the Utah Water Science Center who was not involved in the new research.

The Little Snake River near Dixon, Wyo., experienced a period of low streamflow in 2021. Credit: USGS Wyoming-Montana Water Science Center

River Recovery

Total precipitation is a more observable indicator of drought, but other types of drought exist. Baseflow drought, for example, refers to the depletion of groundwater that feeds streams. This kind of drought lowers a stream's baseflow, affecting the availability of water for drinking, agriculture, and ecosystems.

Streamflow drought, which refers to abnormally dry stream conditions, has worsened in the United States since the 1950s. These droughts are now more severe and last longer. Emerging research has shown that the same is true for baseflow droughts.

"It takes time for our groundwater reservoirs to recover because it takes time for water to infiltrate," said Hoori Ajami, the study's coauthor and a groundwater hydrologist at the University of California, Riverside. "You may have precipitation back to normal, but not baseflow."

In the new study, researchers analyzed data on precipitation, streamflow, baseflow, and more from 358 river catchments in the United States between 1982 and 2012. They found that the lag time between the end of a precipitation drought and the end of a baseflow drought was as long as 3.5 years, with an average lag time of 2.8 months.

Parts of the West Coast, South, and Great Plains showed longer recovery times, which the authors attributed to rising temperatures over time. The researchers also found that baseflow droughts became more severe and prolonged over the decades analyzed because of increasing temperatures.

Water Management on a Drying Continent

River recovery lag times are increasing as climate change makes Earth's atmosphere thirstier, said Jeffrey Mount, a geomorphologist and senior fellow at the Public Policy Institute of California. A drier, hotter atmosphere sucks up precipitation that falls onto a catchment before that water can replenish the groundwater supply.

> **"People must be careful about managing the water they have."**

Increasingly volatile weather, spurred by climate change, may also affect river baseflow recovery, Mount said. Instead of regular periods of rain spread consistently throughout the years, many parts of the United States now see periods of heavy precipitation followed by intense dry periods. When all that water falls at once, the ground is quickly saturated, and more water flows away as runoff rather than entering the groundwater and replenishing baseflow.

Baseflow recovery is a "very big deal" in the West, Mount said, because many parts of the region don't get much rain in the summer months and rely on river baseflows to maintain water supply.

"One key message we want to send is that people must be careful about managing the water they have," hydrologist Sanghyun Lee, the lead author of the study, said in a statement. "Because watershed boundaries often cross state or international lines, preserving precious water resources will require more cooperation." Formerly a postdoctoral scholar in Ajami's lab, Lee is now a postdoctoral fellow at the U.S. Department of Agriculture.

Some policies governing major waterways in the United States struggle to keep up with increased demand for water and lower streamflows, making accurate water forecasts crucial. In 2023, a state auditor found that water managers had "significantly overestimated" California's water supply during the recent drought, a problem Mount said occurred in part because of a limited understanding of baseflow recovery times.

Continuing to track those lag times will help policymakers and water managers maintain sustainable water usage in the face of drought, Miller said.

By **Grace van Deelen** (@GVD__), Staff Writer

Five Head-Scratching Martian Mysteries

Mars looms large in the scientific imagination, as well as in fiction. Of all the worlds of the solar system, it's the only one Earth-like enough for exploration with Earth-like tools: Its atmosphere is thin and transparent, its surface is dry and cold, and it's close enough for regular study.

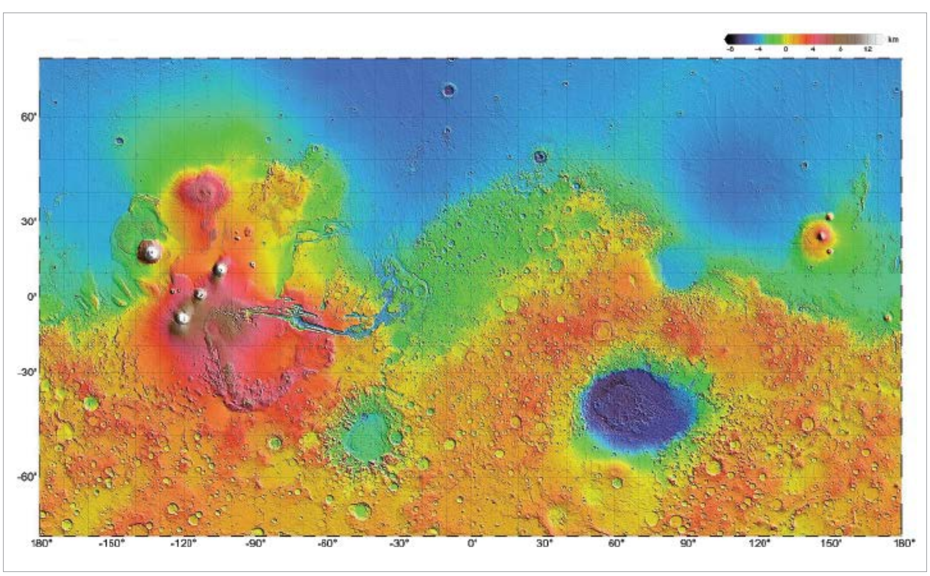
We've probed the Red Planet by telescope for centuries. And over the past 50 years, we've even sent instruments for a closer look. However, in geological terms, that's just a sliver of time. Mars's deep history remains a mystery.

"A major issue that we have pretty much in all of Mars studies is that we just don't know what was going on in the distant past," said planetary scientist Eryn Cangi of the University of Colorado Boulder.

Scientists have found volcanoes, dried lake beds, and other signs that the planet once looked very different, but many mysteries about why and how it changed remain. Here are five linked tangles scientists have yet to unravel.

1. Why Is the Southern Hemisphere So Bulgy?

Maps made by the Viking orbiters from the 1970s—the companions to the Viking 1 and 2 landers—showed that the Martian hemispheres are strikingly different.



This map from the Mars Orbiter Laser Altimeter shows the topographic dichotomy of the hemispheres. Nearly the entire northern hemisphere (blue shades) lies below the average planetary radius, whereas the southern hemisphere (red shades) is higher by several kilometers. Credit: NASA/JPL/USGS

"On average, the southern highlands are 5 kilometers higher in elevation than the lowland, and the crust is tens of kilometers thicker," said planetary geophysicist James Roberts of the Johns Hopkins University Applied Physics Laboratory. The pockmarked southern hemisphere also stands out against the relatively flat north.

"As for why, we don't really know," Roberts said.

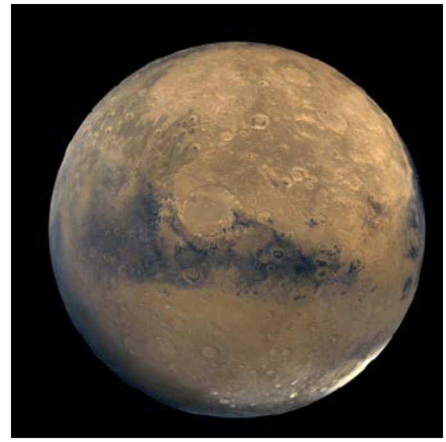
Plate tectonics could explain such a sharp boundary. But data strongly suggest that the Martian crust is one plate, with no faults or strong enough tectonic activity to create what we observe.

Researchers have proposed other explanations, including a large impact early in the solar system's history, similar to the one that formed our Moon. However, such a huge impactor would leave a type of basin scientists have yet to identify, Roberts explained.

Alternately, heating within the planet could have been lopsided. A mantle plume under the southern hemisphere—possibly itself spurred by an impact—could both push up and thicken that half of the planet, explaining the higher elevation and crustal thickness.

The details, however, are difficult to confirm experimentally.

"The way to do that is to get a huge hot buttery network of seismometers on the ground," Roberts said. Such a global spread of observations could help determine whether the hemispheres experience different seismic activity and measure how geologically turbulent the planet is everywhere rather than in just one spot.



Mars holds secrets. Credit: NASA/JPL-Caltech/USGS

"[The InSight lander] was great, but there's only so much you can do with one station," he explained.

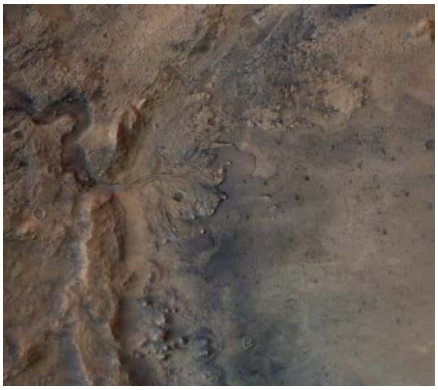
2. Where Has All the Water Gone?

Since the late 1990s, NASA's Mars Global Surveyor and Mars Reconnaissance Orbiter, as well as other orbiters have mapped dried river channels and what look like ancient shorelines. Rovers have found other signs that Mars was wetter in the past than it is today.

"We don't know exactly when the water was particularly stable on the surface," Cangi said. "We think it was very early in Mars's history, but we don't have enough data points to understand how [conditions] changed over time."

It's also unclear what happened to all that water. Cangi and other researchers study how gases escape the Martian atmosphere using hydrogen and its isotope deuterium. These processes could explain how water first evaporated and then disappeared into space, but that still reveals little about conditions millions or billions of years ago.

Some scientists have proposed that an ocean once existed on low-lying areas of the planet's northern hemisphere. Others are more skeptical, pointing out that if we don't know how relatively small lakes and rivers vanished from Mars, it's that much harder to



The Mars Express Orbiter captured signs of an ancient river delta in Jezero crater. Credit: ESA/DLR/FU-Berlin

explain how an ocean dried up. Data supporting a huge body of water are also scant.

"We should see evidence of shorelines, [and] it's just not there!" said planetary scientist Tanya Harrison of the Earth and Planetary Institute of Canada, who has worked extensively with remote sensing data from Mars. "There's also not really any evidence across the northern plains of what you would expect to see [from] marine floor deposits."

"We should see evidence of shorelines, [and] it's just not there!"

3. Why Is Mars an Ice Ball?

One known major reservoir of water is frozen: the Martian cryosphere.

"Mars has ice buried in its near surface and on the surface at the poles," said planetary scientist Margaret Landis of the University of Colorado Boulder. "The problem is, we don't know how it got there [or] if the polar deposits are gaining or losing mass."

The polar caps were first observed in the 17th century, though they were only later confirmed to be ice, when scientists watched them grow and shrink with the seasons. NASA's Mars Odyssey spacecraft and Phoenix lander, which touched down at roughly 68° north latitude, confirmed the presence of subsurface ice when the lander's excavation tool dug up white material that melted.

Getting a handle on the cryosphere's history, Landis said, requires global studies like those that geologists and climatologists carry out on Earth. That means collecting ice cores, rock cores, and other samples that are difficult to obtain on Mars, whether by robot or eventually humans.

4. Is There Methane?

Few things in science are as frustrating as inconsistent data. The European Space Agency's (ESA) Mars Express orbiter first measured methane in the planet's atmosphere in the early 2000s. NASA's Curiosity rover later detected the gas at the surface.

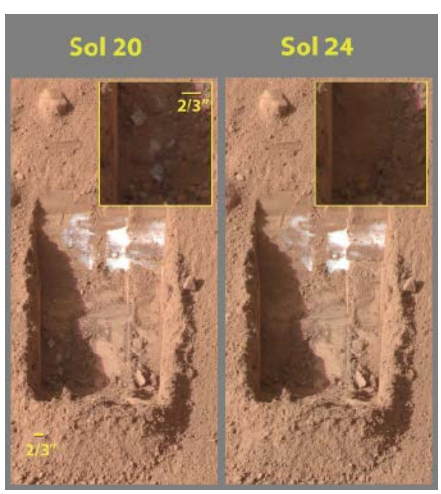
On Earth, methane is commonly produced by life, so finding it on Mars was very exciting.

"Later efforts to detect methane and understand how it changes over a longer timescale have not been very successful," Cangi said, pointing out that the sensitive ESA and Roscosmos ExoMars Trace Gas Orbiter spacecraft has failed to find significant amounts of methane since it reached the planet in 2016. "From below, we think we are seeing methane on the surface, but from above, we're not seeing anything," Cangi puzzled.

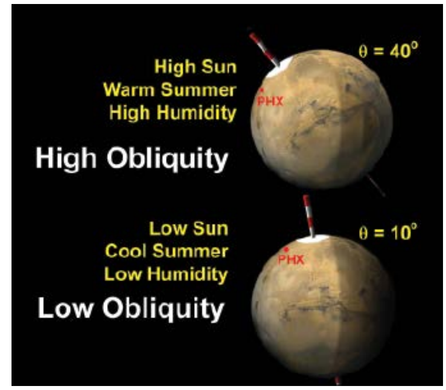
Nonbiological processes can make methane as well (serpentinization is one example), so solving the inconsistencies in data wouldn't help in the search for evidence of life. However, understanding why the measurements don't match is an ongoing priority for Martian research.

5. How Much Does the Planet Wobble?

One link between these mysteries is the lack of data about the Red Planet's obliquity—how



The Phoenix lander dug up evidence of melting ice. Credit: NASA/JPL-Caltech/University of Arizona/Texas A&M University



Scientists think Mars's spin axis wobbles over time. Credit: NASA/JPL/University of Arizona

tilted its spin axis is—which determines how pronounced its seasons are.

Currently, Mars is tilted at almost the same angle as Earth, but both planets wobble over billions of years. We can trace Earth's changes, but we don't have that information for Mars yet.

"We think the obliquity changes chaotically over really long time frames, [so] you can't predict it," Cangi said. "Maybe Mars rotated straight up; maybe it was on its side, like Uranus. That has big implications for the climate: If you have a planet spinning on its side, then there's a whole side where there's no day [for half the year]."

On the other side, long periods of daylight might explain how Mars was once warm enough to hold liquid water. However, hypothesizing that this occurred too far in the past leads to its own problems because the young Sun was fainter and cooler than it is today.

Learning when and how Mars was warm requires a lot more detailed knowledge than researchers can obtain with present and future targeted surface missions, including those by human crews. And there's more at stake than curiosity.

"This is the climate history of another terrestrial planet," Landis said. It could double what we know about how a potentially Earth-like climate evolved. "In a more dire way, how terrestrial planets' climates change is a question we're going to really need a very solid answer to for policymaking decisions here on Earth. It has a lot of far-ranging consequences outside of understanding Mars."

By **Matthew R. Francis** (@DrMRFrancis), Science Writer

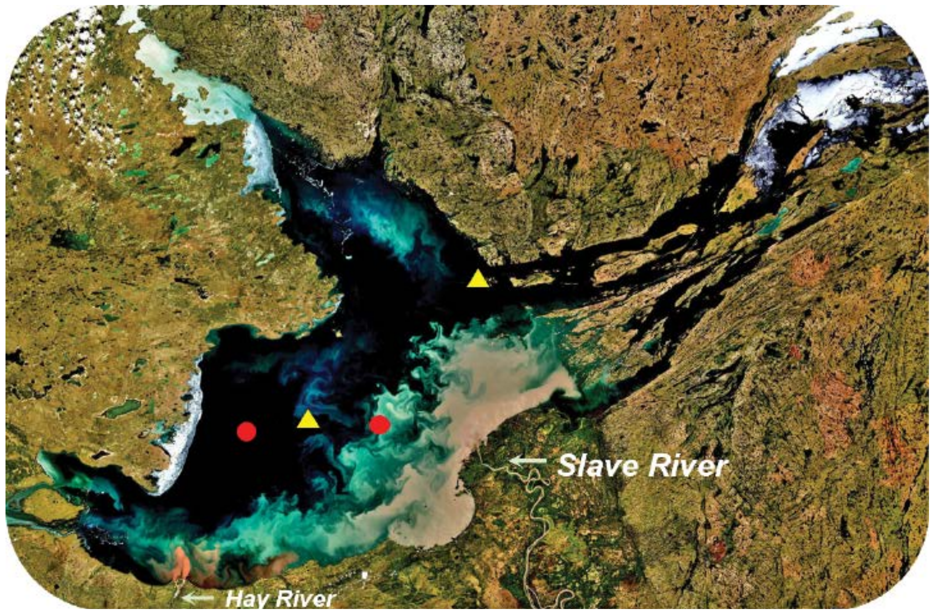
Arctic Warming Triggers Abrupt Ecosystem Shift in North America's Deepest Lake

From the air, Great Slave Lake looks like a giant goose winging across Canada's Northwest Territories. Spanning an area the size of Belgium and reaching depths of up to 614 meters, it's the 10th-largest freshwater lake in the world and North America's deepest.

Its huge mass of cold water has helped shield Great Slave Lake from the climate impacts that have upended the ecosystems of shallower lakes in high northern latitudes. But it no longer does, according to a new study in *Proceedings of the Royal Society B.*

Spurred by accelerating Arctic warming, the microscopic algae, or phytoplankton, at the foundation of the lake's food web have made a radical regime shift since the turn of the century (bit.ly/Great-Slave-Lake-warming). These single-celled organisms, called diatoms, leave behind silica shells that are preserved in lake sediment records. By analyzing the sediment, scientists found that the hefty, chain-forming diatoms that had long ruled Great Slave Lake have now been supplanted by tiny, pancake-shaped counterparts.

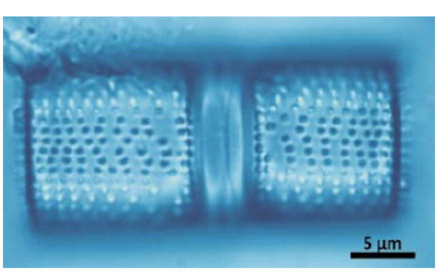
This upheaval in the system's primary energy source could affect the lake's productivity and carbon dynamics, alter its food web, and disturb a significant food and cultural resource for nearby First Nations and Métis communities.



Great Slave Lake in Canada's Northwest Territories is North America's deepest lake. Recent research showed that its enormous mass of cold water no longer shields it from climate change effects. Credit: European Union, Copernicus Sentinel-2A imagery

Profound Change, Cascading Consequences

"In recent history, which we can link to climate warming and less ice cover, it really is a profound change," said John Smol, a paleolimnologist at Queen's University in Kingston, Ont., Canada, and a coauthor of the study. Although the consequences of the regime shift are not yet known, Smol said, the impacts are almost certain to cascade throughout the ecosystem.



Photomicrograph of Aulacoseira islandica, *a diatom that dominated Great Slave Lake prior to 2000. Credit: K. Rühland, Queen's University*

Smol and colleagues compared lake bottom cores extracted in 2014 and the mid-1990s. The two sets of cores provided sediment records stretching back roughly 200 years, from which researchers analyzed diatom remains for changes in species abundance that signal ecosystem transition.

Sediments show that for much of the past century, the lake's ecosystem was dominated by *Aulacoseira islandica*—a heavy, 20-micrometer diatom shaped like a tin can. But beginning in the mid-1990s, a heterotrophic array of small, buoyant plankton about a tenth that size began to muscle in. The shift sharply ramped up around 2000. By the mid-2010s, the analysis found, the tiny interlopers had completely taken over.

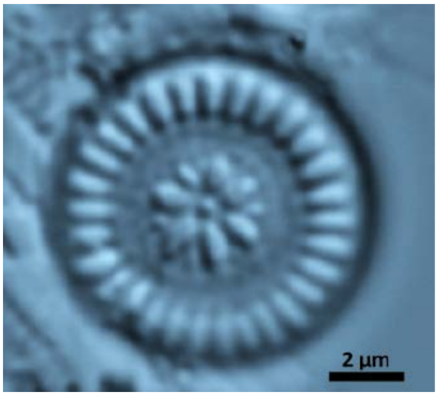
The shift in the dominant species of plankton is unprecedented in the sediment record. Although the warming climate has been triggering rapid shifts in smaller and medium-sized northern lakes since the mid-1900s, findings showed that very large bodies like Great Slave Lake, which had until recently been protected by extensive ice cover and thermal inertia, are no longer able to fend off change (bit.ly/arctic-shifts).

