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# Eos

SCIENCE NEWS BY AGU

Fossil Rivers of the Green Sahara

A Chip off the Old Moon

How Armero Changed Volcanology

# A SEA OF POSSIBILITIES

*How we're rethinking our relationship with the ocean*

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# Science Off the Seashore

In January 2021, the United Nations launched the Decade of Ocean Science for Sustainable Development. The initiative encourages partner nations to fund scientific research that "achieves the ocean we want by 2030." Calls have gone out, proposals are being pitched, and here at *Eos* we very much look forward to seeing this global coalition work toward the seven goals the United Nations has outlined. (Read more at oceandecade.org.)

Inspired by this movement, *Eos* dedicates this issue—and one issue each year through 2030—to the study of the ocean and our relationship with it. We start our decade-long watch on page 22 with a ship that's tied to a 402-year-old event. The *Mayflower Autonomous Ship*, or *MAS*, is the futuristic namesake of the original *Mayflower*, which set sail from Plymouth, England, in 1620. *MAS* will retrace that voyage later this year, guided by an artificial intelligence (AI) captain, as a technology showcase of how we might study the expansive ocean without having to send humans sailing over every inch of it.

Next, we report on a bright idea that can't seem to get off the ground, or perhaps I should say, up from the deep sea. Ocean thermal energy conversion is a fairly simple concept that could help island nations find independence from fossil fuels, but it's suffering from the "innovation valley of death." Read more about the potential of this ocean-based power source (p. 28) and, if you have a few billion lying around, perhaps give someone on the island of Kumejima a call?

We end our feature reporting with an ominously ticking clock. The deep-sea mining industry is impatiently waiting for international regulators to take the leash off so they can begin collection of the rare earth elements waiting on the floor of the Clarion-Clipperton Zone in the Pacific. We report on page 36 on the stakes that are all going to become clear in less than 2 years—for the ocean ecosystems, for the investors in deep-sea mining, and for the renewable energy tech that currently depends on these resources.

I also urge you to take a look at Jeremy Bassis's excellent Opinion on page 19, "Quit Worrying About Uncertainty in Sea Level Projects." Bassis offers an eloquent explainer on how climate scientists can refocus the way they communicate their research to be of better use to policymakers.

Thanks once again to our friend Russ Colson, who brings us a sea-themed crossword puzzle to close the issue. See you next month!

Heather

**Heather Goss,** Editor in Chief



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Randy Fiser, Executive Director/CEO

# CONTENT



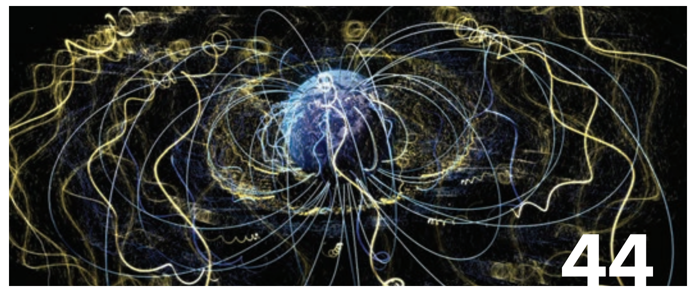

## Features



### On the Cover

A view of the seafloor and an island in the Maldives.
Credit: Ishan @seefromthesky/Unsplash




## Columns



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# Ancient Fish Thrived During a Period of Rapid Global Warming

About 55 million years ago, Earth's climate underwent a rapid and intense period of warming, both on land and at sea. Temperatures soared by more than 5°C, and even Arctic seas turned tropical. Reconstructing this warm era, the Paleocene-Eocene Thermal Maximum (PETM), provides a glimpse into Earth's possible future. "One of the best tools we have to understand how the [ocean] system responds is to look at past instances of global change," said Elizabeth Sibert, a paleoceanographer and paleoecologist at the Yale Institute for Biospheric Studies.

By examining fossil evidence from the PETM preserved in marine sediment cores, Sibert and her colleagues sought to understand how fish might respond to warming oceans. Contrary to the predictions of many models, they found that fish actually grew more abundant as temperatures soared. Sibert and her team presented their research at AGU's Fall Meeting 2021 (bit.ly/fish-resilience).

## Oceans of the Past

When marine fish die, either they sink to the depths of the sea and decompose, or they are eaten by other marine life and expelled through fecal matter. In either case, corrosion-resistant teeth and scales settle onto the seafloor and accumulate in sediments. Layers of these sediments build up over millions of years, preserving records of fish abundance and diversity over time for scientists to decipher.

Sibert and her team examined sediment records in three different cores collected by the Ocean Drilling Program. The drill sites spanned tropical reaches of the north central Pacific, eastern equatorial Pacific, and Atlantic oceans. The researchers filtered microscopic fish scales and teeth from varying depths of the sediment core, counting and sorting them for a window into past ocean life during the PETM.

"This is the first time we have an idea of what mid to upper trophic level groups were doing during this warming event," said team member Richard Norris, a paleobiologist at the Scripps Institution of Oceanography. "Previously, almost all studies of the PETM have been based upon unicellular plankton or microzooplankton."

The results paint a consistent picture of the past across all three samples: Fish became more abundant as temperatures climbed, then gradually decreased again as the warming waned. Plus, the various fish types didn't change much during this temperature flux. "It's really surprising," said Norris. "You'd think that as things warm up you might get a really different community of fishes."

## An Imperfect Proxy

These results are notably different from what current fisheries models predict as Earth faces another period of rapid warming. These alternate predictions could arise from a difference in timescales, the researchers noted. For example, forecasting models often look at decades to a century, whereas sediment records offer glimpses of change over hundreds to thousands of years.

Despite this mismatch, "there's increasing evidence that in past warm periods in Earth's history, biological production actually went up in the ocean," said Norris. Models that predict a dip in fish populations as the seas heat up may very well be accurate, but evidence suggests that will flip in the long term, he said.

Still, Sibert urged caution when comparing fish outcomes during the PETM and what might happen this century—and beyond. "The rate of warming…can have dramatic and differential impacts on marine ecosystems," she noted.

Modern seas face a myriad of challenges beyond rising temperatures, including overfishing and pollution. Therefore, we may need to look to more recent history for an analogue for the modern ocean, said Chris Free, an ecologist at the University of California, Santa Barbara who was not involved in the research. "To prepare coastal communities, livelihoods, and food systems for climate change, we need to have realistic expectations for likely impacts. Recent history may provide a more instructive road map for the challenges ahead," he said.

> **"There's increasing evidence that in past warm periods in Earth's history, biological production actually went up in the ocean."**

Sibert and her fellow researchers plan to expand the study with additional sediment records from environments beyond tropical regions to better understand whether their results represent a global phenomenon during the PETM. They will also continue to refine their research by further accounting for variation in sedimentation rates and density to increase their confidence in the results. But their preliminary findings are hopeful, at least in the long term, Sibert said: "Fish may be more resilient to global change than previously thought."