"The nature and magnitude of these effects is startling," said Warwick Vincent, an ecologist specializing in Arctic lakes at Laval University in Quebec who was not involved in the research. "We expected North America's deepest lake to have a large buffer capacity against global change, and it seems that this has now been exceeded."

Rising Temperatures, Declining Ice Cover, Slowing Winds

Great Slave Lake's abrupt transformation corresponds to accelerating Arctic climate change, said the study's lead author, Queen's University paleolimnologist Kathleen Rühland. The region is now warming several times faster than the global average. Since 2010, average air temperatures in the Arctic have climbed by 1°C. Lake ice cover has also declined significantly, and wind speeds have slowed in recent decades.

As a result of temperature changes, the lake is growing calmer, said Rühland, which is bad news for large phytoplankton like *A. islandica* that require turbulence to stay



In the 21st century, diatoms in Great Slave Lake diversified and included more small-celled organisms like Discotella. *Credit: K. Rühland, Queen's University*

afloat and in reach of light for photosynthesis.

"They quickly sink out of the water column," Rühland said. "But these conditions are ideal for these small, pancake-shaped diatoms that are more buoyant."

The regime shift is "an early warning sign that things are really changing," Rühland said. Further research and monitoring are needed to determine the broader implications.

One big question is how the shift will affect the algal primary production—or the creation of organic matter from inorganic carbon compounds—driving this vast ecosystem's food system (bit.ly/primary-production). Between 2003 and 2018, primary production in Great Slave Lake rose by 27%, according to a remote sensing study in the journal *Water* (bit.ly/lake-carbon-fixation). But the smaller algae now fueling the food web could provide less nutrition for the organisms that eat them, ultimately affecting the food supply for fish and other aquatic life—and the communities that rely on them. In addition, the amount of carbon the new regime sequesters through primary production could rise or fall.

The researchers are now turning their attention to the Northwest Territories' Great Bear Lake, which is farther north, colder, and even bigger than Great Slave Lake. Preliminary data on this lake, the eighth largest in the world, suggest that a similar upheaval is underway there too.

"We think of the Arctic as the miners' canaries of the planet, and the lakes are recording it," said Smol. "And within the lake, the canaries are probably the algae."

By **Cheryl Katz** (@ckatz99), Science Writer

Popping Bubbles Make Glaciers Melt Faster

Xeitl Sít'i Glacier flows into LeConte Bay, a 10-kilometer-long (6-mile-long) fjord in Alaska. Submarine melting happens on the submerged surface of the near-vertical glacier snout seen here. Credit: Erin Pettit

Tidewater glaciers—colossal rivers of ice that flow into the sea—continually sizzle and hiss as their icy underbellies thaw in seawater. These underwater noises, sounding like frying food, are caused by the release of once-trapped air bubbles.

But these tiny pressurized bubbles don't just make noise. New research has shown that energy liberated as the bubbles explode can enhance the underwater melting of these glaciers. Lab experiments showed that bubbly glacier ice melts twice as fast as bubble-free ice.

"These millimeter-sized air bubble explosions have an outsized influence on tidewater glacier melt rates," said Erin Pettit, a glaciologist at Oregon State University and a coauthor of the new study, which was published in *Nature Geoscience* (bit.ly/glacier-bubbles).

The discovery could explain, in part, why some tidewater glaciers, such as Xeitl Sít'i (LeConte) in Alaska, are melting faster underwater than predicted by theoretical models.

Gauging Melting

One of the most dramatic ways that tidewater glaciers contribute to sea level rise is through shedding icebergs from their steep-sided fronts, where ice meets ocean—a process called calving. They also eject meltwater via streams running along their bases and through direct melting of their submerged fronts in warm ocean water.

Scientists want to understand this underwater melting because it can influence glacier stability and iceberg calving, but measuring it directly is challenging.

Instead, they use theoretical models to estimate ice melting based on ocean temperatures and currents. These models also

Glacier ice floats in LeConte Bay near Petersburg, Alaska. Credit: Oregon State University

give a picture of how glaciers might respond to ocean warming caused by climate change.

The trouble with these ice melt models, explained Pettit, is that they are based on observations of bubble-free sea ice. Up to 10% of glacier ice is air, which gets trapped between ice crystals as snow is compressed over time. The air inside these bubbles can be at 20 times normal atmospheric pressure at sea level.

Pettit started studying glacier air bubbles about a decade ago, when she used hydrophones to listen to the soundscape near an Alaskan glacier in a fjord. A chance conversation with Meagan Wengrove, a coastal engineer at Oregon State University, spurred an idea for their lab experiment on popping bubbles. Wengrove is the lead author of the new study.

Testing a Hunch

No one had previously investigated how high-pressure bubbles affect ice melt, Wengrove said, even though "air bubbles are widely known to create turbulent flow in liquids."

Wengrove and her colleagues had a hunch that air bubbles might disturb the thin layer of cold water known to coat glaciers' undersides, bringing warm water in direct contact with the glacier ice and enhancing melting.

To test their theory, the researchers used high-speed cameras to record glacier ice from Oregon State University's ice core lab as it melted in a saltwater tank. They also shone laser light onto the ice surface and used tracer particles to track currents in the surrounding water. Then they repeated the experiment with bubble-free ice donated by an ice sculptor.

Wengrove and colleagues found that air bubbles increased melting by supplying fast moving warm water to the ice surface. In their recordings, they observed that air bubbles popped out of the thawing ice explosively, leaving behind low-pressure voids in the protective boundary layer. They think warm seawater then rushes toward the glacier to fill these voids. The team also found that these air bubbles pulled warm water upward with them as they rose, creating currents that melted the ice further.

Wengrove and coauthor Jonathan Nash, an oceanographer at Oregon State University, built a model simulation to explore the effect of air bubbles at the glacier scale. They saw that the bubbles caused the strongest submarine melting in water less than 60 meters deep, where water pressure is lower and therefore released bubbles expand rapidly and remain in the water column longer.

That means the results are likely most relevant to the tidewater glaciers in the shallow waters around the Arctic, Nash explained. Antarctic glaciers melt at a greater water depth, so this process may be less impactful there, he said.

"These air bubbles clearly have a significant yet overlooked impact on melting," said Twila Moon, a glaciologist at the National Snow and Ice Data Center at the University of Colorado Boulder who was not involved in the study. "By quantifying that impact, this work is an important step in improving the accuracy of our ice melt models," she added.

Currently, models rely mostly on ocean temperature and the strength of freshwater plumes coming from the glacier base to predict ice melt. Scientists know they are missing physics that improve their predictions, including the newly discovered bubble effect.

More Field Data

"These are really neat experiments," said Keith Nicholls, an oceanographer at the British Antarctic Survey who was not involved in the study.

He noted, however, that air bubbles probably don't fully explain the discrepancy between model estimates and real observations of glacier melt.

That's because the environment in front of tidewater glaciers, where meltwater and seawater mix, is particularly complex, Nicholls explained. "Those processes are difficult to replicate in theoretical models or in the lab."

"This work is an important step in improving the accuracy of our ice melt models."

Wengrove and colleagues said they need more field data before they can estimate the relative contribution of air bubbles to melting. Aside from the water conditions around a glacier, other ice properties, such as its surface roughness, can determine how quickly ice melts.

The team recently returned from fieldwork at Xeitl Sít'i Glacier, where they have been using remotely operated vehicles to collect these much needed observations. Following their lab experiments, the all-too-familiar bubbles have taken on a new significance, Nash said. "Now when we get close to an iceberg, all we can hear are these bubbles screaming out at us as they melt away."

By **Erin Martin-Jones** (@Erin_M_J), Science Writer

Crowdsourced Science Pulls Off a Daring WWII Data Rescue

During World War II, sailors aboard U.S. Navy vessels recorded weather and sea conditions as they cruised the Pacific Ocean. After the war, most of these observations languished in classified logbooks for decades and were left out of data sets that formed the backbone of modern climate models. Recently, a crowdsourced science project recovered and digitized those now-declassified meteorological records, rescuing nearly 4 million observations that span a critical wartime data gap.

Before this project, the observations "had never been seen by anybody else except the people who wrote them," said Praveen Teleti, lead researcher on the project and a climate modeler at the University of Reading in the United Kingdom.

This trove of historical weather data will improve the accuracy of our climate models, Teleti said. "Unless we can be very sure about the historical temperature, we can't really be certain about how much climate has changed since then."

Meteorological records from USS Pennsylvania, *seen here off the Virginia coast in 1927, helped fill a gap in 20th-century marine weather records. Credit: U.S. Bureau of Ships, Department of the Navy, U.S. National Archives and Records Administration, Public Domain via Wikimedia Commons*

Maritime Weather Records

Scientists use climate and weather models to understand how our global climate has changed over the past century, how it might change in the future, and what influences those changes. These models depend on meteorological records from around the globe and are only as accurate as the data that anchor them.

Observations over land can be collected by weather stations, but the effort is more complicated at sea. In the early 20th century, before the advent of satellites, most maritime weather data were gathered voluntarily by sailors aboard commercial trading ships.

What data we have from that time are limited in their usefulness, Teleti explained. Commercial ships sailed along a few specific routes, and rarely across the Pacific Ocean. Sailors who collected meteorological data did not follow any one standard process, creating unknown biases. And because the efforts were voluntary, they submitted data only sporadically.

Moreover, the number of observations from trading vessels dropped precipitously during World War II (WWII), especially in the Pacific Ocean, when the few trade routes between the western United States and eastern Asia disappeared completely.

"World War II and other global wars have been challenging for the availability of environmental observations due to changes in observing methods, loss of logbooks, and classification of material," explained Eric Freeman, a surface marine data specialist at NOAA National Centers for Environmental Information in Asheville, N.C., who was not involved with this work.

"World War II and other global wars have been challenging for the availability of environmental observations."

However, other ships traveled the Pacific at that time: U.S. naval vessels deployed after the attack at the U.S. naval station in Pearl Harbor, Hawai'i, in December 1941. Navy regulations from the era specified that each ship must log its position and meteorological conditions every hour and detailed the methods a sailor should use to make the observations. (Whether a sailor followed regulations was, of course, another matter entirely.)

Rescuing Data Lost to Time

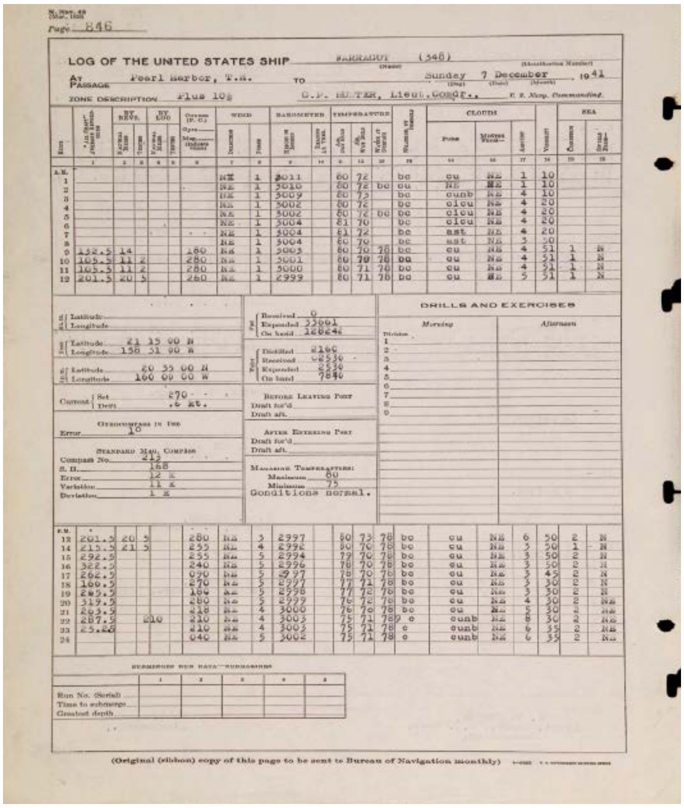
For decades, those logbooks were classified to protect military secrets. But in 2017, the National Declassification Center released nearly 200,000 pages of WWII-era material, including many from those logbooks.

Available, however, did not mean accessible. Most of the pages remained in paper form at the National Archives and Records Administration in Washington, D.C., Teleti explained. To access the data they contain, he and his colleagues worked with archivists to photograph and scan each page.

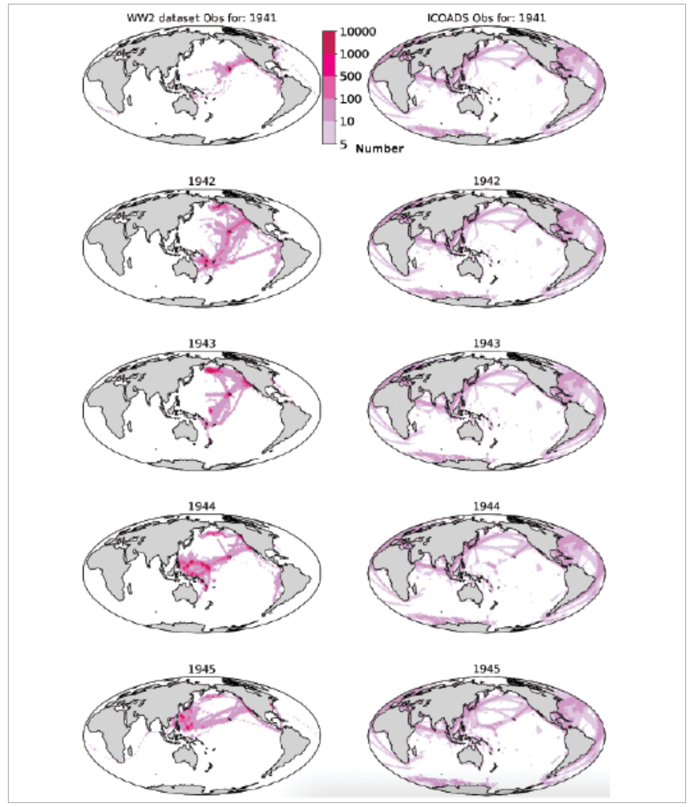
To log the now digital pages, they leveraged the power of the crowd by developing the Old Weather–WW2 project. Participants were presented with images of logbook pages and guided through transcribing ship identifiers, positional information, and any weather observations contained within.

Freeman, who has assisted with other crowdsourced science projects to recover surface marine observations, said these projects can drastically reduce the time and cost to recover historical records. "As long as there is an interest by the public in the data you are trying to digitize," he said, "citizen science is very effective, highly efficient, and typically satisfies many disciplines, providing a large breadth of public use."

In total, 4,050 volunteers helped digitize more than 630,000 records from more than



This naval ship logbook page is from USS Farragut *on 7 December 1941, the day of the attack on Pearl Harbor. It contains the ship's name, passage to/from, date, zone, commanding officer, meteorological information, and navigation information. Credit: Teleti et al., 2023, bit.ly/WWII-logbooks, CC BY 4.0 (bit.ly/ccby4-0)*



Weather data rescued by the Old Weather–WW2 project (left column) add tens of thousands of meteorological data points to the existing data set (right column) for 1941–1945. These data are air pressure observations. Credit: Teleti et al., 2023, CC BY 4.0 (bit.ly/ccby4-0)

28,000 logbook images from 19 ships. Each record contained multiple types of weather observations, like wet- and dry-bulb temperature, wind speed and direction, barometric pressure, sea surface temperature, visibility, and overall weather conditions. In total, the project rescued 3.7 million meteorological observations that span 1941–1945.

The project took a year and a half, Teleti said. "Thanks, I think, to the pandemic, people were spending more time on the computer, so we wrapped up this project relatively quickly."

In some areas of the Pacific, these new data more than double the number of weather observations that were previously available (bit.ly/ICOADS-3). Teleti and his colleagues reported these data in *Geoscience Data Journal* in September and planned to present them at AGU's Annual Meeting 2023 in San Francisco (bit.ly/WWII-logbooks).

"The citizen science aspect of this project is pivotal," said Duo Chan, a climate scientist at the University of Southampton in the United Kingdom who was not involved with the project. "Not only do citizen scientists speed up the conversion of these invaluable historical records, but their efforts also contribute to a valuable data set that can be used to train AI algorithms to perform digitization on even bigger scales."

Solving WWII-Era Mysteries

"These newly recovered observations fill huge voids in the climate record," Freeman said. "Overall, the better coverage we have, the better confidence we have in how our models perform, and our ability to reproduce past climates is enhanced."

The team expressed a hope that these data will not only improve the overall accuracy of climate reconstructions during WWII but also shed light on an anomalously warm period during WWII (bit.ly/WWII-SSTs).

Past records suggest that sea surface temperatures during 1941–1945 were notably warmer than the 5 years before and after, but the uncertainty in the data is several times higher during the war than before or after it. No climate model has been able to reproduce this temporary spike in global mean sea surface temperature, Chan said. The ships' logs can help depict the climate at that time and improve the models' accuracy.

Teleti said that the team also hopes the data might help scientists constrain a strong El Niño event that occurred during that decade and understand the nature of Typhoon Cobra, a tropical cyclone in 1944 that sank three U.S. destroyers and killed nearly 800 sailors (bit.ly/climate-anomaly-40).

"We were very inspired by the sense of duty [the sailors] had for their work," Teleti said. "They probably never thought 80 years from that time anybody would be looking at these observations."

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

Climate Education That Builds Hope and Agency, Not Fear

The urgency of the climate crisis grows every year. Meanwhile, disinformation and politicization have made communicating the science of climate change increasingly challenging. For the past 2 decades, such communication efforts have focused mainly on convincing people that climate change is real while also combating organized campaigns of denialism [*Mann*, 2012]. These efforts have largely succeeded: Polls show that the public overwhelmingly accepts the reality of climate change. In one recent example in the United States, *Leiserowitz et al.* [2022] found that three quarters of those surveyed were "alarmed," "concerned," or "cautious" about climate change, whereas fewer than 20% were "dismissive" or "doubtful."

Students in an ecology of urban environments course at Concordia University in Montreal, Que., plant a campus garden, the outcome of a final project in collaboration with the university's Office of Sustainability. Student projects were guided by the climate goals of the university's Sustainability Action Plan and focused on emissions reduction (e.g., through reduced lawn maintenance) and climate change adaptation (e.g., increased vegetation cover to reduce urban heat). Credit: Sarah O'Driscoll

So although challenging climate change denial may still be necessary in some contexts, scientists, educators, and others who communicate about climate science face a new challenge: the clear gap between the public's concern over climate disruptions and its understanding of what can be done today to affect our tomorrow. We must better convey to audiences the needed changes—in energy sources and land use, for example—and that humanity can, indeed, influence the scale of disruptions that unfold [*Marris*, 2021; *Mann*, 2021].

It is time to reorient our messaging, focusing less on predictions of future hazards as though they are foregone conclusions and instead communicating a "hopeful alarm"

Students are a vital demographic to reach as we shift the prevailing messaging of climate communication.

that simultaneously stresses the urgency of the situation and instills a sense of agency in guiding the future.

Students are a vital demographic to reach as we shift the prevailing messaging of climate communication. Not only do they represent the next generations who must face the challenges of climate change, but also when they are surveyed, students and younger people generally profess concern about the issue and interest in climate action at higher rates than older segments of the population.

Indeed, young people, including many of our own students, are hungry for information: In a 2023 survey, for example, 30% of U.S. teenagers expressed an interest in learning more about jobs related to sustainability and climate change. Meanwhile, hiring for "green jobs" has already been outpacing overall hiring in recent years, and transitioning from fossil fuels to clean energy is forecast to generate millions of jobs in coming decades. Educators and climate communicators can help meet these demands and empower students by providing specific examples of useful actions and relevant tools and opportunities to help them act constructively.

The Hopeful Alarm Approach

We must be a beacon of hope, because if you tell people there's nothing they can do, they will do worse than nothing.
—Margaret Atwood, *The Year of the Flood*

If hopeful alarm sounds like Pollyannaism, rest assured it is not. We can communicate the seriousness of potential perils to humanity and nature from climate change while also offering examples and resources that model constructive engagement, much as a physician would communicate the urgency of a cancer diagnosis while outlining a path forward. That is not heedlessly optimistic—rather, it is simply pragmatic.

Worry, not fear, has been shown to encourage protective, adaptive behaviors [*Marx et al.*, 2007]. Despair and hopelessness, meanwhile, have been documented to lead to "climate anxiety" and to sap motivation to act—indeed, fossil fuel interests deliberately promulgate widespread cynicism and "doomism" among the public as a strategy to prevent meaningful action [*Coan et al.*, 2021].

Any message of hopeful alarm should begin by emphasizing that people have agency, both individually and collectively, to shape the future. The die is not cast: Any actions that reduce carbon emissions today will improve our future, and there are not just two possible outcomes—success or failure. Instead, there is a continuum of potential outcomes, and where we land along that con-

Students from Union College in Schenectady, N.Y., visit a local solar energy facility. During their semester-long course, the students considered the transition to renewable energy from multiple perspectives, including those of solar installers; the New York Independent System Operator, which operates the state's energy grid; and elected officials. Credit: Jeffrey Corbin

tinuum depends on decisions we make now and in the years to come.

Technologies and policies with the potential to reduce atmospheric carbon emissions and greatly moderate the consequences of climate change exist [*Intergovernmental Panel on Climate Change*, 2023]. Adaptation measures can also be undertaken so that future impacts are more manageable. Yet it is rare that these messages are presented clearly to the public.

Implementing these technologies, policies, and measures will be difficult and likely involve discussions, negotiations, and, ultimately, widespread buy-in, not only from lawmakers but also from the public. But if much of the public isn't aware of the options available for dealing with the climate crisis, how are the needed conversations even to begin?

As a part of the effort to broadcast hopeful alarm, educators should reconsider climate-related content in their courses. For example, how much focus is put on messages like "Climate change is happening, and it is serious" versus "Here are solutions and ways to get involved"? We argue that in most curricula, not enough time is devoted to discussing solutions and, especially, to providing students with examples of productive action on behalf of the climate to inspire their own participation.

Bringing Climate Action into the Classroom

Many options exist by which educators can incorporate discussions of climate action into courses of different sizes, durations, and levels (see sidebar). Even single class sessions that include sharing examples of role models and mitigation actions can make a difference for students.

One of the easiest, yet still effective, ways to broaden presentations of climate change is to highlight people and institutions involved in climate action: for example, activists influencing public policy, entrepreneurs bringing new products to market, and municipalities building climate resilience.

Among the individuals we highlight are Swedish activist Greta Thunberg and scientist Katharine Hayhoe, whose identification with the evangelical Christian community resonates with a particular segment of students. We share resources such as the edited volume *All We Can Save* [*Johnson and Wilkinson*, 2020] and the Not Too Late project to help show the range of people involved in climate solutions, and we encourage students to participate in youth movements such as Zero Hour and the Sunrise Movement. We also describe steps that local municipalities have taken, such as instituting climate action plans and projects to con-

Time Available and Course Format	Ideas for Incorporating Climate Action
Single class, lecture courses	• Spotlight a specific person or an example of action or mitigation • Highlight other large-scale problems that have been effectively addressed through science-based action and policy (e.g., the ozone hole via the Montreal Protocol and its amendments, which have also helped mitigate global warming) • Invite students to pose questions about climate change
1–3 classes, lecture courses	• Detail a case study of a potential mitigation action, such as one outlined by Project Drawdown • Have students contribute to a class-wide slide presentation of people taking action to confront or manage climate change • Discuss jobs and careers related to climate adaptation and mitigation
2–3 weeks, lecture courses	• Have students prepare reports about a specific action or solution (see Project Drawdown for examples) • Demonstrate effects of various potential policies on climate change projections using Climate Interactive's EN-ROADS tool • Guide students to contact local leaders or engage family members about issues related to climate action
2–3 weeks in courses with small-class sessions	• Visit and discuss climate action with local stakeholders, such as municipal officials, entrepreneurs, and activists • Direct a climate negotiation simulation, using Climate Interactive's World Climate Simulation
>3 weeks in a small course or a large course with lab sections	• Calculate campus emissions budget from campus data, including for electricity, heating/cooling, and transportation • Develop proposals to reduce campus carbon emissions, following examples such as the Shut the Sash! project
Entire semester in a small class	• Facilitate internships or service learning with local stakeholders, municipal officials, or environmental organizations

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front flooding risks exacerbated by extreme weather and sea level rise.

Classroom discussions of these individuals, movements, and institutions can be tailored to a wide variety of audiences, including students in many non-STEM (science, technology, engineering, and mathematics) fields such as business, sociology, and even the arts. Such stories are empowering and breed a willingness to engage [*Sabherwal et al.*, 2021].

Instructors can offer students more in-depth analysis of how carbon emissions can be targeted. For example, students can evaluate carbon-emitting activities and consider how those activities could be more efficient. Project Drawdown, which highlights dozens of specific actions across a range of sectors that reduce emissions or enhance natural carbon sinks, and Project EDDIE, which provides curricular modules and teaching activities (e.g., exploring green roofs as a solution to climate-induced precipitation increases), are great resources from which to draw. Instructors can also emphasize the rapid growth in emissions-reducing technologies using business-focused analyses to counter perceptions that controlling carbon emissions is dependent solely on government largess.

In courses in which more time is available to focus on climate action (e.g., those featuring supplemental laboratory sessions), students could investigate climate action plans and emissions data from their own campuses to determine where cuts could be made or propose initiatives to reduce emissions. We have, for example, directed students to calculate campus carbon emissions related to electricity, heating and cooling, and transportation. They can also compare the energy provided via conventional versus renewable sources. Such projects make discussions of carbon emissions more concrete because they are centered around students' own experiences while also giving them valuable tools of analysis and even policy action.

> **Such projects make discussions of carbon emissions more concrete because they are centered around students' own experiences.**

The activities described above are largely directed at undergraduate and graduate students, but they can also be undertaken in secondary school classrooms and laboratories. Many, if not all, of them support education standards related to analyzing and interpreting data, using mathematical and computational thinking, and constructing explanations and designing solutions. In addition, the National Center for Science Education offers a "Climate Super Solutions" module for grade 9–12 classes that supports various Earth and space sciences core ideas.

Simulations and Service Learning

Educators can engage students in immersive simulation exercises that illustrate emissions policies and their consequences. For example,

Two Union College students participate in a Climate Interactive World Climate Simulation, detailing their nation bloc's pledge to reduce carbon emissions to their fellow "representatives" in a mock United Nations conference. Credit: Union College

in Climate Interactive's World Climate Simulation, students act as climate negotiators representing one of six major nations or nation blocs at a United Nations conference where the goal is to reach an agreement that keeps global average temperature increases well below 2 degrees Celsius above the preindustrial average.

Students carrying out a World Climate Simulation review briefing papers with information about their bloc's economic and emissions profiles and negotiation goals before adopting any of a variety of pledges to control future emissions and deforestation. Pledges are entered into the associated C-ROADS climate simulator, which provides real-time feedback on how the pledges will affect future climate.

The simulation activity usually involves multiple rounds of negotiations among the different blocs, in which participants refine their pledges and develop a deeper understanding of the timelines and commitments necessary to achieve the climate goal and of the competing interests among countries. Surveys of more than 2,000 participants in the World Climate Simulation have shown that it effectively promotes feelings of both urgency and hope among participants, as well as an intent to learn more and a desire to act [*Rooney-Varga et al.*, 2018]. Our own experience is that the simulations are engaging, lively sessions that result in realistic and unpredictable outcomes.

Internships and service learning opportunities can be among the most effective experiences for students. Instructors can help by publicizing and helping students pursue such experiences. Students who work directly in city or state agency offices, organizations, or companies that do local and regional work on climate solutions, emissions reductions, and mitigation planning gain valuable connections for future employment and action. They also gain an understanding of how concrete policies can make a difference in real-world settings [*Coleman et al.*, 2017]. Seeing how such internships have influenced students' future career paths has been among our most rewarding mentoring experiences.

Finally, educators should encourage students to share with others what they've learned about the urgency of climate change and about ways to combat it. For example, students can email or write postcards to local stakeholders or decisionmakers about the need for action. We also encourage students to view themselves as nerd nodes, or trusted sources on science for people in their networks [*Willingham*, 2013], and to begin conversations with family members and others in their community about climate change.

To help in this effort, we point them to valuable science communication resources to help them think about how best to frame their message. Students have reported feeling empowered to talk with people outside of class about what they have learned and how rewarding that experience was.

From Empowerment to Action

All educators hope their students and audiences internalize what they learn so they can apply the knowledge beyond the classroom. For those of us who educate about climate change, it is especially imperative that we motivate students to act constructively with respect to the climate crisis.

The concept of hopeful alarm reflects the rapid and dramatic shift in public attitudes about climate change in recent years. Instead of asking whether climate change is real and why it matters, many people—notably students and young people—now ask, "Is there any hope?" and "Is there anything I can do?" Hopeful alarm provides a framework for answering those questions through positive, motivating messaging.

The scale of the climate challenge is vast, so the entrée to action can be overwhelming. Students benefit from exposure to specific, practical examples of actions and role models as well as from their own experiences with getting involved. By providing these examples and facilitating these experiences, we highlight clear pathways and equip those most likely to act on behalf of the climate with the tools they need to be successful.

Acknowledgments

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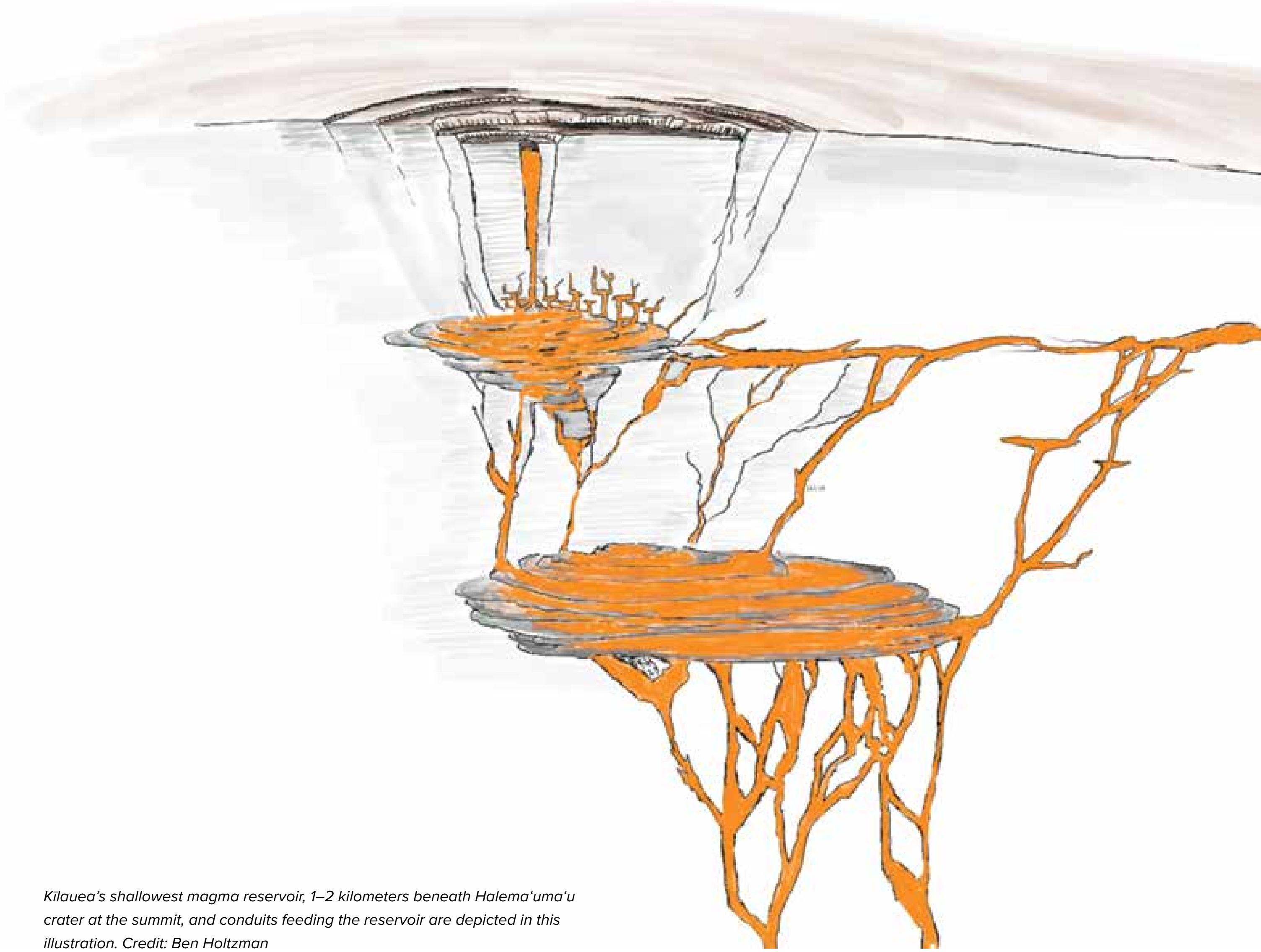
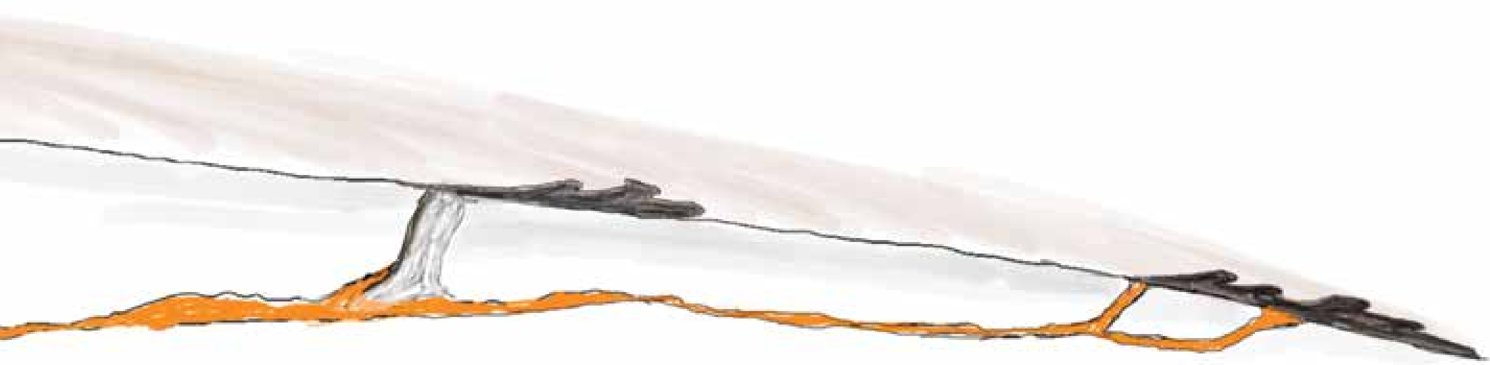
Earth Is Noisy. *Why Should Its Data Be Silent?*



Kīlauea's shallowest magma reservoir, 1–2 kilometers beneath Halemaʻumaʻu crater at the summit, and conduits feeding the reservoir are depicted in this illustration. Credit: Ben Holtzman

COMBINING VISUAL AND SONIC REPRESENTATIONS OF DATA CAN MAKE SCIENCE MORE ACCESSIBLE AND HELP REVEAL SUBTLE DETAILS. A NEW ANALYSIS OF THE RECENT DECADE-LONG ERUPTION OF HAWAIʻI'S KĪLAUEA VOLCANO OFFERS A CASE IN POINT.

BY LEIF KARLSTROM, BEN HOLTZMAN, ANNA BARTH, JOSH CROZIER, AND ARTHUR PATÉ



Volcanic eruptions can engage all our senses. Dramatic scenes of lava flows and ash clouds, the sound and feel of seismic vibrations, the smell and taste of gas emissions and ash, the intensity of the heat—scientific instruments can measure and record the physical and chemical causes of these sensations and preserve them as numerical data. However, when scientists analyze data to look for patterns and anomalies, they turn most often to visual representations. Could our other senses tell us things that our eyes are missing?

Graphs, photos, maps, and videos are familiar and well-used tools for visual display. However, the human auditory system sometimes outperforms vision in helping people detect subtle temporal patterns or teasing out cause-and-effect relationships among multiple data streams. In research, new ways of examining data often lead to discoveries. Auditory display and sonification—the representation of data through sound—thus hold great potential for advancing science by helping scientists take fuller advantage of their creative and deductive capabilities.

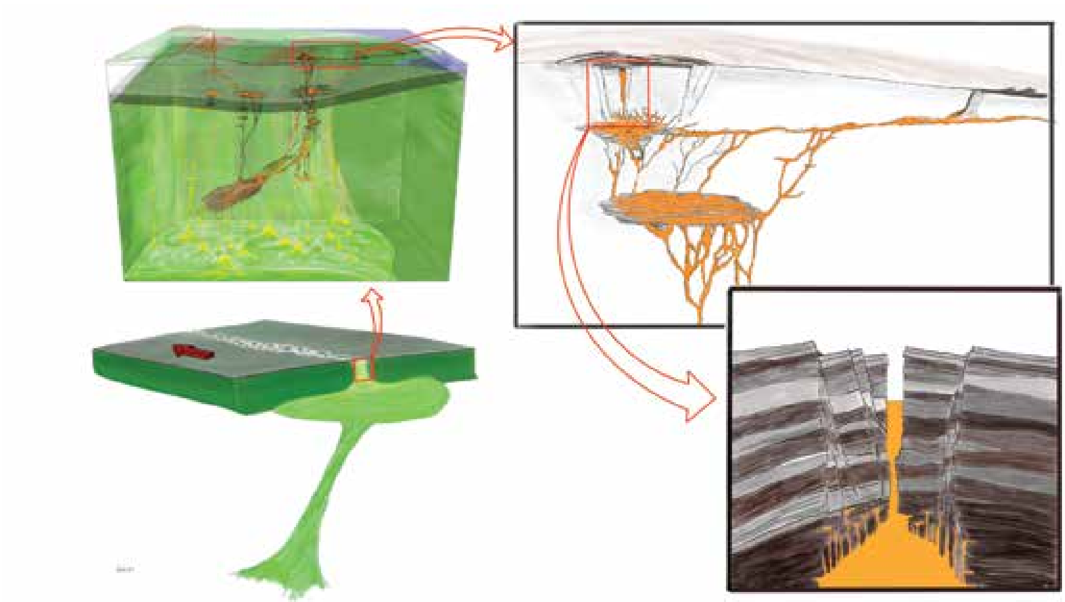


Fig. 1. Kīlauea can be viewed at different scales. At bottom left, the Pacific plate moves over a deep mantle plume (light green). Heat and magma from the plume have worked their way through the oceanic plate (dark green), generating volcanoes, including the Hawaiian Islands, for about 80 million years. The red arrow indicates current plate motion. At top left, magma follows complex pathways as it rises through the uppermost mantle on its way toward Kīlauea (red box) and its neighbor Mauna Loa (illustration is based on recent work by Wilding et al. *[2022]). At top right, reservoirs at a few kilometers deep are final staging places for magma as it ascends toward the surface to feed eruptions at Kīlauea's summit (red box) and rift zones. At bottom right, the conduit from the shallowest reservoir to the lava lake in Halemaʻumaʻu crater at the summit was very active during the 2008–2018 eruption. Credit: Ben Holtzman*

Sonification has been used in limited ways in the past, such as through the well-known sounds of sonar displays and Geiger counters.