By **Elyse DeFranco** (@elyse_defranco), Science Writer

# Hundreds of Volcanic Explosions Detected Underwater at Kīlauea

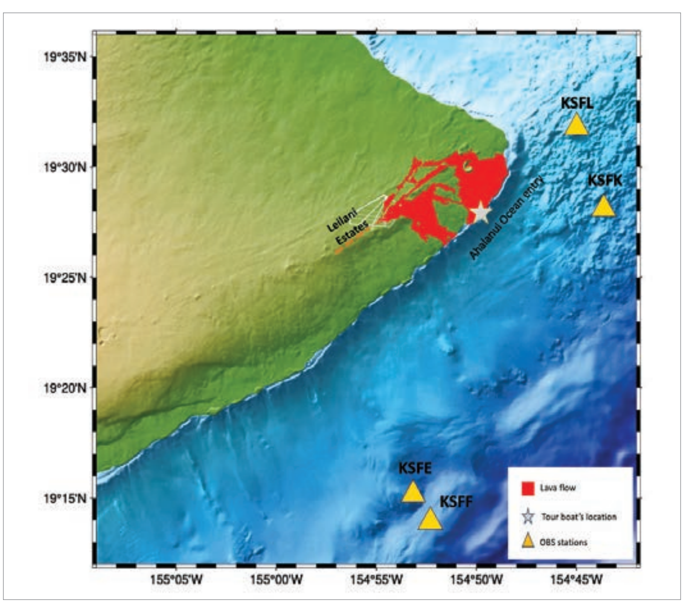
On 16 July 2018, a lava bomb from the Kīlauea volcano tore through the roof of a tour boat just off the Big Island of Hawaii. Sightseers on board described blobs of molten rock smashing into the boat out of nowhere—injuring 23 passengers and breaking a woman's leg.

Now scientists have collaborated with those on the boat to pinpoint the acoustic fingerprint of lava explosions. The finding helped researchers identify hundreds of blasts in the area that year.

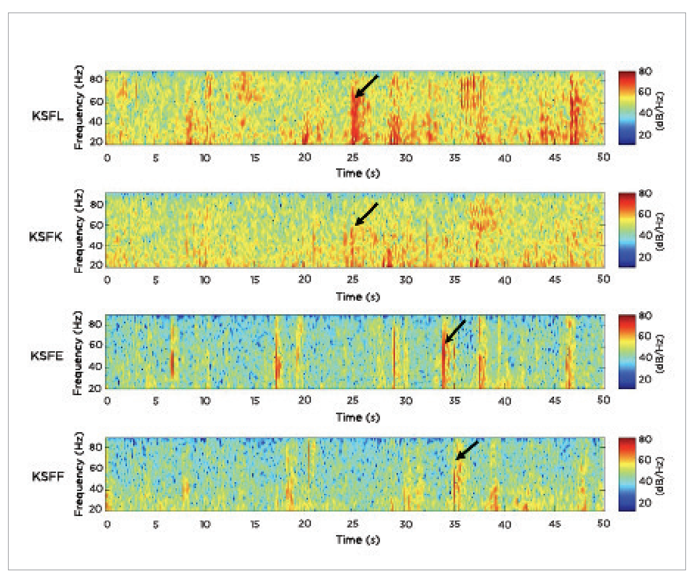
Shortly after Kīlauea entered a new eruptive phase in May 2018, geophysicist Yang Shen and his collaborators installed ocean bottom instruments at 11 locations near the southeastern flank of the volcano. The sensors, placed between 700 and 5,000 meters deep, recorded underwater signals from earthquakes and the outpouring of lava into the sea.

Lava-water explosions in the ocean are steam-driven blasts that in some instances shoot blobs of lava hundreds of meters into the air. These outbursts, called lava bombs, have unique underwater sound signatures, too. "It's very different from earthquakes or submarine landslides," said Shen, a professor

*Lava from Kīlauea formed a small new island on 13 July 2018 (left). A molten lava bomb burst through the roof of a Lava Ocean Tours boat (right) 3 days later while tourists watched the lava. Credit: Hawaii Department of Land and Natural Resources (left), HVO (right)*




*A map of the southeastern flank of Kīlauea volcano on Hawaii's Big Island. Red lines trace the flow of the lava as it met the sea, the gray star shows the location of the tour boat that was struck, and the yellow triangles are the underwater hydrophones placed by the researchers. Credit: Puja Banerjee and Yang Shen*




*The lava bomb that hit the tour boat showed up in spectrograms of ocean noise on 16 July 2018. The spectrogram describes the changes in frequency in hertz over 50 seconds. Arrows denote the explosion at four different hydrophones underwater near the volcano. The sound waves arrived at slightly different times depending on the sensors' location. Credit: Puja Banerjee and Yang Shen*

Opposite: Sebastian Pena Lambarri/Unsplash of oceanography at the University of Rhode Island (URI).

Using time and location data from photographs taken on the tour boat, URI Ph.D. student Puja Banerjee determined the acoustic fingerprint of the 16 July lava bomb using four underwater microphones, or hydrophones. She then combed through the acoustic data from that summer and found that from early July to early August, when the eruption ended, there were at least 644 lava explosions in the area. She presented the research, which has not yet been peer reviewed, at AGU's Fall Meeting 2021 (bit.ly/lava-bombs).

The work "has important implications for mitigating future volcanic hazards," said Robert Dziak, an acoustics scientist at NOAA's Pacific Marine Environmental Laboratory who wasn't involved in the research. The study reveals a hot spot along the coastline where the highest number of hydrovolcanic explosions occurred.

Particles ejected from volcanoes can range in size from dust and ash (millimeters) to lapilli ("little stones" of several centimeters) to bombs (6 centimeters to several meters).

Lava explosions don't always shoot lava into the air, but when they do, the result can be deadly. In 1992, one person was killed and three others were seriously injured when lava bombs exploded from Mount Marapi in Indonesia. In Hawaii in 2018, a bowling ball–sized lava bomb hit a man on the leg outside his home.

Eruptions on land can launch lava bombs, too. The explosions are caused by dissolved gas or vapor in lava that comes out of solution and forms bubbles that then explode.

More than 80% of volcanic eruptions occur in the ocean, said Shen. "We might be able to use those natural acoustic signals to study how acoustic waves propagate in the ocean."

Scientists could use the relationship between acoustic wave speed and seawater temperature to study how climate change is affecting ocean waters, said Yang. The short, clear sound bursts from lava-water explosions may be easier to decipher than the more complex acoustic signals from underwater earthquakes.