The time is ripe for bringing this capability into wider use in research. Science education and outreach efforts can also leverage current cultural trends and technological developments that facilitate immersive multimedia experiences to make information accessible to broader, nontechnical audiences using sound [e.g., *Holtzman et al.*, 2014]. What's more, sonification provides a framework for data to be perceived and evaluated by visually impaired scientists [e.g., *Song and Beilharz*, 2007], who potentially have more highly developed aural perception and awareness than the visually unimpaired.

Sonification involves data processing steps that are sometimes analogous and complementary to those used in machine learning methods [*Holtzman et al.*, 2018], which can quickly reveal important features and useful workflows for exploring data sets [*Barth et al.*, 2020]. Combined with model outputs, which may also be represented aurally, features identified through sonification of physical data can lead to new understandings of complex natural systems in the solid Earth and surface environments.

Listening to Earth

In geoscience, sonification has been used in seismology since the Cold War [*Speeth*, 1961]. Scientists recognized that the human ear could distinguish between bomb blasts and tectonic earthquakes simply by speeding up recordings of ground shaking into the range of human hearing (~20 hertz to 20 kilohertz). This direct sonification is one of the simplest forms of auditory display and can be readily applied (with appropriate preprocessing) to a diverse array of oscillatory data, such as those detailing planetary orbits, seismicity, infrasound, ice core or sedimentary records, and paleomagnetism.

Recent work has demonstrated that humans can distinguish characteristics of seismic wave propagation through Earth from signatures of the earthquake source in auditory displays of seismograms, and this ability improves with training [*Boschi et al.*, 2017]. Because the frequencies of interest in teleseismic earthquake data (0.0001–10 hertz) are far below the lower limit of the human hearing range, direct sonification requires that raw data be shifted to higher frequencies. This frequency shift—multiplying discretely sampled observation times by a speed factor—represents an aesthetic parameter that must be chosen, like the color or size of a symbol on a visual graph.

In sonifying catalogs of earthquakes or other oscillatory data-generating events, researchers can use multiple speed factors to stretch or compress individual events while accurately preserving the time sequencing of the catalog. Audio spatialization may additionally help distinguish sounds or represent spatial parameters, such as earthquake hypocenters, relative to a chosen observation location [*Paté et al.*, 2022].

Sonification for All Types of Data

Sonification can also be applied to data sets that are not simply oscillatory, although additional choices beyond speed factors are required to represent other parameters. A popular approach is parameter-mapping sonification, in which data parameters are mapped to the parameters of sound. For example, the pitch of the continuous whistle of a teakettle goes higher as the water's boiling rate increases. The rising sound frequency indicates a rise in steam flux through the hole in the spout, a physical process that is a sonic proxy for boiling rate.

General sonification approaches accomplish this by transforming data into sound. Other approaches may, for example, depict specific events like earthquakes with a specific sound called an auditory icon. The auditory icon can be modulated on the basis of aspects of the data, such as using a higher pitch and less reverberation for lower-magnitude seismic events.

As musicians well know, many parameters can help distinguish sounds: Pitch, loudness, timbre, and harmonic and temporal complexity can all be manipulated and mapped to data. Approaches such as granular synthesis that are common in audio engineering and computer music also represent powerful tools for representing diverse and high-dimensional scientific data [*Roads*, 2004].

Pairing sonification with animation so that the aural and visual systems can work together is another often useful approach [*Holtzman et al.*, 2014]. The resulting "data movies" typically include an audiovisual key that explains the auditory and visual algorithmic rules for generating the data representation. Animations incorporate visual data representation tools and allow inclusion of more data types as well as models that facilitate interpretation.

To demonstrate the range of sonification techniques and the data movie approach described above, we have worked with multiple data sets recording volcanic activity at Kīlauea volcano in Hawai'i.

A Decade of Kīlauea Volcanic Activity

Kīlauea, one of the most active volcanoes in the world, is fed by decompression melting of a mantle plume that also feeds other active volcanoes on the island of Hawai'i (Figure 1).

The summit vent of Kīlauea was active from 2008 to 2018, and in that time, it hosted an active lava lake that provided an open window into the underlying magma system [*Patrick et al.*, 2021]. This summit activity was accompanied by intermittent effusive (nonexplosive) eruptions along Kīlauea's East Rift Zone, such as the Kamoamoa eruption in 2011. The activity culminated in 2018 with an East Rift Zone eruption that produced roughly 1 cubic kilometer of magma, damaging nearby neighborhoods and infrastructure, and induced a months-long sequence of earthquake-generating caldera collapse events at the summit.

Analysis of this decade-long eruption, as well as more than a century of preceding study, has made Kīlauea one of the world's best understood active volcanoes.

The general structure of Kīlauea's shallow magma system has been known for decades, although researchers are continually refining the picture and important questions remain unanswered. Above a deep magma transport network rising from the underlying mantle plume, magma is inferred to be stored in a few locations: in a reservoir about 1–2 kilometers beneath the summit Halema'uma'u crater vent, in another region 3–5 kilometers beneath the summit vent, and along dike-like structures extending laterally from the summit to the volcano's rift zones. During much of 2008–2018, a direct conduit existed between the shallower magma reservoir and the summit lava lake.

Although the spatial structure and temporal connectivity of subsurface magma at Kīlauea are not fully understood, we have incorporated available information in a series of conceptual sketches of the magma system. These sketches contextualize our focus on the uppermost plumbing of the volcano in a data movie that represents the evolution of the shallow summit magma system over two time windows during the recent eruptive period.

PAIRING SONIFICATION WITH ANIMATION SO THAT THE AURAL AND VISUAL SYSTEMS CAN WORK TOGETHER IS ANOTHER OFTEN USEFUL APPROACH.

Multiscale Magma Dynamics in Sight and Sound

The composite data movie includes an introduction and aural key (with voice-over of text for accessibility) to introduce the sonification techniques and the geologic context. The first time window illustrates decadal-scale dynamics of the Halema'uma'u crater from 2008 to 2018, during which a wide range of activity occurred (Figure 2, left); the second zooms in on the summit caldera collapse sequence and lower East Rift Zone eruption in 2018 (Figure 2, right). For the first window, the 120-second duration of the data movie means that each second in the movie represents roughly 1 month of real time; for the zoomed-in 2018 collapse sequence between 11 May and 7 August, each second represents about 1 day. (For both cases we have also made 60-second versions of the movies to demonstrate how the time scaling changes the detail with which events can be examined.)

We chose three data sets to sonify for the 2008–2018 data movie. Near-summit earthquakes, from an island-wide seismic catalog, track the volcano's time-evolving stress state. A separate catalog [*Crozier and Karlstrom*, 2021] of small earthquakes associated with rockfalls from crater walls into the lava lake reflects very long period (VLP) seismicity, with dominant oscillation periods longer than 10 seconds. And radial ground deformation data gathered by near-summit Global Navigation Satellite System (GNSS) sensors track inflation and deflation of the ground surface [*Patrick et al.*, 2021].

We sonified these three data sets using methods designed to represent qualitatively the physical processes that the different data sampled.

For near-summit earthquakes, we used a simple direct sonification of near-summit vertical ground motions from a station (NPT/NPB) in the U.S. Geological Survey's Hawaiian Volcano Observatory network. For each earthquake, we applied a speed factor of 150, meaning that seismic frequencies originally above about 0.13 hertz are audible in the movie.

Differences in the magnitudes and durations of individual earthquakes are reflected in loudness and timbre. Combined with an animation of the hypocentral location (directly under each earthquake's epicenter), this approach permits clear identification of stress changes and patterns of fracturing inside the volcano through time. We further used left-right stereo panning (i.e., partitioning sound unevenly into different channels) to represent the longitudinal distance of each earthquake from the crater center.

VLP seismicity, on the other hand, tells a story about the evolving magma system beneath Kīlauea. As soon as the Halemaʻumaʻu crater opened in 2008, exposed crater walls began progressively collapsing into the churning lava lake, and by 2018 the lava lake diameter had grown by a factor of 4. Seismometers detected damped, resonant sloshing of magma in and out of the shallow (1- to 2-kilometer-deep) Halemaʻumaʻu reservoir caused by large rocks falling onto the lava lake surface. The duration and frequencies (both the fundamental mode and overtones) of this remarkable resonance depend on the geometry of the magma system and on magma properties such as temperature and bubble content. Variations in resonant characteristics over time thus reflect changes within the magma system [*Crozier and Karlstrom*, 2022].

Although these VLP waveforms are often quite tonal (i.e., they exhibit few overtones), direct sonification leads to short sounds that do not represent the complexity of the real events well. To allow listeners to hear the temporal structure in the VLP seismicity, we sonified the

WATCH AND LISTEN! HOW SCIENTISTS SONIFIED KĪLAUEA

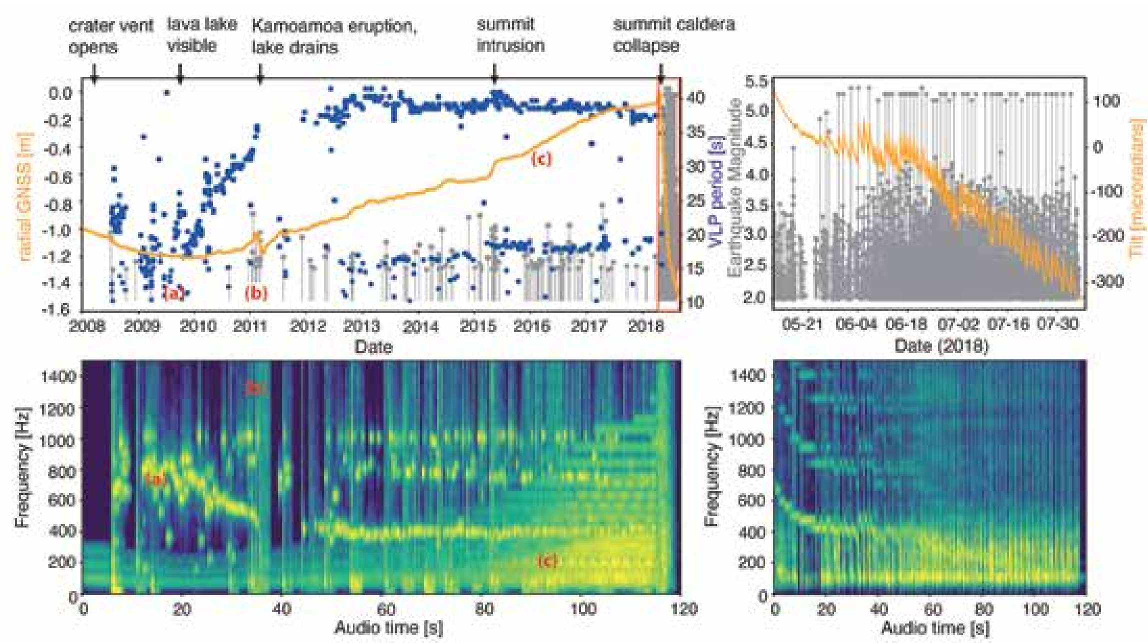


Fig. 2. The top plots show data sets from Kīlauea volcano used to sonify data and produce data movies. At top left is the timeline from 2008 to 2018, with blue dots representing periods of very long period (VLP) seismic events, gray bars representing the magnitude of earthquakes detected at Kīlauea's summit, and the orange curve representing radial ground deformation measured by Global Navigation Satellite System (GNSS) sensors. At top right is the timeline for the 4-month eruption and caldera collapse sequence lasting from 11 May to 7 August 2018, with gray bars again representing earthquake magnitudes and the orange curve representing tiltmeter data. The bottom plots show spectrograms of composite sonified data corresponding to the top plots, with audio frequency plotted versus score durations (120 seconds in both cases). Letters in the left plots indicate where the raw data sets appear in the sonification spectrogram (a, VLP events; b, earthquakes; c, ground deformation). Watch the data movies (see QR code above) to see how this representation translates to sound.

strongest spectral peaks in each seismogram by synthesizing pure sinusoidal tones—with frequencies between 200 and 500 hertz and sound durations of 1 second—that preserve the relative frequency spacing and temporal envelopes in the seismic data (Figure 3).

Animation again provides a key aid in interpreting the sound: We associate each VLP event with a splash of color within a sketch of the summit lava lake and shallow plumbing system. The color scale corresponds to the period of the VLP fundamental mode, with cooler colors representing shorter periods. Because the period and decay rate of VLP seismicity track magma temperature and volatile contents within the shallow reservoir and conduit [*Crozier and Karlstrom*, 2022], this animation provides a tool for examining how internal dynamics of the volcano likely evolved through the eruption.

Finally, we sonified geodetic (radial GNSS) data collected around Kīlauea's summit that track magma buildup below the summit. This magma helped drive lava lake dynamics and supply the climactic eruptive sequence in 2018, and the GNSS data capture deformation occurring over larger areas and longer timescales than the earthquake data do.

We chose a sonification method that represents the relatively slow increases or decreases in radial deformation by adding or removing notes, respectively, from a chord of synthesized tones. We built this chord using notes of Lydian mode (a seven-note musical scale) spanning three octaves. The gradual swelling of the volcano leading up to the sudden collapse in 2018 is thus represented aurally with steadily increasing tone density and frequencies. Small variations in deformation embedded in the long-term inflationary trend are represented by scaling the loudness of the chord through time with these short-term, detrended fluctuations.

Visually, the deformation is represented as a circle of varying radius located at the inferred centroid of the Halema'uma'u reservoir where magma was accumulating.

For the 2018 caldera collapse sequence, we sonified only geodetic and earthquake catalog data, allowing a more focused examination of cyclic behavior during the climactic eruptive episode. In this sequence, 62 earthquakes of about magnitude 5, occurring roughly daily, accompanied steplike drops in the caldera floor recorded by a near-summit tiltmeter (a different type of geodetic measurement than GNSS). Hundreds of smaller earthquakes occurred between these collapse events, with the time between events decreasing as stress drops.

We used the chord sweep approach developed by *Barth et al.* [2020] to sonify the tiltmeter data, resulting in continuous tone clusters that rise and fall on a symmetric octatonic musical scale with the caldera collapse. Direct sonification of earthquakes, using a speed factor of 280 (original frequencies above about 0.07 hertz are audible), permits clear differentiation among different event magnitudes, and left-right stereo panning relative to the center of the caldera provides a spatial sense of caldera collapse. We sonified roughly 16,000 earthquakes with

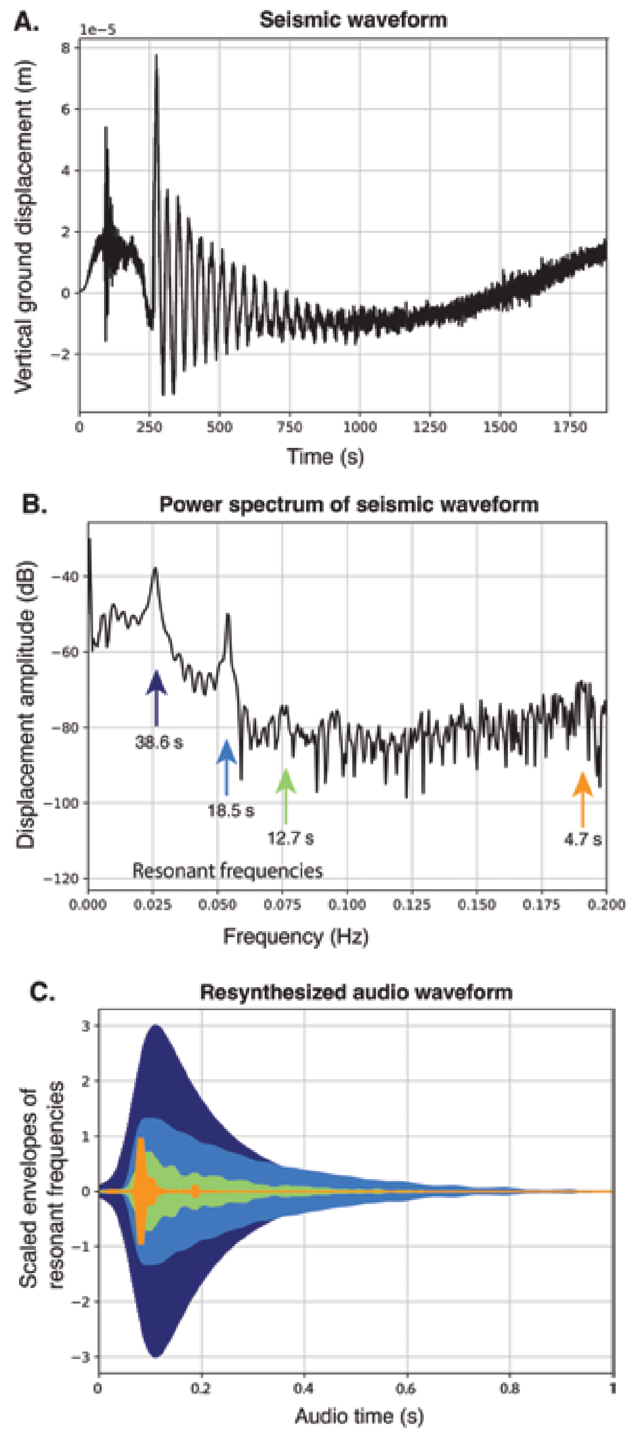


*Fig. 3. This example workflow for the sonification of a VLP seismic event at Kīlauea shows (a) the vertical deformation seismogram recorded at station NPT beginning at 09:00 UTC on 21 May 2017 [*Crozier and Karlstrom*, 2021]; (b) the power spectrum of this seismogram, highlighting four strong peaks associated with resonant fluid motions in the shallow plumbing system; and (c) the resulting sonification, a composite 1-second-duration audio waveform. The synthesized audio was created by extracting envelopes at the four resonant frequencies from seismic data, stretching these envelopes to 1-second duration, then multiplying the envelopes by audible sinusoidal tones that preserve the original relative spacing between seismic frequencies.*

DATA MOVIES HOLD LAYERS OF MEANING THAT CAN EMERGE WITH MULTIPLE VIEWINGS AND LISTENINGS AND WITH INCREASED SCIENTIFIC KNOWLEDGE.

magnitudes greater than 1.5 [*Shelly and Thelen*, 2019] recorded at a station (PUHI) away from the summit to avoid signal clipping.

For the accompanying visualization, we animated and colored the hypocenters and depths of earthquakes atop an image of regional topography and under a timeline of ground tilt. This visual approach illustrates the dramatic caldera collapse at the end of the 2018 sequence using topographic data collected afterward.

A Listener's Guide to Kīlauea

Well-constructed data movies can be viewed on multiple levels. More so than standard, static plots of time series data, data movies excite curiosity even in viewers with no scientific background or training. If an audiovisual key is provided, visual patterns and sounds promote rapid assessments of causality and spatial structure. One can also view and listen to data movies purely as aesthetic creations independent of the underlying science. Indeed, our approaches to sonifying data for the Kīlauea data movie mirror data-driven techniques used in computer music composition, and volcanic unrest episodes naturally involve compelling musical elements of tension and release.

Beneath the aesthetic appeal, however, like any good technical graph, data movies hold layers of meaning that can emerge with multiple viewings and listenings and with increased scientific knowledge. For example, if you watch our movie a few times (or perhaps even only once, if you're very perceptive), you may notice shifts in VLP period that covary with patterns of other earthquakes around the volcano and ground inflation between 2008 and 2018. You may also notice the remarkable sequences of small foreshock earthquakes that preceded larger-magnitude events in 2018 and were spatially localized around multiple evolving fault structures that hosted the large-scale caldera collapse.

Some of these patterns have already been addressed in the peer-reviewed literature. But others have yet to be studied or explained. So what do *you* hear? Do clear patterns of deformation, VLP seismicity, or earthquakes seem to precede the 2018 eruptive sequence or other eruptive events? Do patterns of earthquakes and deformation change throughout the 2018 eruptive sequence?

Sonification as a tool for representing Earth science data is in its infancy. We hope the application presented here, further details of which can be found at the Volcano Listening Project, inspires others to experiment with listening to their data. We look forward to seeing—and hearing—the results.

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The 21st Century's "Music of the Spheres"

Scientists and artists are giving voice to everything from planets to black holes, enriching the research experience and bringing wonders of the universe to new audiences.

By Damond Benningfield

Data sonification provides a new method to analyze and appreciate cosmic objects like the center of our galaxy, here visualized with combined data from NASA's Chandra X-ray Observatory, Hubble Space Telescope, and Spitzer Space Telescope. Credit: NASA/JPL-Caltech/ESA/CXC/STScI

The supermassive black hole at the core of NGC 1275, a galaxy in the heart of the Perseus cluster, moans like a goblin in a Halloween haunted house. The moan is produced as radiation from an accretion disk around the 800-million-solar-mass black hole pushes against gas falling into the black hole's maw. The interaction creates sound waves in the gas, producing the deepest sound ever discovered—57 octaves below middle C.

"It's hundreds of keyboards too low for us to hear," said Kimberly Kowal Arcand, a visualization scientist who works with Chandra X-Ray Observatory data at the Harvard & Smithsonian Center for Astrophysics.

The sound doesn't travel across the intergalactic void to Earth—at least not directly. Instead, astronomers see the ripples in images of the cluster's gas clouds. A team of researchers converted the light waves to sound, then pitched them into the range of human hearing. "We kept [the sound] on the low end because it wouldn't make intuitive sense to pitch it higher," said Matt Russo, a physicist at the University of Toronto who worked with Arcand and others to produce the sound.

"People say it sounds exactly like they'd expect a black hole to sound—dark, ominous, mysterious. It really touched a nerve," said Russo.

Many nerves, to be precise. The audio has been played or downloaded more than 2 billion times, and the story was featured in more than 1,200 news broadcasts, websites, magazines, and other outlets in just 1 month, Arcand said. "The reaction was just insane."

Although it is by far the most popular example, NGC 1275's black hole isn't the first astronomical "voice" to ring out across the cosmos. Scientists have enabled us to hear planets, moons, stars, supernovas, galaxies, and many other objects. Their efforts range from direct recordings of the sounds on Mars to artistic interpretations of some of the spectacular images from Chandra, James Webb, Hubble, and other space telescopes.

The sonifications—audio produced from scientific data—provide new ways for scientists to interpret massive data sets and allow blind or visually impaired (BVI) astronomers to share in research efforts more fully. "Sonification of data can…provide a complementary method for analysing observations and avoiding biases," suggested an editorial in the November 2022 issue of *Nature Astronomy.* "Our ears…can pick out weak signals against a noisy background and are sensitive to perceiving time-based changes and patterns."

A survey article in the *Nature Astronomy* issue logged almost 100 completed or ongoing sonification projects, with more in the planning stages. It is a burgeoning field, said Arcand. "There's definitely a movement toward increasing the use of sound as a tool for research or communication or art."

"People say it sounds exactly like they'd expect a black hole to sound—dark, ominous, mysterious. It really touched a nerve."

Expanding Inclusivity

Chris Harrison, an astrophysicist at Newcastle University in the United Kingdom who heads a project known as Audio Universe, wrote and directed a half-hour program, "Tour of the Solar System," that combines visuals with sonifications of data about the planets and moons.

"Some of the blind audience members discussed being able to engage with astronomy for the first time, or those who lost their vision later in life [getting] back in touch with their younger joy in the subject," Harrison said.

Blind astronomers have felt that same joy after sonification tools helped them return to their research—or take it up for the first time.

"With sonification, I regained hope of being a productive member of the field I had worked so hard to be part of," said astrophysicist Wanda Díaz Merced of the European Gravitational Observatory in Cascina, Italy, during a 2016 TED Talk. Merced, who lost her vision after a prolonged illness a decade earlier, became a pioneer at sonifying data for research purposes, not just for outreach. "Today I'm able to do physics at the level of the best astronomers, using sound," she said.

Also in 2016, Garry Foran, an Australian scientist who had lost almost all vision, heard about Merced's work. After earning a Ph.D. in chemistry, Foran developed precision instruments for a project that used synchrotron radiation to probe the structure of matter.

He lacked the accommodations he needed to continue in chemistry, but the opportunities offered by sonification contributed to his decision to pursue a doctorate in astrophysics at Swinburne University of Technology. "I always had a lay interest in astronomy and astrophysics," Foran said. "I kept a close eye on developments in the field through podcasts and radio interviews."

Foran contacted Merced, and they collaborated on sonification projects for several years. Foran also worked with colleagues in Australia to develop StarSound, a free, downloadable tool for sonifying data.

Foran uses StarSound to analyze spectra from high-redshift galaxies, which are billions of light-years away from Earth. Using either a text-based interface or an audio mixing board, he can produce an overview of the spectrum or examine any individual data point in detail.

"I can listen to things at different rates, characterize the spectra, find features of interest, move to them, find the peaks, find the troughs," said Foran, who completed his Ph.D. in 2022. "Then I can use those results in another software package for my research or my writing."

Foran and his colleagues are working on a more powerful tool to sonify detailed images and other sophisticated data sets. But he said sonification tools need wider acceptance to become successful. "If sonification is to be sustainable and self-supporting, it needs to be more than just an accessibility tool," he said. "It needs to find a place in science's mainstream. It needs to be taught from the beginning and used as a common tool."

Eavesdropping on Mars

If you were to attend a symphony performance on Mars (assuming the thin, carbon dioxide–rich atmosphere wasn't a problem for you or the musicians), you'd notice something odd: The high notes of the piccolos and the low notes of the cellos would reach your ears at different times.

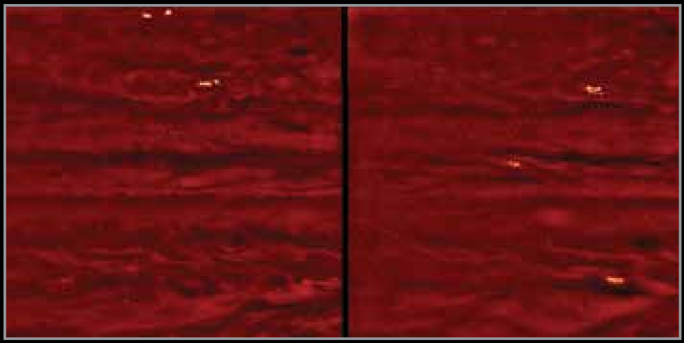
"The speed of sound on Mars is different for different frequencies. This is unheard of on Earth, literally," said Roger Craig Wiens, a planetary scientist at Purdue University and principal investigator of the Perseverance rover's SuperCam instrument suite, which includes a tiny microphone. "We scratched our heads and wondered how this [phenomenon] might work. We decided that in a carbon dioxide atmosphere, the vibration modes are different from those in the nitrogen-oxygen atmosphere on Earth."

"There's definitely a movement toward increasing the use of sound as a tool for research or communication or art."

Perseverance's microphone is a rarity: an instrument that directly records sounds in an extraterrestrial environment. The Huygens lander recorded the sounds of its descent through the cold, dense atmosphere of Saturn's giant moon Titan in 2005, but nothing from the surface. Two prior Mars missions carried microphones, but Mars Polar Lander crashed and the Phoenix lander's microphone couldn't be turned on because of an electronics glitch.

SuperCam fires laser bolts at rocks and soil, then uses a spectrometer to analyze the composition of the vaporized material. The microphone records the zaps, the sounds of which reveal the hardness of the original material, which, in turn, reveals details about its formation.

This Hubble Space Telescope image shows the giant galaxy NGC 1275, which contains a supermassive black hole in its core. Sound waves ripple through the gas around the black hole, which researchers have pitched into the range of human hearing, creating a creepy "moaning" sound. Credit: NASA, ESA, Hubble Heritage, A. Fabian (University of Cambridge, UK)



Voyager 1 discovered lightning on Jupiter by detecting its radio waves. Later, the Galileo orbiter photographed several lightning flashes on the giant planet's moonlit nightside. Credit: NASA/JPL-Caltech

The central precincts of the Milky Way Galaxy form bright whirls, arches, and streamers in this multiwavelength image. This chaotic "downtown of the Milky Way" was sonified with piano, glockenspiels, and violins. Credit: X-ray: NASA/CXC/UMass/D. Wang et al.; Optical: NASA/ESA/STScI/D. Wang et al.; IR: NASA/JPL-Caltech/SSC/S. Stolovy

In addition, the microphone has recorded the pops and clicks of the rover itself, a dust devil sweeping across Perseverance, the sigh of gentle breezes, and the whine of the Ingenuity helicopter—a sound that brought another surprise. "We heard the helicopter from almost a football field away, but we hadn't expected to hear it at all," said Wiens. "That was a fascinating surprise—[Mars's] sounds propagate better than we expected."

Lightning Crackles from Gas Giants

No other sounds of the universe are as directly observed as those from Mars, but some are close. Through a branch of sonification known as audification, scientists can perform a nearly one-to-one conversion of data to sounds.

Some conversions are as simple as audifying the "tick, tick, tick" of dust grains hitting a spacecraft, or recording the radio crackle of lightning in a planet's atmosphere. Such recordings might need to be sped up a little to make the patterns more obvious, or pitched into the range of human hearing, but they're realistic portrayals of the actual physical events.

"If you've ever been listening to an AM radio station while you're driving at night, close to a thunderstorm, you hear a lot of crackling and popping. That's… what Cassini recorded from Saturn."

Scientists at the University of Iowa, for example, have been audifying signals from solar system explorers since the Voyager missions of the 1980s. "Fred Schaaf showed up at one of the Voyager press briefings with observations from the plasma wave experiment converted to sound," said William Kurth, an Iowa research scientist who has participated in several missions. (Schaaf is a longtime *Sky & Telescope* writer and editor.) "The data were pretty esoteric, and [Schaaf] was afraid the reporters' eyes would gloss over just looking at these 'wiggly line plots.' But people would relate to these sounds. And everything was right in the audio frequency range, so he didn't even have to change the pitch," Kurth said.

Among many other findings, the Voyager instruments revealed lightning in the roiling clouds of Jupiter. Lightning bolts produce a wide range of electromagnetic energy, from visible light to radio waves. The energy propagates freely into space, where it can be detected by spacecraft. Voyager 1 recorded signals known as whistlers—low-frequency radio waves that are characteristic of lightning on Earth—but they were subtle and could have been produced by other phenomena.

"We wanted to be darn sure we knew what we were talking about before we claimed that we found lightning at Jupiter," Kurth said. "So we listened to the sound. Based on years of experience listening to a lot of these things, those tones convinced us they really were lightning whistlers and not something else. It was another step in our verification."

Years later, the Cassini spacecraft, which orbited Saturn for 13 years, similarly revealed lightning in the ringed planet's atmosphere. "If you've ever been listening to an AM radio station while you're driving at night, close to a thunderstorm, you hear a lot of crackling and popping," said Kurth. "That's radio emissions from the lightning strokes. And that's what Cassini recorded from Saturn."

Cassini also recorded dust strikes, which sounded like a hailstorm pounding an unlucky car.

Recordings from these missions have found life far beyond scientific circles. In the 1996 movie *The Arrival*, Charlie Sheen's character discovers that aliens are about to invade Earth. "He puts together a bunch of satellite dishes to make a radio telescope, and hears a funny sound," said Kurth. "He explains to a kid that it's Voyager 2. And they used sounds it recorded at Uranus, which was a cute thing."

Another instance of science serving as artistic inspiration is composer and musician Terry Riley's Sun Rings. This performance by the Kronos Quartet and a 60-voice choir is based on Voyager's "greatest hits" and premiered at the University of Iowa in 2002.

Sun Rings gained renewed interest during the pandemic, as one critic noted that "music of the spheres may be a concept as old as human imagination, and whistlers have been rudimentarily known about for some time, but it has taken a sanguine modern shaman of the string quartet to expose their musicality."

The promise of inspiration continues today, as the twin Voyager probes are recording the magnetic field of interstellar space and its interaction with the Sun's magnetic bubble, the heliosphere.

White Noise from a Yellow Star

Audification efforts extend far beyond the planets of our solar system, as well as straight to the star at its center.

The "boiling" motions of hot gas in the Sun's outer layers create sound waves that ripple all the way to our star's core. The waves travel differently at different depths and latitudes, so studying them—a field called helioseismology—can reveal details about conditions throughout the Sun. The ripples cause tiny changes in the Sun's brightness, so astronomers monitor those variations with Sun-watching satellites.

"There are actually millions of harmonics," said Timothy Larson, an astrophysicist who has produced audio clips of helioseismology observations for Stanford University and others. "By combining thousands and thousands of them, we can infer the pressure and density inside the Sun. We can also measure the rotation of the Sun, which is different at different latitudes and depths because it's not a solid object. This is the only way to probe the Sun's interior."

Converting the millions of "notes" that reverberate through the Sun to sound requires a bit of work, admitted Seth Shafer, a collaborator with Larson and an assistant professor of music technology at the University of Nebraska Omaha. "If you go to the raw data, [they just sound] like white noise. But by building some filters, we can narrow down the number of harmonics and actually tune in to a particular depth inside the Sun, from the surface all the way to the core."

Shafer, who produced a multimedia program, "Instrument: One Antarctic Night," based on data from telescopes at the South Pole for the Perot Museum of Nature and Science in Dallas, is developing a software tool that will allow "both scientists and creatives" to sonify any data set. "The hope is that some new discoveries will come out of these sounds," Shafer said.

"The goal is to maintain scientific accuracy while creating an aesthetic and meaningful musical representation."

A More Creative Approach

Another branch of sonification uses a more creative strategy. It produces audio from images or other complex products, a technique that often requires a musical approach to data. "The goal is to maintain scientific accuracy while creating an aesthetic and meaningful musical representation," said Domenico Vicinanza, a scientist and composer at Anglia Ruskin University in the United Kingdom, who has produced sonifications using data from the Voyager missions, the European Organization for Nuclear Research (CERN), climate-studying satellites, and other sources.

This branch of sonification features a wide range of practitioners, including scientists, musicians, visualization specialists, accessibility experts, and computer programmers—a roster of self-described computer geeks, music geeks, and sundry other geekdoms. Several have said they couldn't really decide what to be when they grew up, so they decided to do it all.

Arcand, for example, has a background in computer science and astrophysics, and was creating 3D representations of astronomical

Scientists were surprised when they could hear the Ingenuity helicopter, shown here during its 54th flight in April 2023, almost a football field away from the Perseverance rover, indicating that the Martian atmosphere is better at propagating sounds than was expected. Credit: NASA/JPL-Caltech/ASU/MSSS

Some audifications of the Pillars of Creation, seen in this composite optical and X-ray image, have created sounds of the "young stars having tantrums." Hot young stars, captured in X-rays, shine like bulbs on a strand of Christmas lights. Credit: NASA/CXC/INAF/M, Guarcello et al.; Optical: NASA/STScI

The known planets of TRAPPIST-1 line up next to their parent star in this artist's concept. A sonification uses musical notes to depict the resonances of each of the planets' orbits. Credit: NASA/JPL-Caltech/R. Hurt, T. Pyle (IPAC) objects when she discovered sonification. Shafer studied tuba and music composition in college. Russo has one degree in jazz guitar and others in astrophysics, and played with a hip-hop band that briefly signed with a record label. ("It didn't go so well," he said.)

Russo entered the field of sonification in 2017, when he was giving talks about exoplanets to elementary school students. He was trying to explain the orbits of the planets of TRAPPIST-1. "I needed a way to make that more impactful," he remembered, "and I realized [the planets'] orbital resonances could be expressed as musical rhythms and harmonies. When I showed it to the first classroom, they were yelling and clapping, so I knew I was on the right track."

TRAPPIST-1, a star with seven known planets (some of which might lie inside the star's habitable zone), isn't the first system to have its planets' orbits converted to music, according to Vicinanza. He told the 2023 SXSW EDU Conference & Festival attendees that in the early 1600s, Johannes Kepler produced a piano piece depicting the orbits of the planets of the solar system to help explain his discovery that the planets follow elliptical paths. "He was using music as a powerful storytelling language," Vicinanza said.

Outreach is the main focus of most of these types of sonification efforts, with a special emphasis on serving the blind and visually impaired.

"I spent the first decade-plus of my career finding ways to visualize the high-energy universe," said Arcand. "Chandra reveals exploding stars, colliding galaxies, planetary nebulae, blazars, quasars—all sorts of cool things. It's in the kind of light that's invisible to human eyes, so I was mapping those photons to pixels. I love that, but it was missing a large chunk of the population—people who couldn't process data the way I can."

Arcand teamed with Russo and his colleagues ("they adopted me into the band"), and they've collaborated many times since. They've produced more than 2 dozen sonifications for Chandra, using images that combine Chandra's X-ray observations with visible, infrared, and other wavelengths from the Hubble, James Webb, and Spitzer space telescopes. "We opened up Chandra's data vaults for this," Arcand said.

"We're looking for images with some dramatic structure or maybe an interesting texture," said Russo. "We can't communicate everything, so we focus on the most interesting aspects. We have to make an artistic choice of which parts to highlight.... We have to inject some musicality. That turns it more into an art form than a scientific translation."

> *"We took a more symphonic approach.... Science directs the sound, but it's all about marrying the data in a way that's pleasant to listen to."*

Marrying Glockenspiels and Black Holes

Sonifications represent different visual features as different notes played on different instruments. Some sonifications pan across the image, whereas others radiate outward from a central point, or scan like a radar beam.

To sonify the inner few hundred light-years of the Milky Way Galaxy, for example, Arcand and Russo have music pan from left to right, passing across gas clouds, star clusters, and the Milky Way's central supermassive black hole, Sagittarius A*. The music swells as it scans denser regions, and reaches its crescendo at the black hole.

"This is a very dense region—the 'downtown' of the Milky Way," said Arcand. "It's like being in Times Square, with a lot of noise, crowds, energy. We wanted to showcase that frenetic activity, especially as you get closer to Sagittarius A*. We took a more symphonic approach, with soft piano to represent the infrared, a glockenspiel to represent bips and boops in the X-ray, and violins for the arches and strings. Science directs the sound, but it's all about marrying the data in a way that's pleasant to listen to."

For the Pillars of Creation, a star-forming region made famous by a Hubble image, the scientists had the music scan from bottom to top. "We have tall pillars of gas and dust where baby stars are forming," Arcand said. "We have young stars that are having tantrums. It's kind of an eerie sound—more synthesized. Hearing the sounds with those interacting pieces really helps tell the story in such a neat way."

Voices from Beyond

We can expect to hear many more voices from beyond in the years ahead.

A "huge number" of sonification projects are in the works, said Russo, especially with the 25th anniversary of Chandra's launch in 2024. Several sonification practitioners are developing software to allow scientists to convert their own data sets to audio. Engineers are developing a microphone for Dragonfly, a helicopter that will buzz through the atmosphere of Titan in the next decade. The Iowa scientists are audifying observations from the current Juno mission at Jupiter, and plan to do the same with Europa Clipper data when the spacecraft reaches the Jovian system, as early as 2030.

"I would argue we are still in the early days [of sonification] and the potential has yet to be unleashed," said Harrison. "Sonification will help astronomers to gain initial insights more efficiently from the ever increasing, complex, large data sets. It may lead to new insights, too, because we will be exploring the data in completely new ways."

"The benefits for accessibility and making more immersive and engaging educational resources are more obvious," Harrison continued. "I expect to see more people being able to engage with science, from education through to professional scientists, as sonification becomes a more mainstream approach to data representation."