Previous research has suggested that sound from lava-water explosions travels far: Hydrophones placed more than 5,000 kilometers from Kīlauea recorded explosions, according to a 2001 study.

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

# Scientists Plan a Home Away from Home for Mars Samples

Perseverance has barely started its rock hounding on Mars, but scientists are already planning how to handle the rover's samples when they're dispatched to Earth. They're pondering how to keep the samples safe from Earth and Earth safe from the samples while making them accessible to researchers for decades to come.

The potential for life on Mars "is a twofold thing," said Carl Agee, director of the Institute of Meteoritics at the University of New Mexico and a member of an advisory committee that reviewed requirements for a possible Mars sample facility. "It's the major science driver for a sample return mission, the major science motivator. But it's also a major hurdle that has to be overcome. You have to protect Earth from potential microscopic organisms, but you also have to prevent contamination in the samples so you don't have any confusion if they have evidence of life."

Perseverance, which has trundled through Jezero crater since February, is the first half of a possible two-step Mars Sample Return (MSR) mission. It will collect almost 40 core samples, each about the size of a stick of chalk, in titanium tubes, which will be sealed tightly. The rover will deposit the samples for collection by a second rover, which is under development by the European Space Agency (ESA). The retrieval rover will load the samples inside a small rocket, which will ferry them to a Mars orbiter for the trip to Earth. (NASA hasn't given formal approval for the return mission, although it is expected to do so, with launch targeted before 2030.)

NASA and ESA still have to work out the details on a receiving and curation laboratory for the samples, including its size, the scientific gear it will contain, its location, and even whether they might want more than one facility. But the advisory committee, MSR Science Planning Group Phase 2 (MSPG2, some of whose findings were presented at AGU's Fall Meeting 2021), and experts within both agencies have outlined the basic challenges and requirements (bit.ly/mars-sample).

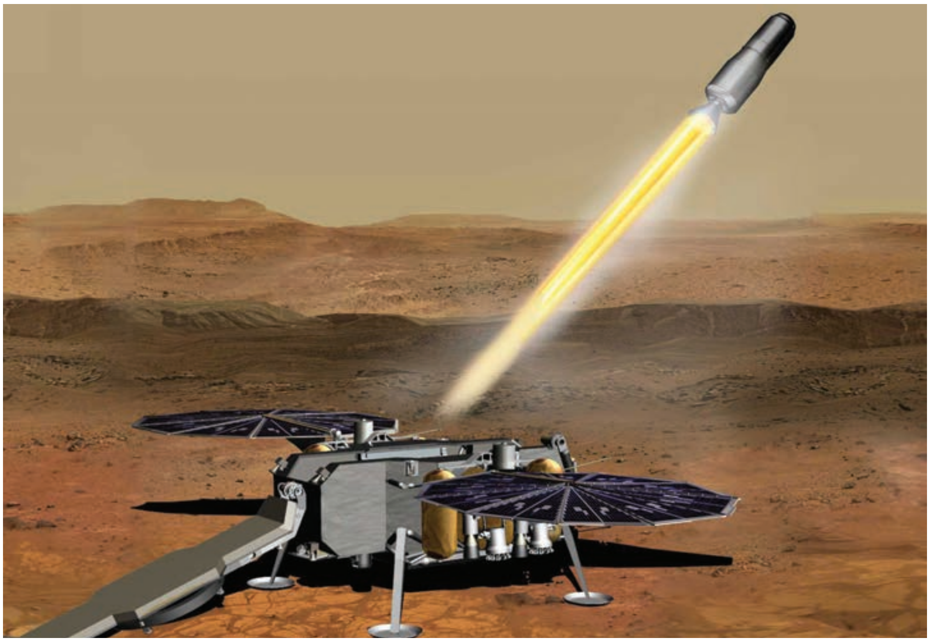
### Protecting Earth from Mars

The key requirements are to evaluate whether the samples contain any living organisms and, if so, to keep them locked safely away, preventing any possible contagion.

"The chances they will contain extant life are extremely low," said Andrea Harrington, Mars sample curator at Johnson Space Center. "If we find something, it's more likely to be extinct. But we're taking a very careful approach. We'll protect Earth from the samples."

Initially, the samples will be stored and handled in a biosafety level 4 facility, which provides the highest level of protection against releasing dangerous agents into the environment. The air pressure will be lower inside the facility, ensuring that nothing accidentally

*Perseverance is shown here next to Rochette, the rock from which it extracted the first two samples for possible return to Earth. Credit: NASA/JPL-Caltech/MSSS*



*This artist's conception shows an ascent vehicle carrying samples collected by Perseverance as it heads toward a rendezvous with the Earth return craft in orbit around Mars. Credit: NASA/JPL-Caltech*

flows out. Samples will be stored and evaluated in sterilized cabinets made from special materials and filled with nitrogen or other gases, and planners are considering fully robotic systems for handling the samples.

Once they are proven to be free of Martian bugs, the samples will be moved to less restrictive quarters, where the emphasis will be on protecting them from Earthly contamination. "We want to protect them from humidity, dirt, microbes, fungus, people with grubby fingers—you name it," said Agee. "They'll be kept extremely clean and pristine."

### On to the Science

Most of the detailed scientific work will be performed by individual scientists at their own laboratories, so the initial evaluations at the sample return facility will be designed to prevent altering or contaminating the samples in any way.

"The first step will be a basic characterization," said Kim Tait, senior curator of minerals at the Royal Ontario Museum in Toronto and a member of both MSPG2 and its predecessor, MSPG1. "The material will be weighed, photographed—we'll have eyes on to determine what kinds of rocks they are. We'll already have some of that since the rover is scrutinizing the rocks and gathering a lot of field information."

Initial analysis might include extracting some of the Martian atmosphere from the core tubes, conducting X-ray tomography or computed tomography (CT) scans to get an idea of what's inside the tubes, taking microscopic images of the samples, and other tests. "Technology is evolving quickly, so the instruments we propose today might be completely different in 10 years anyway," said Tait. "What we really want to get down is the types of information that people will want to extract from the samples."

**"You have to protect Earth from potential microscopic organisms, but you also have to prevent contamination in the samples so you don't have any confusion if they have evidence of life."**

"The main purpose is to describe the samples to the extent needed so scientists know what to ask for," said Agee, who worked more than 2 decades ago at NASA's lunar samples facility, where he studied concepts for a Mars sample lab to support an earlier mission concept. "It's like a library book. You want to know the title, the author—a few basic things. The point is, we want to have everything accessible to the broader research community as soon as possible."

Once the samples are ready, the facility will dole out tiny amounts of them—milligrams or even micrograms at a time. With the amount of material expected to be returned from Perseverance's excursion, that's enough for researchers to conduct thousands of studies, Tait said. "There will be more than enough material for my lifetime and the lifetimes of many future observers."