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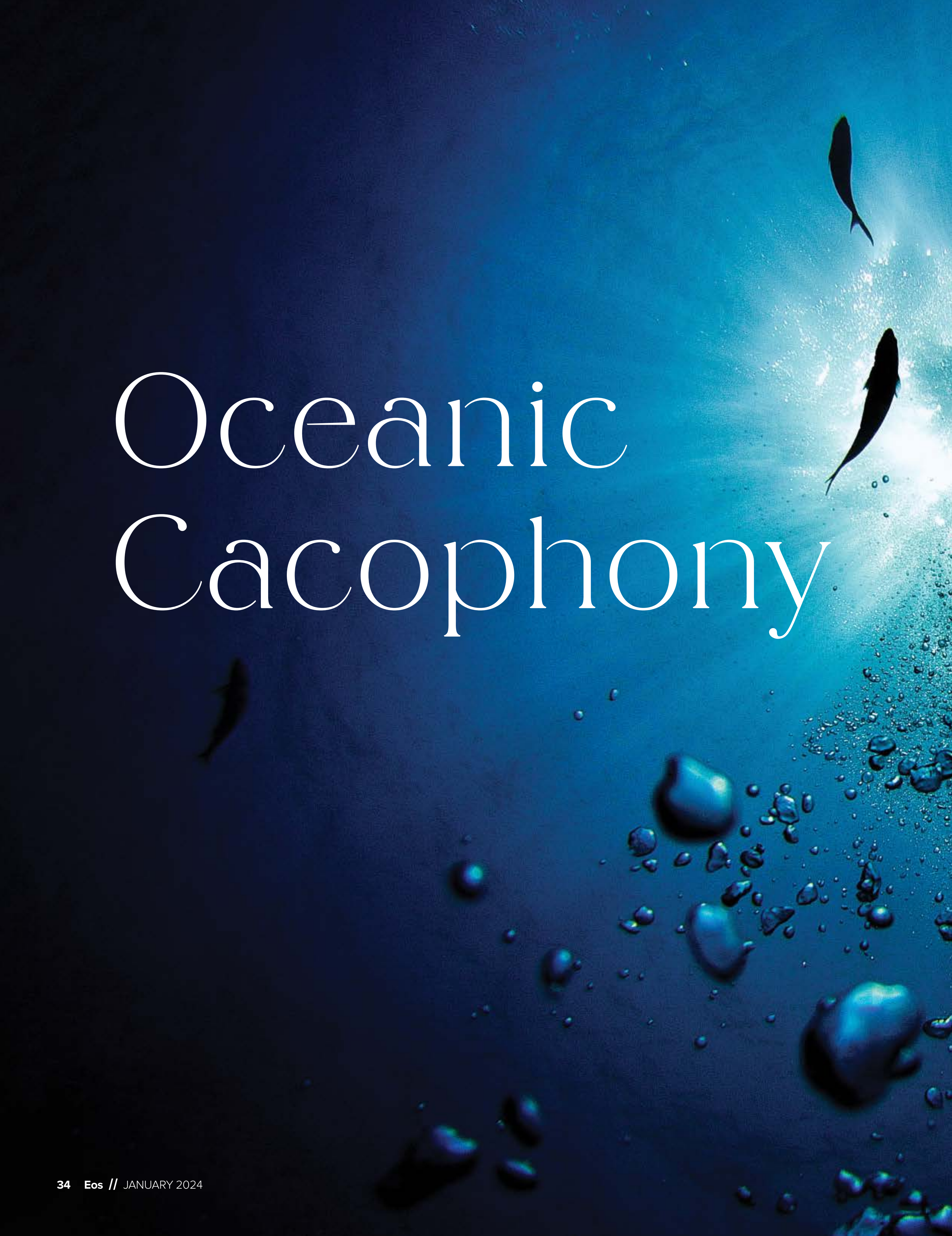
Oceanic Cacophony



By Alka Tripathy-Lang

The ocean is a pretty loud place, and anthropogenic noise is adding another layer to the soundscape.

Humans, marine animals, and even Earth itself contribute noise to the deep. Credit: Max Gotts/Unsplash

Imagine a tropical reef in which the constant clatter of snapping shrimp overwhelms the soundscape. Artisanal fishing boats putter overhead as dolphins whistle and splash. In another scene described by Kate Stafford, an oceanographer at Oregon State University, the setting is Arctic winter, and the creaking and groaning sounds of ice are interrupted by vocal marine mammals—the moan of a bowhead whale or the knocking and ringing of a male walrus ready to mate. What you hear in these acoustic environments depends on where you are and what time of year it is, Stafford said.

Noise permeates the seas. Earth's abiotic sounds include earthquakes and volcanoes, as well as winds and ice. Biologic sounds come from marine mammals, fish, and invertebrates. Added to the natural oceanic cacophony is the "anthrophony" of human-driven activity, including the pings of sonar systems mapping the ocean floor, the din of oil and gas exploration, and the roar of ships transporting goods between continents.

When scientists listen with sensors placed throughout the oceans, Stafford said, "it can seem quite loud and chaotic." Marine wildlife like whales, dolphins, and many fish "are not visual like most of us humans are," Stafford said, and "largely rely on their sense of hearing to navigate their world." Adding persistent, loud artificial noise makes it challenging for them to conduct their lives.

As the global ocean warms, hydroacoustics—the science of sound in water—can help scientists play the role of physicians with stethoscopes, listening for signs of ecosystem health and ocean temperature changes, according to Kyle Becker, a program officer at the Office of Naval Research. "If we don't understand the environment itself," he asked, "how can we understand how animals interact with it?"

Sound Goes SOFAR

The ocean's interior is actually easier to hear than to see. The reason is that in the ocean, light doesn't travel very far, but sound—a compressional wave—can travel without losing much energy, explained Robert Dziak, a research oceanographer at NOAA's Pacific Marine Environmental Laboratory.

Different wave frequencies, or pitches, travel different distances. Low-frequency sounds, like the deep tones of an upright bass in an orchestra, can travel far. High-frequency noises, like the bright, lilting violin's song, will dissipate more rapidly.

Ocean sound speed is affected by temperature, pressure, and, to a lesser degree, salinity, Stafford said.

Temperature decreases with depth to a point where it remains cold but stable; there, sound speed is at a minimum. At greater depths, increasing pressure speeds up sound. The low-velocity layer forms the axis of the sound fixing and ranging (SOFAR) channel.

Sound waves—especially low-frequency ones—can get caught in this layer because refraction bends the waves toward this zone of minimum sound speed. As a result, sound waves can travel thousands of kilometers without losing much acoustic energy, Stafford said.

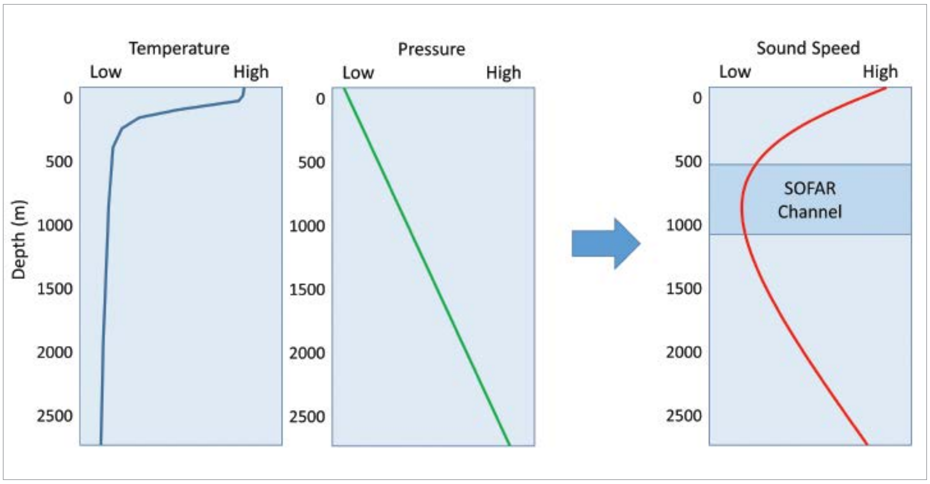
Among the first to take advantage of the SOFAR channel was the U.S. Navy: During World War II it experimented with detonating SOFAR bombs in the channel to triangulate the location of downed pilots.

Scientists use underwater microphones to hear and locate ocean sounds inside and outside the SOFAR channel. These sensors, called hydrophones, can detect a range of frequencies, some of which are inaudible to people. To find the source of a sound, a single hydrophone won't suffice, said Sarah Bazin, a researcher at Institut Universitaire Européen de la Mer. Three or more are needed to triangulate its origin, she added.

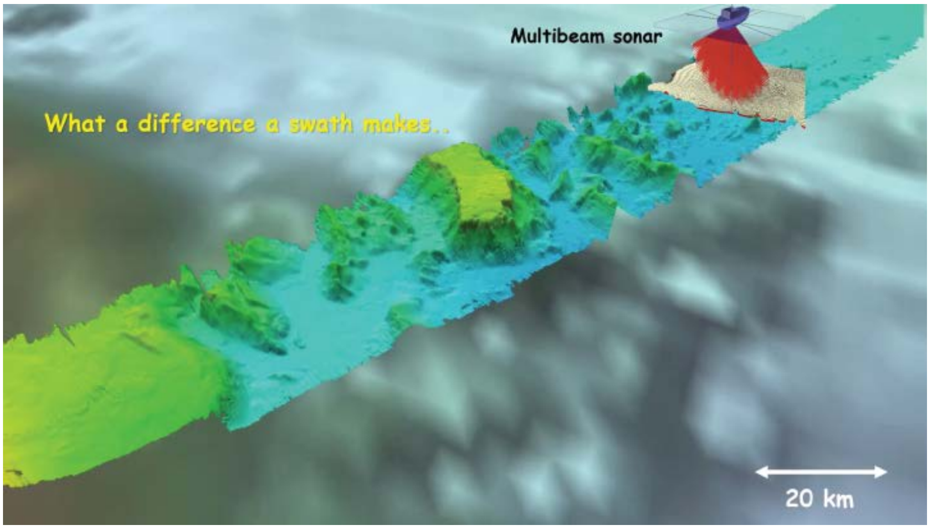
To hear distant sources, said Stafford, "you want your hydrophones in the SOFAR channel, [and] if you are more interested in local events…you put [them] on the seafloor." Because the SOFAR channel is highly temperature dependent, its depth varies with both season and latitude. In the Arctic, it's very shallow, whereas in tropical regions, it's closer to 1,000 meters deep, Dziak said.

Installing a hydrophone in the SOFAR channel requires information about how temperature and salinity, which is directly related to conductivity, vary with depth. A CTD (conductivity, temperature, and depth) device can measure the requisite vertical profiles to find the channel, Bazin said. The hydrophone is then placed in a buoy that's moored to the seafloor with a rope and anchor. Often installed in remote waters, moored hydrophones are designed to last months to years before a team must recover the instrument, collect the data, and redeploy the hydrophone.

"If we don't understand the environment itself, how can we understand how animals interact with it?"



Sound speed mostly depends on ocean temperature and pressure. Where sound speed is at a minimum, the sound fixing and ranging (SOFAR) channel can carry sound waves thousands of kilometers. Credit: Introduction to Oceanography *by Paul Webb, CC BY 4.0 (bit.ly/ccby4-0)*



In the background are data obtained via single-beam echo sounder. A ship equipped with a multibeam sonar (upper right) can collect a much higher resolution swath, as shown in brighter colors. Credit: Larry Mayer and John E. Hughes Clarke

Hydrophones can be linked to land by cables for near-real-time transmission of data, said Morgane Le Saout, a postdoctoral researcher at GEOMAR Helmholtz Centre for Ocean Research in Kiel, Germany.

The International Monitoring System, maintained by the Vienna-based Comprehensive Nuclear-Test-Ban Treaty Organization, or CTBTO, listens for underwater nuclear explosions primarily using hydrophones suspended in the SOFAR channel that are tethered to six onshore stations for satellite transmission, said Mario Zampolli, a hydroacoustic engineer at CTBTO.

"This data set, which has been listening to all sorts of [phenomena] in the ocean, atmosphere and solid Earth for [more than] 20 years," Zampolli said, "can reveal many things about Earth processes."

Indeed, the CTBTO data set, which is one of the longest time series of hydroacoustic data, can be made accessible to researchers who have relevant scientific questions, Stafford said.

Listening to Earth

To understand abiotic processes in the ocean environment, hydrophone arrays keep their ears on the seafloor, water column, and ocean surface. For example, in 2016, Dziak and colleagues heard the breakup of the Nansen ice shelf in the Ross Sea via hydrophones suspended near the SOFAR channel about 2 months before satellite images caught the cracking. "It broke free, but it remained pinned in place," Dziak said, "until a big storm system came through."

At the seafloor, ocean bottom seismometers can sense vibrations caused by earthquakes, Le Saout said. And hydrophones can hear these rumblings when the seismic waves transition from crust to water, turning into hydroacoustic signals.

For instance, hydrophones heard the magnitude 9.0 Great Thoku earthquake, which struck offshore Japan in 2011. "It was incredibly loud and projected a huge amount of sound energy into the ocean," Dziak said.

Unlike earthquakes, which produce long, low-frequency signals, volcanic eruptions often produce short-pulsed signatures, Le Saout said, allowing listeners to distinguish these sounds. A 2015 eruption of the Axial Seamount on the Juan de Fuca Ridge produced tens of thousands of impulsive acoustic signals generated by the interaction of lava and seawater, she said.

In another example of scientific use of hydrophones, French research institutions are monitoring a growing submarine volcano that in 2018 unexpectedly sprouted off the coast of Mayotte, a small French-administered island in the western Indian Ocean. Bazin listens for the volcano's burbling submarine lava with four hydrophones deployed in the SOFAR channel within 50 kilometers of the new volcano. A second array of hydrophones installed throughout the Indian Ocean has also heard similar lava-water interactions coming from the Indian mid-ocean ridges. Such eruption signals, Bazin said, "look very similar whether we record them 50 kilometers or 3,000 kilometers away," thanks to the SOFAR channel.

As earthquakes and eruptions create signals for hydroacoustic stations to hear, so, too, do whales. At the same time as one of the large earthquakes near Mayotte, "there was a whale singing near [one hydrophone]," Bazin said.

"When whales are relatively nearby or very loud, you can distinguish the songs [of individuals]," Zampolli said. Whale song even helped researchers identify a new subspecies of blue whale in the Indian Ocean, he said.

Like people, marine mammals likely hear in the same range that they vocalize, Stafford said. In fact, some large whales may be able to take advantage of the SOFAR channel because they vocalize with low-frequency signals. "It doesn't mean that a blue whale off California says, 'hey, buddy,' and that's going to be heard by a whale off Japan," she said, but the vocalization can alert the whale in Japan to head in the direction of its California counterpart. "It's more of a navigation beacon versus an actual conversation."

Sonar Sources Map the Seafloor

By passively listening, scientists can learn about a variety of ocean processes and ecosystems, but they sometimes make their own sounds via active acoustics. For instance, single-beam sonar systems can help boats determine depth, Dziak said.

In such systems, a voltage excites a round ceramic device, creating a pressure wave—a downgoing ping, said Larry Mayer, director of the Center for Coastal and Ocean Mapping at the University of New Hampshire. That sound bounces off the seafloor and returns, at a lower amplitude, to the same ceramic surface, creating a measurable voltage. With knowledge of ocean sound speed, time can be converted to depth, and boats can avoid running aground.

This method was how oceanographers mapped the seafloor through much of the past century. Then, multibeam sonar systems were introduced with numerous ceramic elements placed in complex arrays, Mayer explained. The acoustic source creates a narrow band of sound, like a flashlight with a thin, rectangular slit. A different set of ceramics perpendicular to the source measures the return signal, he explained. With some signal processing, the result is a detailed picture of cracks, crevasses, mountains, and sediments on the seafloor.

Multibeam sonar "was this absolute revolution in the way we look at the seafloor," Mayer said. Still, only about 25% of the ocean has been mapped in great detail via multibeam sonar. (Bathymetry for the other 75% comes from satellite data, which is far less accurate and, in some cases, hundreds of meters off.)

The U.S. Navy uses sonar to spot stealthy submarines. "That's where midfrequency sonars come into play," Becker said.

Mid-frequency Navy sonar, Mayer explained, operates at the same decibel level as multibeam sonar used for mapping, but to find objects throughout the water rather than just on the seafloor, its pulses go out in almost all directions. The pulses are also much longer—seconds of sound versus milliseconds—and the overall amount of energy emitted is much greater, he said.

Sonar used for depth sounding and fish finding operates at high frequencies and low amplitudes that aren't likely to affect many marine species, Stafford said. However, she continued, midfrequency sonar "has been implicated in beached whale strandings around the world." Whether strandings result from "scaring" whales, causing them to surface quickly and get the bends (decompression sickness caused by rapid decrease of water pressure), or from some other aspect of the military exercise, is unclear, she said.

"Noise for certain people is actually the source [of data] for another type of researcher."

To test the relationship between midfrequency sonar and whale behavior, the Navy monitored Cuvier's beaked whales at the Southern California Anti-Submarine Warfare Range. When the whales were feeding during Navy sonar transmission, the noise interrupted their behavior, and in some cases, the whales left the range for several days, Mayer said. "There was a clear, direct impact."

To see whether multibeam sonar systems have the same effect, Mayer and his team brought their loudest multibeam sonar—one that produces low frequencies that can map down to 11,000 meters below sea level—to the same range to repeat the same experiment. They found no change in the feeding behavior of the same population of whales that initially fled the range.

Anthropogenic Air Guns, Commercial Cacophony

Large whales sing at the same frequency as the sounds of commercial shipping and oil and gas exploration. When the frequency of a human-made sound overlaps with that of marine animals, Stafford said, animals' ability to hear predators or navigate is affected. "That's problematic."

Yet both oil and gas exploration surveys and geologists who study the oceanic crust to a depth of several kilometers need very large air gun surveys, Bazin said. For instance, mapping underground details of Mayotte's new volcano required geologists to tow air guns behind a ship, using their shots as seismic sources.

But the air gun surveys near Mayotte also masked the sounds of subsea lava emerging from the new volcano, hiding the sounds Bazin was seeking. "Noise for certain people is actually the source [of data] for another type of researcher," she said.

Air guns produce a pulse of high energy across many low frequencies, Dziak said, which ensures that the signals get to the seafloor and then into the crust to bounce off geologic structures. "There's a lot of oil exploration going on in the world," Dziak said. "There's periods where you see lots and lots of air gun noise."

Only intermittent topographic features of the seafloor, said Bazin, keep these sounds from traveling long distances through the SOFAR channel and into receivers, whether they be hydrophones or whales' ears.

Hydrophones (and probably also whales) around the world hear the constant hum of commercial shipping, as well as air guns, Stafford said. To explore shipping noise over time at a global scale, Jukka-Pekka Jalkanen, a researcher at the Finnish Meteorological Institute, and his team combined transponder data and vessel descriptions for the global fleet, tracking where each ship went. To convert that information into shipping noise, they applied a noise model that predicts noise emissions for individual ships, he said. The team found that container ships are the largest contributor to shipping noise, mostly because they are large vessels that go fast.

One major culprit is cavitation, a process that describes the formation and collapse of bubbles. Ship propellers form bubbles as they rotate, and often have imperfections that yield more bubbles. Faster ships make more bubbles. When the bubbles break it's noisy, Stafford said. But machinery clunking into the water and improperly secured engines also contribute to shipping noise. "A really well built ship will be a quieter ship," she said.

At the same time that technology is improving ship quality, which would reduce associated noise like cavitation, the total amount of shipping is increasing. Jalkanen likened this to buying a fuel-efficient car and driving it more often than the gas-guzzler you previously owned.

In the short term, changes in shipping activity such as slowing down and avoiding marine protected areas can help protect marine ecosystems from excess noise, Jalkanen said. Long-term changes necessitate both modifying ship design and retrofitting existing ships. At the moment, however, there are no legal obligations for noise reduction, though underwater noise is recognized by the European Union as a pollutant.