### Planning for the Future

Keeping the samples in good shape for those future scientists is another focus of a storage facility. Samples gathered by Apollo astronauts have been stored at Johnson Space Center for almost half a century, with some opened and studied for the first time in just the past few years. A Mars laboratory must be prepared to keep its samples safe and ready for new scientific investigations for a similar span, with some lying untouched for decades.

"We have to be ready for however long people want to continue doing science," said Harrington. "We have to be able to get a lot of science out of the samples beyond the first couple of years. That's the plan."

Planners are looking at the experience of the Apollo curation team to determine what has worked well and what hasn't.

"In the Apollo curation facility, a lot of the best practices have been developed since the 1970s, and a lot of them will be adapted for the Mars samples," said Agee. "A lot of the mistakes have already happened, so we don't have to go through that again."

NASA has initiated a study to determine a specific plan for the Mars sample facility, which will take several years to build and test. The agency is considering everything from renting a relatively small facility to building a larger new one, with a ready-to-receive date of 2031 or 2033.

"This is still very much a work in progress," said Harrington. "We're still making decisions and identifying benefits and drawbacks of different implementation strategies. But we're starting to narrow our focus. And I have no doubt we'll be ready for it."

By **Damond Benningfield,** Science Writer

# Bright Lights, Big Cities Attract Migratory Birds

Like moths to a lamp, billions of birds flock to brightly lighted urban areas—far from the natural resources they need on their journeys—as they migrate across North America during spring and fall. Light pollution is attracting migratory birds.

"It almost acts as a beacon to them, and they gravitate toward it," said Amy Collins, a postdoctoral research fellow in fish, wildlife, and conservation biology at Colorado State University.

As these avian species fly over urban sprawl, they waste precious energy navigating urban environments and are most affected during dusk and dawn, when most migratory birds usually take flight.

Although experts already knew that noise and light pollution can affect bird species, the extent of the intrusion isn't well defined. To provide more answers, Collins and colleagues created a new atlas of stopover locations and migratory hot spots that was presented at AGU's Fall Meeting 2021 (bit.ly/stopover-atlas). The new work shows the extent to which cities affect the travel plans of birds—and the factors driving these stopover decisions.

"Urban life can be disorienting for migrating birds…and a lot of wildlife is struggling to adapt to that setting," said Danielle Ferraro, a natural resources specialist for the Center for Environmental Management of Military Lands at Colorado State University who was not involved in the study. The new project provides important information to help the preservation of natural areas key to the birds' safe passage.

### Mapping Birds on the Wing

Many natural habitats attract and support migratory birds, including forest cover, corridors along rivers and streams, marshes, ponds, and stretches of vegetation lining bodies of water. Birds gravitate toward forests or forested habitats to rest in protected areas, while riparian corridors provide water and food.

**A heavily lighted area "almost acts as a beacon to [migrating birds], and they gravitate toward it."**

In contrast, light pollution and tall buildings artificially attract migrating flocks, challenging them with high levels of interaction with humans, structures, and roadways.

To shed light on the problem, Collins and her colleagues at Colorado State University combined weather radar data from 2016 to 2020 across 143 locations with environmental models to catch birds on the wing after sunset across the contiguous 48 states. Weather radars, along with data from NASA satellites like Landsat, register the massive densities of thousands of birds taking off during dusk and help predict regional hot spots during the spring and fall migration seasons.

The scope of this project, however, only recently became feasible. "The technology and advances that we've seen with satellite and radar information in the last 20 years have been such that we can now do these kinds of studies," said Collins. "I would say even 5 years ago we probably wouldn't have been able to do this."

**"The technology and advances that we've seen with satellite and radar information in the last 20 years have been such that we can now do these kinds of studies."**

Historically, ornithologists would complete laborious in-person bird surveys in particular migratory locations—a constant logistical challenge for access and staffing. Now the radar and satellite data offer another way to identify migration hot spots to study and protect. "It's a nice complement for all those other forms of data that we've been collecting for years and years," Collins said.

The new data helped show Collins and colleagues the birds' hot spot stopovers. "We're seeing spring hot spots in California, Texas, a bit of the Midwest," she said, "and then in fall, real hot spots in the Midwest." With "aeroecology" becoming more critical as the threats to migratory birds increase, Collins noted, a combination of radar, satellite, and field research seems like a natural next step.

By **Brian Phan** (@PhantasticTides), Science Writer

# Peruvian Farmers Threatened by Water Stress

Agriculture is an important part of city life in Arequipa, Peru, a regional capital that has seen its population grow to nearly a million, from just 160,000 in 1960. People are drawn to the city by financial and social opportunities and because of internal conflict that particularly has affected Peru's rural communities.

Water is supplied to urban farms via a pre-Incan canal network, which distributes water from the Chili River. But as the city has expanded into surrounding rural areas, many farmers are choosing to sell their land to developers.

Researchers noted that as smallholder farmers sell their land, traditional agricultural knowledge may be lost, although the region's growing population means that agriculture itself is expanding into previously arid regions. "There is a real danger that Traditional Knowledge, such as crop rotation and drought adaptation, will be lost and the city will be less resilient," said Abigail Tomasek, a geoengineer at Oregon State University in Corvallis. Tomasek presented findings from her research at AGU's Fall Meeting 2021 in New Orleans (bit.ly/water-imbalance).

Historically, Arequipeños have grown a variety of crops, including potatoes, broccoli, and alfalfa. In recent years, market forces have driven city farmers to focus on monoculture crops such as onions and garlic, which are more profitable but also prone to price crashes and sometimes are more dependent on irrigation. Currently, there is a drive to grow avocados in Arequipa, for instance, which require significant amounts of water to cultivate.

Tomasek is part of a research project, supported by the Arequipa Nexus Institute, investigating water disparities in the Arequipa region. She is particularly concerned about plans to build a new hydroelectric plant in the city's northern outskirts that will flood historic farmland. As a result of the dam, water for Arequipa's city farms would be pumped rather than fed by gravity—leaving farmers more exposed to supply issues.

Environmentalists are also concerned about what effect continued expansion of the Cerro Verde open-pit copper mine, 32 kilometers southwest of Arequipa, might have on the region's water supply. Mine officials said that wastewater is treated to ensure that heavy metals (such as copper, arsenic, and cadmium) don't pollute local water networks.

### Flooding the Desert

Meanwhile, just 88 kilometers west of the city of Arequipa (but still in the Department of Arequipa) is the Majes District, a newer settlement facing its own water stress. Peruvians began moving to this arid area after the Majes-Siguas irrigation project was established in 1983. The project transfers water from the Colca River in the Andean Highlands to the Atacama Desert below, creating a fertile area of roughly 23,000 hectares. In the early days of the project, plots of land (5 hectares each) were sold inexpensively through a lottery system.