Sound Speed Takes Center Stage

As the ocean warms, the SOFAR channel deepens, and overall, ocean sound speed increases. With climate change resulting in extreme ocean temperatures, changes in sound speed can affect animals' ability to feed, migrate, or even mate. "Almost all marine mammals that we know of rely on sound as their primary modality," Stafford said.

A study modeling ocean sound speed under a business-as-usual climate change scenario suggests that increases aren't likely to be uniform, said Chiara Scaini, a

Cuvier's beaked whales are sensitive to sonar. Credit: Wanax01/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

researcher at the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale in Trieste, Italy, and coauthor of the modeling study. In this scenario, researchers have identified certain acoustic hot spots predicted to substantially up their sound speeds.

To demonstrate how these changes might affect mammals who live in one such hot spot in the northern Atlantic, Scaini and her colleagues focused on vocalizations of the critically endangered North Atlantic right whale. The whales' calls should propagate farther in a warmer ocean, said Alice Affatati, the lead author of the study, also at the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale. But sounds in general would propagate faster in a warm ocean, including anthropogenic noise that might be more swiftly transported around the ocean via changes in the SOFAR channel. In other words, the background noise level may increase, making it harder for whales and other marine wildlife to hear each other.

Taking the Ocean's Temperature

Warming waters are also forcing species to change where they go and when. Hydrophones can hear fish and marine mammals moving farther north into the Arctic than they used to, Stafford said. The instruments can also directly help gauge ocean temperature increases resulting from climate change.

The ocean acts like a battery that stores heat, Zampolli said, so small increases in temperature over a large volume can mean big changes in the amount of energy stored. Keeping track of the heat helps scientists see some of the effects of climate change and learn how marine life responds. Satellites can monitor temperatures at the surface. Underwater instruments, known as Argo floats, descend to depths of 2,000 meters, drift for 10 days, and then resurface, sending vertical profiles of temperature via satellite. "But [Argo floats are] always a point sample, and they are spaced a few hundred kilometers apart."

To measure temperature variations over time at high resolution across immense volumes of ocean, acoustic tomography shows great promise, Zampolli said. If an acoustic source is known precisely in both space and time, its propagation path is well understood, and the source sends its sound signal via the SOFAR channel for measurement at distant hydrophones; then repeated measurements of the signal's travel time over years will yield information about long-term changes in sound speed and therefore changes in average ocean temperature along the propagation path. The hotter the water is, the faster the signal propagates.

However, the history of this method is fraught. The main project that ran between 1996 and 2006, called Acoustic Thermometry of Ocean Climate, or ATOC, was designed to send low-frequency signals for 20 minutes every 4 hours through the northern Pacific basin. Because of early concerns over the effect of these sound sources on marine mammals that vocalize in the same frequencies, ATOC was eventually defunded.

Now, scientists are finding other acoustic tomography methods to safely study the ocean's temperatures by using either natural sources, such as repeating earthquakes, or very low level human-produced sounds that are transmitted in a particular sequence. Nevertheless, a noisy ocean can potentially decrease the detectability of these sometimes subtle acoustic tomography signals.

"There's a lost couple of decades," Becker said, because acoustic tomography was taken off the table. "I don't know of any other way you can synoptically probe the interior of the ocean on basin scales."

"The human cry that was raised about [ATOC] and about the use of Navy sonar actually ended up driving a tremendous amount of research to figure out how animals make sound and the impacts of sound on animals," Stafford said. ATOC taught scientists a lot about doing experiments responsibly, she said, and served as a reminder that "we're not the only creatures on the planet."

Cartography of Loss

The study on future ocean sounds has been translated into a performance, "Cartography of Loss," choreographed by Giulia Bean and performed by Chiara Nadalutti. The dance turns sound speed profiles, which are just numbers, into movement. In the piece, half of the dancer's body moves according to today's profile as her other half demonstrates the predicted future profile. "Even if you are not used to reading a graph, you can look at the dancer and see her moving very differently for present and future," Affatati said.

From this literal stage, the ocean acoustic environment and its many actors and scenes might find a new audience.

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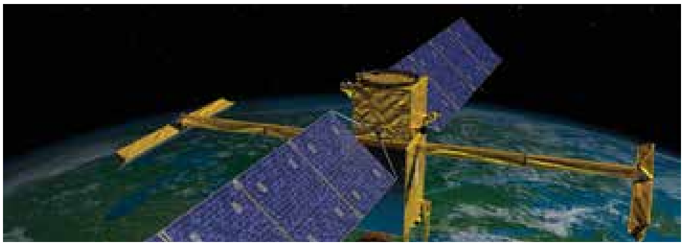
Machine Learning Provides a Clearer Window into Ocean Motion



This artist's concept depicts the Surface Water and Ocean Topography (SWOT) satellite, launched in December 2022. Credit: NASA/Jet Propulsion Laboratory

Oceanographers use satellites to peer down at Earth and measure the elevation of the ocean's surface. This information can help them map the circulation of the ocean's currents and understand the role this movement plays in heat transport and climate change. Launched in late 2022, the Surface Water and Ocean Topography (SWOT) satellite can take snapshots of sea surface heights at a finer scale than ever before possible—tens of kilometers instead of hundreds.

The catch? Simple, physics-based methods for translating sea surface heights into meaningful information about ocean currents do not apply at such high resolutions. This is because looking at the ocean so closely also means detecting waves beneath the water's surface. Although these subsurface waves do not affect ocean currents, they add noise to observations of sea surface height.

Now, *Xiao et al.* present a novel, machine learning method for using SWOT sea surface height data to estimate various aspects of current flow in the upper ocean. The method applies a computational approach inspired by human vision known as a convolutional neural network, which the research team trained on data from realistic simulations of sea surface heights and current dynamics.

The researchers demonstrated that their convolutional neural network approach can use fine-scale sea surface heights to estimate some characteristics of current flow. By improving understanding of how currents transport heat and carbon, scientists could better understand and predict climate change.

The researchers note that this initial achievement represents a proof of concept, and further research is needed to refine the new method before it can be reliably used with SWOT data.

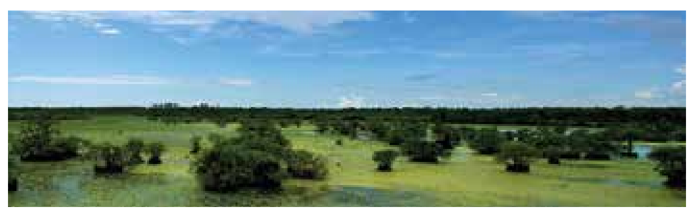
In the meantime, SWOT will keep busy capturing high-resolution images of not only Earth's oceans, but also almost all surface water around the world, including lakes, rivers, and reservoirs. (*Journal of Advances in Modeling Earth Systems (JAMES)*, https://doi.org/10.1029/2023MS003709, 2023) **—Sarah Stanley,** *Science Writer*

Better Bottom-Up Estimates of Wetland Methane Emissions

Methane is one of the most important greenhouse gases globally, second only to carbon dioxide in atmospheric abundance. A large portion of natural methane emissions comes from wetlands, although exactly how much is unclear. Figuring out the magnitudes and locations of wetlands' methane contribution more precisely is crucial for improving our understanding of climate change.

One difficulty is that some models of wetland methane emission disagree with each other, making it difficult to assess trends. New analyses using more data could help shed light on methane emissions worldwide and help reduce uncertainty in climate models.

McNicol et al. used 119 site-years of data from 43 wetland sites tracked in the FLUXNET-CH4 global eddy covariance methane flux database, which was compiled by the Global Carbon Project (GCP) in close partnership with AmeriFlux and the European Eddy Fluxes Database Cluster. The authors used the data to train a random forest model ensemble to estimate total methane emissions from wetlands worldwide. Their results agreed generally with those from existing models of methane emissions but diverged from results for the tropics, indicating a need for better data and modeling of tropical wetland methane sources.



Sri Lanka's Kumana National Park is a haven for wildlife and perhaps also a significant source of methane. Credit: Dilanthaonline/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

As in previous studies, the new results indicated that about 68% of wetland methane emissions come from tropical wetlands. But they differed on where within tropical wetlands the emissions originate. For example, the new model indicated that the semiarid monsoon Sahel was responsible for 3 times as much methane as previous models using GCP data have indicated. Meanwhile, the model found far lower emissions totals from humid tropical forested wetlands like those in the Amazon, Congo, and Indonesian archipelago.

One reason for the disparities could be that current methane monitoring systems lack robust coverage in tropical regions and are overrepresented in certain ecosystems, the authors say. Those factors could bias existing data on tropical methane emissions.

The researchers suggest that methane contributions from humid and seasonally wet tropical wetlands could currently be underestimated or overestimated across different methane emissions models. Reconciling outputs from these models could help firm up projections of future methane release as well as estimations of future warming. (*AGU Advances*, https://doi.org/10.1029/2023AV000956, 2023) **—Nathaniel Scharping,** *Science Writer*

James Webb Space Telescope Captures Saturn's Changing Seasons

Winter is coming—and not just for Earth's Northern Hemisphere. Northern summer on Saturn, which completes its orbit around the Sun about once every 30 years, is coming to a close after about 7.5 years, with its fall equinox coming up in 2025. Just like on Earth, Saturn's changing seasons are accompanied by changes in its weather.

Now, as reported by *Fletcher et al.*, images captured by the Mid-Infrared Instrument (MIRI) aboard the James Webb Space Telescope (JWST) show how Saturn's atmospheric dynamics have evolved since the Cassini-Huygens spacecraft ended its 13-year investigation of the planet in 2017.

Launched in December 2021, JWST set its sights on Saturn in November 2022, with the goal of putting MIRI's small fields of view to the test against the planet's large size, rapid rotation, iconic rings, and unusually high infrared brightness compared with MIRI's other targets. Researchers used MIRI to capture infrared images of Saturn bit by bit and create a mosaic map of Saturn's northern hemisphere in summertime.

The images captured the structure of Saturn's clouds and allowed researchers to measure the spatial distribution of different temperatures and chemicals in the atmosphere, revealing a number of notable seasonal changes.

For instance, the images show that the planet's north polar stratospheric vortex—a high-atmosphere circulation pattern of gases first detected by Cassini during Saturn's spring—warmed during the summer; it should cool and dissipate as winter approaches.

The images also highlight a complete reversal of an airflow pattern in Saturn's stratosphere that Cassini observed during the northern winter. At that point, large quantities of air rose to higher altitudes in the southern hemisphere, crossed the equator, and sank to lower altitudes in the northern hemisphere, enriching the air in gases like hydrocarbons. Now, the MIRI data suggest that air is rising in the north and flowing south, creating a scarcity of hydrocarbons at northern latitudes. This seasonal circulation pattern may continue to change as fall approaches.

Because of MIRI's exceptional sensitivity and its ability to capture wavelengths of light that Cassini could not, the new images also map the distribution of several gases for the first time, including water in the troposphere and ethylene, benzene, methyl, and carbon dioxide in the stratosphere. The new images also reveal high levels of ammonia at the equator, suggesting that Saturn's equator may feature processes similar to Jupiter's, which is also rich in ammonia.

Together these findings provide the first real glimpse into late summertime in Saturn's northern hemisphere and demonstrate the advanced capabilities of JWST and MIRI. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2023JE007924, 2023) **—Sarah Stanley,** *Science Writer*

Aurora Records Reveal Shortened Solar Cycle During Maunder Minimum

A large solar flare erupts from the Sun's surface in this image from NASA's Solar Dynamics Observatory, taken on 7 March 2012. Credit: NASA/GSFC/SDO

Sunspots change in number depending on how much magnetic activity the solar dynamo generates. But there's not total chaos: These changes occur in a cycle, which lasts about 11 years on average. The Sun also experiences extended periods of low activity that can last for decades, called grand minima. The Maunder Minimum, which occurred between 1645 and 1715, is often viewed as an archetypal example of the Sun's behavior during these abnormal periods.

Historical data on the Sun's behavior during the Maunder Minimum, including records of sunspot activity and radionuclide deposition, are sparse and do not always align. To bolster knowledge of the solar dynamo during the Maunder Minimum, *Yan et al.* turned to a new source of data: observations of equatorial aurorae in Korean historical texts.

Korean historians kept meticulous records of events during the Joseon dynasty, which spanned the 14th–19th centuries. These records include observations of the night sky, such as aurorae, which could be seen regularly during much of the Joseon dynasty because of a geomagnetic anomaly in the western Pacific. Aurorae are correlated with the solar cycle and happen more frequently during periods of high activity.

The researchers used an existing database of Korean historical records to analyze a set of 1,012 aurorae between 1620 and 1810. By noting when aurorae happened more and less frequently, they found a relatively short, 8-year solar cycle during the Maunder Minimum.

Their work adds to other sources of data on the Sun's activity and provides evidence that the solar cycle was temporarily shortened during the Maunder Minimum. This change could indicate that the solar dynamo enters a distinct cyclic mode during grand minima, though why that happens remains unclear. (*AGU Advances*, https://doi.org/10.1029/2023AV000964, 2023) **—Nathaniel Scharping,** *Science Writer*

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WASHINGTON COLLEGE

DIRECTOR OF WATERSHED INNOVATION

DESCRIPTION

Reporting directly to the CES Director, the Director of Watershed Innovation is a key member of CES's leadership team who will work to enhance the Center's research mission on the Chester River, a tributary of the Chesapeake Bay, and comparable national and international watersheds. The Director will be responsible for creating, developing, and managing innovative and entrepreneurial science programs that can create effective solutions for real-world environmental problems. The intent is to incubate and grow ideas into marketable instruments, applications, and/or other tools that support sustainable development. Partnership with the College's Makerspace is open. The Director should use this charge to link undergraduates, faculty, and staff at Washington College with NGOs, corporations, and government agencies through this initiative.

ESSENTIAL FUNCTIONS

- Develop an applied research agenda inclusive of undergraduate students and external partners that results in a variety of potential research products, such as scientific and popular publications, data visualizations, briefs, reports, products, patents, copyrights.
- Collaborate closely with Washington College faculty, academic programs and departments, ensuring CES enjoys strong relationships across the institution and the greater community
- Participate in and foster a team-oriented, transdisciplinary, and collaborative culture at CES
- Teach one course per year to develop interest and capacity of students to engage in research and scholarship at CES
- Mentor student projects and internships, and support students' professional development
- Represent CES and communicate research to multiple internal and external audiences
- Successful seek external funding, individually and/or as a part of research teams
- Collaborate with appropriate partners to develop, commercialize or market innovations
- Work with CES Director to align with strategic goals of the Center and College
- Report annually on activities
- Manage the budget, assets, and physical space of the Watershed Innovation Lab
- Contribute to the larger mission of CES in service to the Center and the College

QUALIFICATIONS

- A PhD in a relevant field, such as environmental science, earth sciences, physics, engineering, mathematical or computational sciences is required
- At least five years of professional experience in higher education or research in any sector, particularly transdisciplinary research or team science
- **Please see application link below for full list of qualifications.**

APPLICATION INSTRUCTIONS

https://findajob.agu.org/job/8023168/director-of-watershed-innovation/

PRINCETON UNIVERSITY

OPEN RANK FACULTY POSITION

The Department of Geosciences at Princeton University is seeking applications for an **open-rank (tenure track or tenured) faculty position in Climate Science**. We are seeking candidates with an outstanding research track record in the area of climate dynamics broadly interpreted, expertise in advanced theories and concepts of the atmospheric general circulation and geophysical fluid dynamics, and commitment to mentoring and advising the next generation of climate scientists. The appointee will be also a member of the Program in Atmospheric and Oceanic Sciences, a joint program between the Department of Geosciences and the NOAA Geophysical Fluid Dynamics Laboratory.

Applicants should submit a curriculum vitae, including a publication list, statements of research and teaching interests, and contact information for three references at: **https://puwebp.princeton.edu/AcadHire/position/32504**. Evaluation of applications will begin as they arrive; for fullest consideration, apply by **February 29, 2024**; but applications will be accepted until the position is filled.

Diversity and inclusion are central to Princeton University's educational mission and its desire to serve society. Members of the Geosciences department have a deep commitment to being inclusive. We believe that commitment to principles of fairness and respect for all is favorable to the free and open exchange of ideas, so we seek to reach out as widely as possible in order to attract outstanding individuals as students, faculty, and staff. As noted in the University's non-discrimination statement, we are committed to nondiscrimination on the basis of personal beliefs or characteristics: https://dof.princeton.edu/governance/policies/non-discrimination-statement.

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

EPFL

Faculty Position in Urban and Territorial Information Systems

at the Ecole polytechnique fédérale de Lausanne (EPFL)

The EPFL School of Architecture, Civil and Environmental Engineering (ENAC) invites applications for a Tenure Track Assistant Professor of Urban and Territorial Information Systems. The professor will be attached to the Institutes of Environmental Engineering and Architecture and the City.

Urban regions have high resource and energy demands, with impacts on multiple scales that reach well beyond urbanized areas. Sustainable design of urban regions, thus, involves complex, multifaceted goals with the need to address disparate dimensions including ecosystem preservation as well as social acceptance and amenity. Nevertheless, the fast increase in geospatial data availability enables to innovate urban systems and territorial design approaches for a broad range of challenges involving climate change, environmental health, equity, biodiversity, mobility, blue and green infrastructure, and urban water management.

This professorship will bridge the disciplines of architecture and environmental engineering within an internationally recognized research program in urban and territorial Information systems. We seek applications from individuals who will advance the state-of-the-art of sustainable urban design through development and utilization of spatial information systems that aim to improve quality of life, guide sustainable resource use, and mitigate environmental impacts. Data science and artificial intelligence can play a major role in designing such systems.

The appointee will develop a research program that leverages multiscale data and information to advance understanding and design principles in support of sustainable urban systems. The scope of this challenge is broad, and candidates from a variety of disciplines are welcomed, including architecture, artificial intelligence or data science, civil and environmental engineering, environmental sciences, geography, human-computer interaction, imaging and computer science, and urban planning. It is envisaged that this professorship will pursue a research agenda built upon novel theoretical approaches, innovative methodological developments, geoAI and spatial/temporal modelling that will stimulate solutions for design of sustainable urban and territorial systems.

EPFL professors are committed to excellence in undergraduate and graduate level teaching. Within ENAC, all professors contribute to disciplinary and cross-disciplinary teaching programs.

With its main campus located in Lausanne, on the shores of Lake Geneva, EPFL is a dynamic, well-funded institution fostering excellence and diversity. It is well equipped with experimental and computational infrastructure and offers a fertile environment for research collaboration between various disciplines. The EPFL environment is multilingual and multicultural, with English serving as a common interface. EPFL offers internationally competitive start-up resources, salaries and benefits.

The following documents are requested in PDF format: cover letter including a statement of motivation, curriculum vitae, publication list (including portfolio if relevant), concise statements of research and teaching interests (up to 5 pages each) as well as names of three (but not more than five) individuals who are willing to provide a reference letter upon request. Applications should be uploaded to the EPFL recruitment web site:

https://facultyrecruiting.epfl.ch/position/51281924

Formal evaluation of the applications will begin on **15 January 2024**.

Further enquiries should be made to:
Prof. Devis Tuia
Chair of the Search Committee
e-mail: **Urbandterritorialsys@epfl.ch**

For additional information on EPFL, please consult: www.epfl.ch, https://enac.epfl.ch, https://iie.epfl.ch, https://ia.epfl.ch, https://climact.ch

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

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

Hydrogeochemist/Water Quality Modeler

DESCRIPTION

The Kansas Geological Survey (KGS) conducts fundamental and applied research significant to Kansas. Scientific staff are expected to develop research programs of international stature and relevant to Kansas. The individual in this position will develop and lead a research program centered around studying subsurface hydrogeochemical processes from the site- to regional-scale using numerical modeling approaches, potentially complemented by field- and laboratory-based study. Areas of research could include, but not be limited to: hydrogeochemical characterization of sedimentary aquifer systems; simulation of groundwater flow and solute transport processes; surface-water/groundwater interactions; contaminant transport and source identification. While these are areas of potential focus, demonstrated research excellence and future research potential are more important than the candidate's specific area of specialization.