**As farmers sell their land, "there is a real danger that Traditional Knowledge, such as crop rotation and drought adaptation, will be lost and the city will be less resilient."**

*Anna Erwin interviews a migrant farmworker at the Majes-Siguas irrigation project in Peru. Credit: Arequipa Nexus Institute*

Majes is officially home to more than 60,000 people, although some estimates put its population as high as 120,000. The year-round water supply ensured by the Majes-Siguas project attracts migrant farmers and farmworkers who previously had limited growing seasons. Many of these farmers hail from Andean Highland communities that historically relied on seasonal meltwaters from glaciers, which are now retreating because of climate change. Many landowners in the region hail from Arequipa and hire farmworkers from Peru's highlands and other cities such as Puno.

"Multiple factors drive people to live in a place like Majes where there is work, where there are better schools. Climate is definitely a factor, but it's not the only one," said Anna Erwin, a social scientist from Purdue University in Indiana who this year will begin a new post at the University of Texas Rio Grande Valley.

To prepare for dry periods, registered landowners store water in reservoirs and take other measures agreed to through an irrigation commission. Migrant farmworkers usually do not have a voice in these commissions; legally, they cannot access water from the irrigation project.

Erwin interviewed migrant farmworkers and a range of other actors in Majes in 2019 as part of the same research project as Tomasek's. In December 2021, Erwin returned to

Majes for a follow-up study, funded by Purdue's Clifford B. Kinley Trust, that also considered the effects of the COVID-19 pandemic on the migrant farming community. She discussed this work at AGU's Fall Meeting 2021 (bit.ly/migrant-water).

"When there is no water, the harvest dries out, everything [dries out], and there is nothing to drink," one migrant farmworker (who preferred to remain anonymous) told Erwin during her research. If water cuts out for even a couple of days, flowering crops like potatoes and peppers can die, and pests can thrive.

**"When there is no water, the harvest dries out, everything [dries out], and there is nothing to drink."**

In these circumstances, migrant farmworkers are often forced to buy water at exorbitant prices. Some resort to stealing water from the irrigation system, which leads to landowners blaming migrants for reductions in the water flow supplying their farms.

### Majes-Siguas II

There are now plans for a public-private partnership to create an additional 38,500-hectare irrigation zone dubbed Majes-Siguas II. Individual plots will be significantly larger than in Majes-Siguas I, so it will likely attract bigger business.

In an upcoming research paper, Erwin and co-researchers describe how migrant communities currently self-organize to pool water resources and obtain electricity supplies. The team recommends that these farmers be included in existing water organizations to strengthen resilience.

Jorge Delgado Ochoa, a psychologist and sustainable development consultant based in Cusco, said that baseline water use studies (such as those from Tomasek and Erwin) can inform interventions to support Peru's rural communities. "Peru is famous for its geographical diversity and resources, so it is relevant to find a middle point to keep traditions but also keep mining operations and electricity generation," he said.

By **James Dacey** (@jamesdacey), Science Writer

# Hostile Workplaces Drive Minorities from the Geosciences

Recruitment efforts have helped even out gender divides and increase the presence of people from minoritized groups in Earth, space, and ecological sciences (ESE), but hostile workplace conditions and the persistence of discriminatory, sexist, ableist, and racist behaviors continue to damage retention rates, a new survey has found.

"I don't think that many academics and scientific fields acknowledge that retention is also an important factor in increasing diversity in STEM," said Emily Diaz-Vallejo, a doctoral student in geography at the University of Wisconsin–Madison and lead author of a poster on the findings, which she presented during AGU's Fall Meeting 2021 (bit.ly/hostile-workplace). "If this is not fixed, then diversity in the geosciences may still continue to be what it is."

With 2,489 respondents from scientific memberships and organizations, the survey results showed that people in minoritized groups, including people of color, women, and people with disabilities, had more negative experiences. They also reported an increased desire to leave the field, feeling unsafe, and experiencing low productivity at work as a result of these experiences. Respondents were split among early-career (20%) and later-career (80%) professionals.

"There is this idea that if we get a lot of these minority groups in the recruitment processes, then if they accept to be in the field or in the academy, then we will have more representation," Diaz-Vallejo said.

Yet survey results showed that recruitment alone isn't enough.

Overall, 32% of nonbinary respondents and 22% of women reported receiving disrespectful and derogatory comments in ESE workplaces, and survey data showed a negative correlation between these harmful remarks and respectful workplace environments. Intimidation was reported most often by people with disabilities (12%), who were also the most likely to fear for their physical safety. People of color (7%) were more likely than other groups to experience sabotage or challenges to their expertise; these behaviors were associated with workplaces where workers felt that their opinions were not considered or safe to share. On the whole, people who experienced bullying, sabotage, challenges to expertise, or derogatory remarks were 1.5–2.5 times more likely to consider leaving ESE fields than their peers.

The findings come from the ADVANCEGeo Partnership climate survey and represent one outcome of a 4-year partnership between the Association for Women Geoscientists, Earth Science Women's Network, and AGU to address sexual harassment in ESE. The effort is funded by the National Science Foundation's ADVANCE program and is tasked with developing bystander intervention workshops for academia.

### A Long-Standing Problem

Diaz-Vallejo said that even within STEM, ESE fields have exceptionally low representation despite recruitment efforts. It's a problem that's hardly news to Ebony Omotola McGee, a professor of diversity and STEM (science, technology, engineering, and mathematics) education at Vanderbilt University and the author of *Black, Brown, Bruised: How Racialized STEM Education Stifles Innovation.* She said that the size of the survey and its specificity to the geosciences might be new but that hostile workplaces affecting diversity in STEM was a frustratingly familiar problem—and one that has been centuries in the making. Addressing it, McGee said, requires broader, systemic changes, like questioning the way STEM departments are set up.

"How is STEM functioning within that space? How was it created? Who are the creators?" she asked. "What part of that creation story is foundational to even somebody who walks into our current geoscience classrooms? Who are the faculty? How were they hired? Was there bias in their hiring?"

Still, why is the emphasis on recruitment, as Diaz-Vallejo describes, when hostile workplace environments are directly linked to attrition? McGee said it comes down to systemic bias and widespread structural problems.

"The people who are built in [STEM] are white, male, middle to upper middle class and have been socialized to think that they are somehow neutral, universal, objective, and there's nothing political about what they do—it's not racist," McGee said. "And this ideology, the lack of interrogation of how race and racism may play a role or being minoritized may play a role within that culture, is just simply not done. It's not done despite the nice, glossy diversity statements."

By **Robin Donovan** (@RobinKD), Science Writer

# A Hotter Earth Means Stronger Tornadoes


*To the left of a tornado that formed near Goodland, Kan., on 9 June is a funnel cloud, that also became a tornado. Credit: Matthew Woods*

On 20 May 2013 at 2:56 p.m., a tornado touched down in central Oklahoma. Over the next 40 minutes, it ripped through the towns of Newcastle, Moore, and south Oklahoma City. The storm destroyed dozens of houses and cars, two farms, two elementary schools, a strip mall, and several other buildings as it killed 24 people and injured hundreds.

Climate change is known to affect many types of extreme weather, such as hurricanes, droughts, and floods. But until recently, few studies had addressed whether it will affect tornado outbreaks like the one that decimated central Oklahoma. Matthew Woods, a recent graduate of the University of Illinois at Urbana-Champaign, aimed to fill that gap with his recent research in atmospheric sciences and meteorology.

"Climate change certainly raises the ceiling for future tornadoes, in terms of strength," Woods said. Using a modeling framework that the researchers called pseudo-global warming methodology, he predicted that the frequency of warm-season tornadoes will decrease slightly in the United States, but those that do occur may be stronger. Meanwhile, the cool season is likely to see both more frequent and more intense tornadoes. Woods shared his results at AGU's Fall Meeting 2021 during a poster session (bit.ly/tornado-intensity).

### Studying the Past to Predict the Future

Tornadoes are very localized, which makes them difficult for climatologists to study. Climate models are intended to describe widespread effects, and most consider only points spaced tens or hundreds of kilometers apart, whereas most tornadoes are around 50–100 meters across. "Climate models, they don't explicitly resolve or capture storms because the storms fall between the grid points," Woods said.

Instead, Woods turned to pseudo-global warming methodology, in which researchers model historical weather events over small geographic areas using conditions that mimic what future weather conditions could look like. Woods modeled two historical events: the 20 May 2013 Oklahoma tornado outbreak and a 10 February 2013 outbreak that took place along the U.S. Gulf Coast. Both events involved extremely strong tornadoes capable of inflicting severe damage.

Woods adjusted conditions such as temperature, humidity, wind, and soil moisture to account for changes that are predicted to occur by the 2090s according to five different climate models, then simulated what the Oklahoma and Gulf Coast tornado outbreaks would look like in each scenario. Simulating the spring Oklahoma outbreak suggested that tornado occurrence will decrease by about 15% during the warm season, but tornadoes that do occur are likely to be nearly 100% stronger. Meanwhile, modeling the winter Gulf Coast outbreak told him that the probability of tornado occurrence in the cool season will increase by around 400%, with substantial increases in storm intensity.

Mateusz Taszarek, a researcher of severe thunderstorms from Adam Mickiewicz University in Poland, said that pseudo-global warming methodology complements two approaches that researchers have previously used to study how severe storms (which have the potential to cause tornadoes) will change under future climate conditions. He and other researchers have examined changes in severe storm frequency over the past few decades and have also assessed the potential for future atmospheric conditions to support severe storms.

Results have recapitulated Woods's findings, but Taszarek thinks the locations Woods examined are as important as the seasons. Previous research predicted that tornado frequency will decrease in the Great Plains but increase along the Gulf Coast. Taszarek added that strong winds brought on by the jet stream are likely to further increase tornado frequency along the Gulf Coast during the winter months, the season when the outbreak Woods modeled occurred.

Meteorologist Pieter Groenemeijer from the European Severe Storms Laboratory agreed that Woods's approach is a valuable complement to previous work, but he and Taszarek stressed the need to examine more events. "I think this is actually probably the thing that is most important—that they would simulate more of these historical outbreaks and see if they get a consistent signal," Groenemeijer said.

### Protecting Vulnerable Populations

Taszarek is particularly interested in Woods's model of the Gulf Coast tornado outbreak because it took place in a highly populated region with variable landscapes where it's difficult to see storms approaching. In addition to performing more studies like Woods's, he thinks scientists need to research communication strategies that will help the public appreciate the risks posed by storms. "I think there's a lot of social science that needs to be done," he said.

Woods also worries about the potential for future storms to affect population centers. "The risk in the future is going to likely increase, not only because of climate change, but just because of population growth," he said. "We're making the target bigger."

By **Saima Sidik** (@saimamaysidik), Science Writer

# Earthquakes Ripple Through 3D-Printed Models of Los Angeles

Some of the world's largest cities—including Los Angeles, Mexico City, and Santiago—are located in naturally occurring sedimentary basins. Add in the fact that these cities are prone to earthquakes, and that's potentially a recipe for disaster: Numerical modeling has suggested that ground shaking is amplified within basins.

But such modeling—an oft-used resource for understanding ground motion in sedimentary basins—is often limited in its spatial resolution and is furthermore constrained by the equations it receives as input. Now, to more thoroughly study how seismic waves travel through a sedimentary basin, researchers have conducted a series of seismic experiments using 3D-printed models of the underbelly of Los Angeles. They found that the highest-frequency seismic waves—those that generate sudden changes in acceleration and are therefore the most destructive to buildings—were actually attenuated within the models' basin. That's wholly unpredicted by numerical models, the team noted.

## Trade-Offs to Consider

Sedimentary basins are complex geological structures. They start out as depressions that over time become filled with lower-density material deposited by rivers and landslides. "Imagine a bowl being filled up with stuff," said Chukwuebuka C. Nweke, a civil engineer who works on natural hazards at the University of Southern California in Los Angeles who was not involved in the research.

But reproducing the small-scale details of a sedimentary basin in a numerical model is challenging, said Nweke, given inherent trade-offs between a model's spatial resolution and the computational time required to run it. "We don't want to have our model running for 20 years."

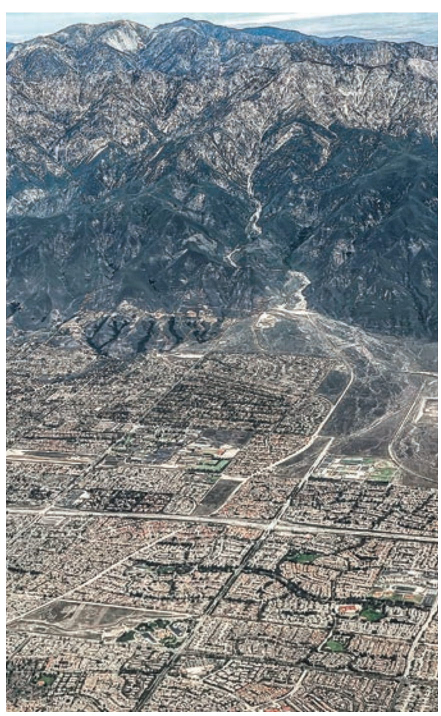
## A Boost in Resolution

For that reason, Sunyoung "Sunny" Park, a seismologist at the University of Chicago, and her colleagues recently began 3D printing models of the Los Angeles basin. Park and her team realized that they could reproduce even relatively small natural variations in density—corresponding to about 10 meters in size in real life—in their 3D-printed models. That's roughly a factor of 10 better than the spatial resolution of a numerical model that's commonly used to study the Los Angeles basin, said Park.