Scientists at the KGS are hard-funded, faculty-equivalent academic staff with sabbatical eligibility. Scientific staff are expected to develop research programs that are of international stature and highly relevant to Kansas, with similar standards to academic faculty in terms of research productivity, obtaining external funding to support projects, and advancement through ranks. Scientific staff also can teach and serve as advisors of graduate research, and typically have courtesy appointments with one or more academic departments. A candidate at the assistant scientist level is preferred, but exceptional applicants at the associate or senior scientist levels will also be considered.

APPLICATION INSTRUCTIONS

Review begins November 13, 2023 and continues until a qualified pool of applicants is identified.
https://findajob.agu.org/job/8021999/hydrogeochemist-water-quality-modeler-/

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

Hydrologic Data Scientist

DESCRIPTION

The Kansas Geological Survey (KGS) at the University of Kansas (KU) is seeking a hydrologic data scientist to develop and lead a research program of international stature using cutting-edge data science and geostatistical techniques to investigate water resources questions of relevance to Kansas. Specific areas of research expertise may include, but are not limited to: machine learning, deep learning, or artificial intelligence approaches applied to investigations of water resources; work on water quantity and/or quality in groundwater and/or surface water systems; assessment of subsurface hydrostratigraphy; and data-driven investigations of hydrogeology, hydrology, or ecohydrology in human-dominated landscapes. While these are areas of potential focus, demonstrated research excellence and future research potential are more important than the candidate's specific area of specialization.

Scientists at the KGS are hard-funded, faculty-equivalent academic staff with sabbatical eligibility. Scientific staff are expected to develop research programs that are of international stature and highly relevant to Kansas, with similar standards to academic faculty in terms of research productivity, obtaining external funding to support projects, and advancement through ranks. Scientific staff also can teach and serve as advisors of graduate research, and typically have courtesy appointments with one or more academic departments. A candidate at the assistant scientist level is preferred, but exceptional applicants at the associate or senior scientist levels will also be considered.

APPLICATION INSTRUCTIONS

Review begins November 13, 2023 and continues until a qualified pool of applicants is identified.
https://findajob.agu.org/job/8021998/hydrologic-data-scientist-/

THE UNIVERSITY OF MEMPHIS.

TENURE TRACK POSITION IN SEISMOLOGY

The Center for Earthquake Research and Information (CERI) at the University of Memphis invites applications for a **tenure-track faculty position at the Assistant Professor level to begin in August 2024**. Appointment at the Associate level will be considered based on the applicant's experience. We are searching for an individual to complement our existing strengths in seismology, geodesy, computational tectonics, earthquake rupture dynamics, earthquake physics, and seismic hazard. We are particularly interested in applicants with a strong theoretical background in any subfield of seismology. CERI is committed to creating a diverse and inclusive culture for all faculty and graduate students and we strongly encourage members of underrepresented groups to apply.

Applicants must have a Ph.D. at the time of employment and show a demonstrated record or strong promise of research productivity. The successful candidate is expected to build a vigorous, externally funded research program, mentor MS and PhD graduate students, and teach graduate courses, one per semester, in her or his specialty. As part of a University interdisciplinary research center, CERI faculty are engaged in a variety of regional, national, and international research projects (**https://www.memphis.edu/ceri/**). More information about this position can be obtained by contacting the chair of the search committee, Eunseo Choi (**echoi2@memphis.edu**).

CERI is a state recognized Center of Excellence and is an independent academic unit within the College of Arts and Sciences. The MS and PhD Concentration in Geophysics is housed alongside the Earth Sciences graduate program and has academic and research ties with the Departments of Earth Sciences and Civil Engineering. CERI has an additional role as a State of Tennessee entity that is periodically reviewed by the State legislature. CERI is a core member of SCEC, Statewide California Earthquake Center. Our facilities include access to the campus high-performance computing facility, a rock deformation laboratory, and an earthquake modeling and visualization laboratory. CERI has an extensive outreach and education program and is a fundamental source of information regarding the region's earthquake science and seismic hazard.

Applicants should submit an application with cover letter, full curriculum vitae, statements of research, teaching and diversity, and the names and addresses (with phone numbers and email) of at least three references. To receive full consideration, applications must be submitted through the University of Memphis WorkForUM online application system **(https://workforum.memphis.edu/postings/38341) by February 2, 2024**.

The University of Memphis is an Equal Opportunity/Affirmative Action employer.

Tulane University

PROFESSOR OF PRACTICE IN EARTH AND ENVIRONMENTAL SCIENCES

The Department of Earth & Environmental Sciences seeks to fill a **Professor of Practice** position to begin in **July 1, 2024**. We seek an Earth and Environmental scientist with teaching interest in geospatial analysis who will contribute to our inter-disciplinary GIS Certificate Program. The position is a non-tenured, full-time academic year (nine month) teaching position with renewable 3-year appointments, and opportunities for additional summer teaching. The responsibilities of this position include teaching courses comprising the undergraduate curriculum, teaching courses in the applicant's area of specialization, and service to the educational mission of the department and university. Opportunities exist for advising undergraduate research and co-advising research students, and for development of service-learning courses required of all undergraduates. We would like to broaden participation in the study of the Earth and environment and therefore encourage applications from groups that are historically underrepresented in the sciences.

Review of applications will begin **December 4, 2023** and continue until the position is filled. Applicants should submit a cover letter that highlights why they are interested in this opportunity, prior experiences educating and mentoring undergraduate students, and how they build inclusive educational environments, CV, statement of teaching philosophy, any previous teaching evaluations or other evidence of teaching excellence, and contact information for three references familiar with the applicant's teaching abilities. Applications must be submitted electronically via the following link: **http://apply.interfolio.com/133503**. Any inquiries may be directed to Dr. Cynthia Ebinger (**cebinger@tulane.edu**), Department of Earth and Environmental Sciences, Tulane University, 6823 St. Charles Ave., New Orleans, LA 70118-5698. Further information about the department and university can be obtained at **https://sse.tulane.edu/eens** .

Tulane is in New Orleans — a city with tremendous diversity of cultures and community. Tulane is actively building a campus culture based on values of equity, diversity, inclusion and anti-racism. Tulane University is an Equal Employment Opportunity/ Affirmative Action (EEO/AA) employer committed to maintaining a non-discriminatory, diverse work and learning environment. Tulane does not discriminate on the basis of race, color, sex, religion, national origin, age, disability, genetic information, sexual orientation, gender identity, gender expression, pregnancy, marital status, military status, veteran status (or any other classification protected by applicable law) in any of its programs, activities, or employment. This policy applies to all terms and conditions of employment, including recruiting, hiring, placement, promotion, termination, layoff, recall, transfer, leaves of absence, compensation, and training. For more information on this policy and its purpose, please read the Equal Opportunity/Anti-Discrimination Policy. Further information about the department and university can be obtained at http://tulane.edu/sse/eens. Tulane University is an EEO/ADA/AA employer.

Earth Sciences

TENURE TRACK ASSISTANT PROFESSOR IN PALEOCLIMATOLOGY

The Department of Earth Sciences in the School of Ocean and Earth Science and Technology (SOEST), University of Hawai'i at Mānoa seeks to fill a faculty position at the level of **Assistant Professor in the area of paleoclimatology**. We are interested in an individual who develops records of climate variability and change that enhance our understanding of past, present and future climate change and improves projections from climate simulations. Candidates are encouraged to describe how their scholarly activities address recent climate change, potential mitigation strategies, coupled human and natural systems or other societal implications of their work. The successful candidate will have opportunities for expanding interdisciplinary links within the department as well as across campus. The successful applicant is expected to establish an externally funded and internationally recognized research program, enthusiastically contribute to graduate and undergraduate advising and teaching, and carry out professional service activities. Preference will be given to an individual whose research focuses on the water cycle and implications for forecasting water resources, on interconnections across terrestrial and marine environments, paleoclimate perspectives on climate dynamics and natural variability, and/or the detection of climate hazards and ecological change. We are particularly interested in an individual who will teach courses in environmental Earth science topics. The ideal candidate will build synergies across SOEST and with other units across the UH Mānoa Campus, and work with local and state community organizations and agencies. Desire and ability to engage with faculty, staff, and students in a collaborative fashion that supports Indigenous values and perspectives, as well as diversity and inclusivity, is essential. We expect this candidate will contribute to the University's mission of becoming a Native Hawaiian place of learning (**https://manoa.hawaii.edu/nhpol/**).

The Department of Earth Sciences (**http://www.soest.hawaii.edu/earthsciences/**) is one of thirteen research units and four academic departments within SOEST (**https://www.soest.hawaii.edu/soestwp/**), a world-class research and academic institution focused on informing solutions to some of the world's most vexing problems. The Department has 21 tenured or tenure-track faculty as well as 28 additional cooperating graduate faculty in the Hawai'i Institute of Geophysics and Planetology (**https://www.higp.hawaii.edu/**). Together these faculty instruct and advise approximately 60 graduate students and over 100 undergraduate majors.

The University of Hawai'i at Mānoa is one of 115 Research-1 Universities in the country, and is one of only a handful of land-, sea-, space-, and sun-grant institutions. It is a world leader in Earth and environmental sciences, consistently ranked among the top 15 universities internationally in these disciplines. UH Mānoa is proud of its diverse, multiethnic heritage. Located in Hawai'i's capital city of Honolulu at the crossroads of the Pacific, the campus is home to students, faculty and staff from Hawai'i, the continental U.S., and more than 100 countries around the world. UH Mānoa's programs often rank among the nation's most diverse. We seek applicants who will embrace this diversity, and welcome candidates whose professional or personal perspectives will enrich the communities within the University, SOEST, and the Department, as well as the public we serve.

Applications must be filed online at: **https://www.governmentjobs.com/careers/hawaiiedu** Search for position title: **Assistant Professor (Paleoclimatology)** or the **position number 82011**. Click on the "Apply" button on the top right corner of the screen and attach the required documents described below. Note: if this is your first time using NEOGOV, you will need to create an account. Applicants must compile a single PDF file containing six parts, in this order, **(1)** a one-page cover letter; **(2)** a statement describing your research interests, your accomplishments to date, and your future research plans; **(3)** a statement describing experiences in, and approaches to, teaching and mentoring students; **(4)** a statement describing your experiences in contributing to diversity, equity and inclusion, and plans to foster an inclusive environment in your teaching and mentoring; the statement must also include plans for contributing to the University's mission of becoming a Native Hawaiian place of learning; **(5)** a curriculum vitae with a publication list, and record of research funding if applicable; **(6)** the names and contact information of no more than three individuals willing to provide professional reference letters. Items (2)-(4) should not exceed six pages total. Official transcripts will be required upon hire. For full details of the duties, minimum and desirable qualifications, and how to apply, please search for the position title: **Assistant Professor (Paleoclimatology) at https://www.governmentjobs.com/careers/hawaiiedu**

Review of application will begin **January 8, 2024**. Applications received after this date may be considered. Additional questions about this faculty position can be addressed to Prof. Brian N. Popp (**popp@hawaii.edu**).

The University of Hawai'i is an Equal Opportunity/Affirmative Action Institution..

PRINCETON UNIVERSITY

TRAINING MACHINE LEARNED PARAMETERIZATIONS OF SUBGRID SCALE PROCESSES USING OCEAN DATA ASSIMILATION

DESCRIPTION

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), seeks a postdoctoral or more senior research scientist to conduct research on developing and using machine learned parameterizations developed from ocean-data assimilation increments.

The goal is to develop parameterizations of unresolved processes that will improve ocean circulation models. A neural network has already been demonstrated to model the misfit between the ocean model and observations. The new research will involve training a new machine-learned model to represent some missing physics contained within this dataset, interpret the new model, implement it as a parameterization in a global circulation model (MOM6), and evaluate the new parameterization within a global-scale climate model.

The work is part of a larger project, M2LInES, covering eleven institutions. The overall goal is to reduce climate model biases at the air-sea/ice interface by improving subgrid physics in the ocean, sea ice and atmosphere components of existing coarse (¼° to 1°) resolution IPCC-class climate models, and their coupling, using machine learning. This part of the research at Princeton University/GFDL will involve working with the SPEAR ocean data assimilation system and the MOM6 ocean circulation model. The prognostic parameterizations will be state-dependent and trained to minimize model-observation misfits with the aim of reducing inherent biases in free-running climate simulations. The research will require analysis and interpretation of model output, the management of large datasets and the application of neural nets or other machine learning techniques to those data. The postdoc will be expected to collaborate with other postdocs at Princeton and with other members of the M2LInES project across multiple institutions.

QUALIFICATIONS

In addition to a quantitative background, the selected candidates will ideally have one or more of the following attributes: a) a background in physical oceanography, or machine learning, or a closely related field; b) experience with ocean-circulation or climate models, or ocean data-assimilation systems; and c) experience, or demonstrated interest, in machine learning.

Candidates must have a Ph.D. and preferably in oceanography, geophysical fluid dynamics, computer science, or a closely related field. The initial appointment is for one year with the possibility of a second-year renewal subject to satisfactory performance and available funding.

APPLICATION INSTRUCTIONS

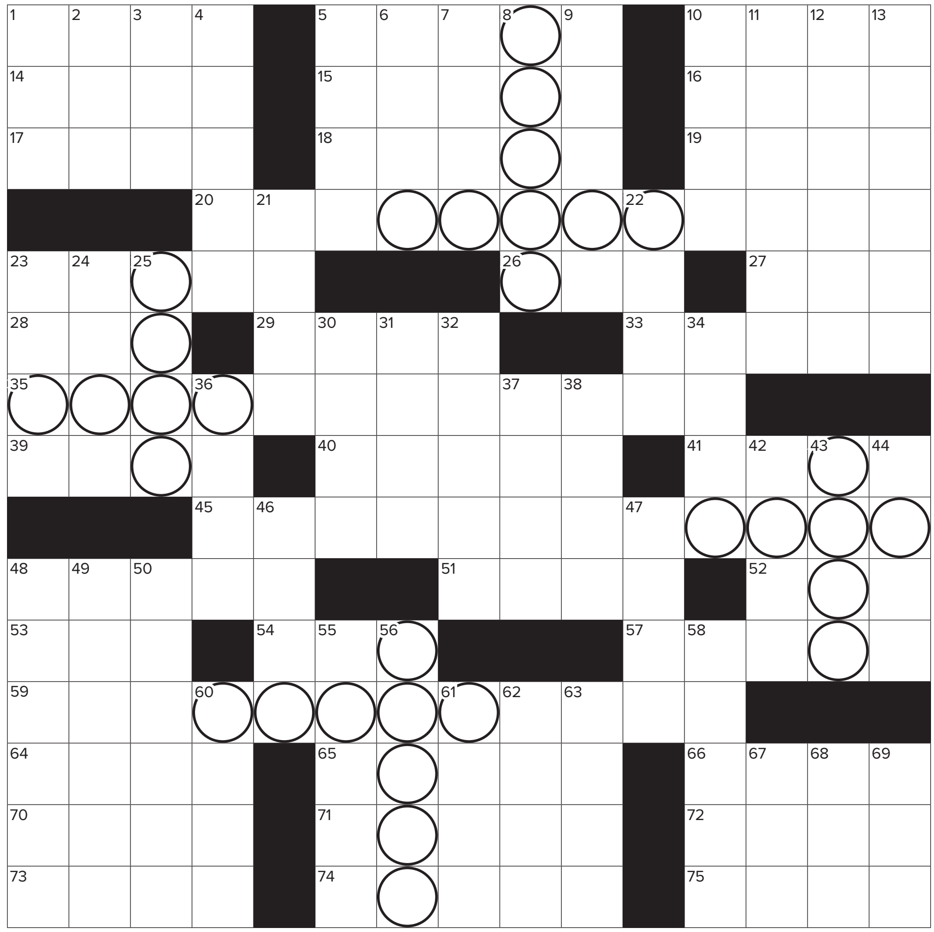
Complete applications, including a cover letter, CV, publication list, research statement (no more than 2 pages incl. references), and 3 letters of recommendation should be submitted by December 22, 2023, 11:59 pm EST for full consideration.

https://findajob.agu.org/job/8023109/training-machine-learned-parameterizations-of-subgrid-scale-processes-using-ocean-data-assimilation/

Sounds Like Fun

By Russ Colson, Minnesota State University Moorhead

Letters that appear in circles will spell out words related to the puzzle's theme: sound and audio.



ACROSS

1 Counterpart to sciences
5 Carve, more commonly ending with "t"
10 Moose, mule, and roe
14 Survivor of climate catastrophe in the Bible
15 Traditional transportation of the Minnesota Anishinaabe
16 Start for pendent or cent
17 Common way to order food (2 words)
18 Neither dead nor inanimate
19 What bad guys do to throats?
20 One thing that infrasonic waves can reveal about the stratosphere (2 words)
23 Hit the 4th note of the scale (solfège) at the 14th letter of the alphabet? or a mix-up of Martinique's most famous anti-colonialist philosopher
26 Div. funding environmental biology within the <38 down> grant programs
27 Absorb (with "up")
28 King or mode (2 words)
29 Alternative to visual or written
33 "In addition to" in Paris, "outlandish" in New York
35 Pathway through which waves can travel a great distance due to back and forth refraction near the thermocline (2 words)
39 Program or certificate preparing Engl. instructors for non-native speakers
40 What one does with justice (with "out")
41 Org. that Finland joined in 2023
45 One thing that echo soundings can reveal about the ocean (3 words)
48 Like happy hearts or hearths
51 Climate-influencing cycle, abbr.
52 Is, when past
53 Hawaiian staple made from taro root
54 Scottish urge, or an aggressive ending for "ass"
57 Charmingly dated
59 One thing that ocean-based seismic reflections can reveal (by detecting sediment layers) that informs us about prehistoric climate change (3 words)
64 Not a bass
65 Escape through cunning
66 Either something that holds tightly or something to let go of
70 Reclines
71 Margin
72 Type of fist?
73 Key component of telescopes and magnifying glasses
74 Stream channel that, with climate change, becomes a ridge
75 Between silt and gravel

DOWN

1 Member of a superorganism?
2 Hopper with a pocket, for short
3 Children's playground game
4 Revealed
5 CT or ultrasound
6 Beginning for "era" that makes a volcanic word
7 Inst. of higher learning
8 Adored
9 Oscar-winning writer and director Jordan
10 Kind of golf
11 Sign up. The mix-up with 50 down offers a hint for the circled letters
12 Word wrangler?
13 Enter text again
21 Non-C material, abbr., or "Are you ____ ____ out?"
22 Woodwind
23 Refrain from eating
24 Subtropical succulent
25 Foolish bumblers
30 Cops between AK and ME
31 Thermodynamic counterpart to work, with letters mixed in the style of this puzzle
32 Machine to turn wood
34 Arm bone
36 Ecologist and Sand County Almanac author Leopold
37 Noble gas
38 Belonging to a prominent granting agency, as in "The ____ mission is to advance the progress of science"
42 Like a wrestler ready for a match, abbr.
43 What one might shed
44 Approximately (2 words)
46 Girls with wool coats
47 Was dressed in
48 Disgust
49 Position on a soccer team
50 When you can't look into Earth's mysteries, you can ____. The mix-up with 11 down offers a hint for the circled letters
55 Superhero movie actor Christopher
56 Stories
58 "Love Me Tender" singer
60 Discard
61 What monsters do under the bed
62 Margin
63 Meteorological counterpart to "back" (wind direction change)
67 Investment option (abbr.)
68 Scam
69 This is it for this puzzle

See p. 14 for the answer key.