After experimenting with such materials as rubber and plastic, Park and her colleagues settled on stainless steel as their preferred printing medium. That choice was mainly dictated by steel's rigidity, said Park. "If it's rigid, it has a much larger range of material properties."

The researchers printed their models much in the same way that ink is printed on paper: They laid down successive layers of powdered stainless steel and then used a laser to heat and join (sinter) the layers together. By changing the printing parameters—including the speed of the sintering laser and its power—it's possible to control how much pore space remains, said Park. "That's how you can print a variable range of densities."

The models the researchers produced, measuring roughly 20 × 4 × 1 centimeters thick, aren't much to look at from the outside, said Park. But each one captures a range of geological structures within the 50-kilometer-wide Los Angeles basin at a scale of 1:250,000. "It has all these structures within it," said Park.



*To better understand earthquake hazards in the Los Angeles basin, researchers are turning to 3D-printed models. Credit: iStock.com/eyfoto*

## Earthquakes from Lasers

The team members generated extremely tiny earthquakes in their models by bombarding them with megahertz-frequency laser light. The thermal energy of the laser pulses heated the models, resulting in differential stresses that translated into movement, albeit very small: Park and her colleagues recorded ground motion at the top of the models on the order of tenths of nanometers.

**"We don't want to have our model running for 20 years."**

The researchers found that higher frequencies of ground motion in their models—corresponding to real-life frequencies above 1 hertz—were generally reduced within basins. Those waves tended to be selectively reflected back at the edges of a basin, the team showed.

That's a surprise, said Park, because sedimentary basins have long been believed to be amplifiers of ground motion. "[These results] are in some sense opposite of our conventional understanding."

These results were presented at AGU's Fall Meeting 2021 (bit.ly/3D-LA-models).

There's plenty more to investigate using these models, the researchers suggested. One unexpected finding from the scientists' experiments was that their laser pulses triggered not only seismic waves but also airborne waves that skimmed over the models' top surfaces. Because such waves are strongly affected by local topography, logical follow-on work could include adding features like hills and mountains to the models' surfaces and then measuring how the airborne waves propagate, Park said.

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

# Asteroid May Be a Chip off the Old Moon

Near-Earth objects are fragments of rock that orbit the Sun along paths that remain close to Earth. Researchers study these objects to assess their threat level and also to improve our understanding of the solar system. Most of these objects are difficult to measure, but one asteroid, Kamoʻoalewa, maintains a stable orbit and makes a regular pass of Earth every April, opening a window to study this chunk of rock in greater detail.

A team of researchers at the University of Arizona has evaluated spectral data collected over several years and determined that Kamoʻoalewa may actually be a fragment of the Moon. The results of the study were published in *Nature Communications Earth and Environment* (bit.ly/lunar-silicate).

"What was supposed to be a quick one-and-done summer project turned out to be way more interesting," said Benjamin Sharkey, a graduate student in the Lunar and Planetary Laboratory at the University of Arizona and lead author on the paper. "As we keep pushing discoveries to fainter things in different parts of the sky, it is exciting to open new populations [of objects] to characterize," he said. Such analysis allows scientists "to rewind time to explain how the solar system formed and evolved."

*Near-Earth asteroid Kamoʻoalewa, shown here in an artists illustration, might be a lost fragment of the Moon. Credit: Addy Graham/University of Arizona*

**"This would be the first time we have evidence that an asteroid originated in the Earth-Moon system."**

## Analyzing an Oscillating Fragment

The fragment was discovered in 2016 by Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) facilities at Haleakala Observatory in Hawaii. Kamoʻoalewa's name is derived from Hawaiian and means "the oscillating fragment." It is relatively large for a near-Earth object, measuring about 46 meters in diameter, and has followed an orbit similar to Earth's for several centuries. At its closest pass, Kamoʻoalewa travels within 14.5 million kilometers of Earth, more than 37 times the distance between Earth and the Moon. During this limited time, astronomers can make observations on the faint cosmic phantom.

Sharkey and his team gathered data about Kamoʻoalewa using two powerful telescopes in Arizona, the Large Binocular Telescope on Mount Graham and the Lowell Discovery Telescope in Flagstaff. They measured the asteroid's spectrum of electromagnetic radiation to determine its composition.

"We do geology by looking out with telescopes rather than [by] looking down," explained Vishnu Reddy, an associate professor at the Lunar and Planetary Laboratory and a contributing author on the paper.

The team compared Kamoʻoalewa's spectral data to stony and chondrite-rich asteroids and meteorites, as well as to lunar rocks collected during the Apollo 14 mission. Kamoʻoalewa's reflectance spectrum is redder (indicating higher reflectance at increasing wavelength) than either the asteroids or the meteorites, but when Sharkey compared It's data to an Apollo 14 lunar rock, they were a match.

"When I first looked at the data, I thought, this is too good to be true," said Reddy.

But was it?

Reddy encouraged Sharkey to explore every option to explain the spectral data. Reddening, for instance, can be influenced by the angle between a celestial object and the observing telescope. Particle size on the object's surface, the metal content of surface rocks, and the level of space weathering can also contribute to reddening. Sharkey investigated, and none of those options provided an adequate explanation for Kamoʻoalewa's spectral data. A lunar match made the most sense.

## Maybe a Missing Link

"The general understanding is that near-Earth objects evolved from collisions in the main asteroid belt, and then through gravitational resonances their orbits evolved to be near the Earth," said Paul Chodas, manager of the Center for Near-Earth Object Studies at the Jet Propulsion Laboratory in California. Chodas did not participate in this study. "This would be the first time we have evidence that an asteroid originated in the Earth-Moon system."

Reddy, Sharkey, and their colleagues wanted to gather more data to confirm these startling results, but they had to wait 2 years, having lost their opportunity in 2020 because of the pandemic.

Sharkey collected new data in 2021 and they supported the original analysis: Kamoʻoalewa most likely originated on the Moon. How and when it broke free from the lunar surface remain a mystery.

"This could be the missing link between the craters on the Moon and lunar meteorites on Earth," said Reddy. "We need to conduct follow-up studies to explore other objects in the solar system, but it is exciting to see what is to come."

By **Stacy Kish** (@StacyWKish), Science Writer

# A New Technique Could Identify Algae from Space

Algae form the basis for many aquatic food webs, but when certain algae, bacteria, or other tiny photosynthetic organisms start to grow out of control—a phenomenon called an algal bloom—they can cause major problems. Harmful algal blooms (HABs) disrupt ecosystems, negatively affect drinking water supplies, and threaten human health worldwide, costing an estimated $4 billion per year in the United States alone, said Tyler King, a hydrologist at the U.S. Geological Survey's (USGS) Idaho Water Science Center.

Because of the sheer scale of the problem, HABs are difficult to monitor from the ground, so scientists are working on ways to monitor them more effectively from space. Currently, scientists, including those at the U.S. interagency Cyanobacteria Assessment Network (CyAN) project, are working on using satellite images to identify and monitor the spread of algal blooms that involve cyanobacteria, which can be particularly problematic.

**The problem of algal blooms "is going to only increase in significance in the future, because one of the risk factors is elevated water temperatures."**

But there are many, many types of microbes associated with HABs—even the term cyanobacteria encompasses thousands of species—and available technology isn't very good at telling them apart using satellite data. This is important, because although many species are relatively benign (at least in terms of danger to human health), blooms of certain species produce potent toxins that affect the nervous system or liver. Determining whether a bloom is made up of these dangerous species is a key part of creating an effective management plan to protect people from the negative effects of the bloom.

Scientists at USGS, including King, are hard at work on this problem, developing a technique called Spectral Mixture Analysis for Surveillance of Harmful Algal Blooms (SMASH) that they hope will one day allow us to determine the type of microbe in a bloom from satellite images. The scientists presented their research at AGU's Fall Meeting 2021 (bit.ly/habs-inland).

For now, said Carl Legleiter, a hydrologist at the USGS Geomorphology and Sediment Transport Laboratory and one of the scientists working on the SMASH technique, the research is still in the proof-of-concept stage. Currently, he said, researchers are working on creating a spectral library—a set of reflectance characteristics for various microbes, measured using a microscope and a hyperspectral camera. Using this library, along with the reflectance of the water in a lake, they try to identify the best match for an algal bloom in a satellite image. Early successes included identifying blooms of the freshwater cyanobacteria *Microcystis* and *Aphanizomenon* (both of which can produce toxins damaging to human health) in lakes in New York and Oregon, respectively.

Other specialists in remote sensing of algal blooms are also enthusiastic about the technique. "It would be great if you could get more specific about what type of plankton is in the system," said Bridget Seegers, the NASA lead scientist on the CyAN project, who was not involved in developing SMASH.

*Algal blooms, like the one pictured here in Lake Erie, threaten ecosystems and human health. Credit: European Space Agency, CC BY-SA 2.0 (bit.ly/ccbysa2-0)*

## Preparing for the Future

Right now, most satellites aren't capable of gathering the hyperspectral images needed for this kind of analysis. SMASH uses data collected by a device on the International Space Station, which means that the coverage is limited, said Legleiter. But it won't be this way forever. "There are multiple hyperspectral satellites slated for launch in the coming years," he said.

Techniques like SMASH, said Seegers, "are good prep for the kind of satellites that are coming."

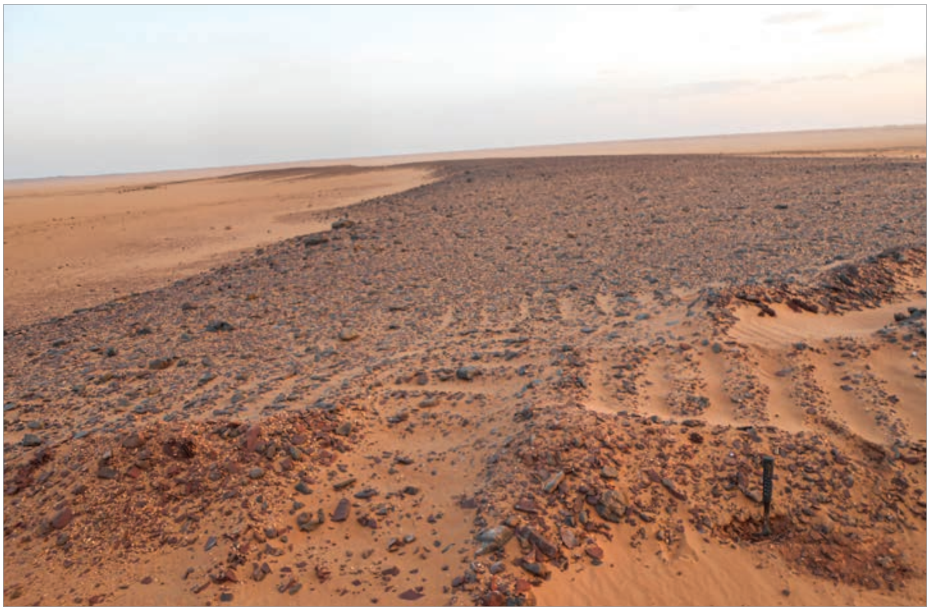
In the meantime, researchers will be busy adding more species to the spectral library and trying out SMASH in more lakes across the United States.

The problem of algal blooms, said Legleiter, "is going to only increase in significance in the future, because one of the risk factors is elevated water temperatures. You may have heard—things are warming up on this planet. And another potential driver is nutrient enrichment from agricultural runoff. So changes in land use and poor soil management practices, those kinds of things, can also be contributors."

Indeed, a 2019 study showed that globally, freshwater blooms have generally become more intense over the past few decades (bit.ly/lake-blooms). Seegers said that currently, efforts are focused on improving our ability to monitor these blooms in near-real time. However, tracking the prevalence of blooms in a specific location over time might enable researchers to identify local changes (like differences in land use or agricultural practices) associated with increased blooms, which could help identify ways to prevent them in the future. The more we understand about harmful algal blooms—which species are involved, the conditions that precipitate them—the better we'll be able to address this global problem.

By **Hannah Thomasy** (@HannahThomasy), Science Writer

# The "Green Sahara" Left Behind Fossil Rivers



*Ancient riverbeds appear as ridges in the modern landscape in southern Egypt and northern Sudan. Credit: Abdallah Zaki*

More than 10,000 years ago, when the Sahara was still green, people living near the Nile migrated hundreds of kilometers from the river's fertile banks.

During this African Humid Period, the frequency of heavy rainfall events rose fourfold, increasing flooding of the Nile. The flooding forced populations to migrate out to rivers that are now extinct—smaller rivers shooting off from the Nile, less prone to such extreme water rises, whose paths line southern Egypt and northern Sudan.

Recently, geologists led by researchers from the University of Geneva (UNIGE) in Switzerland reconstructed the paleohydrology of six fossil rivers distributed across 38,000 square kilometers of the region. Satellite imagery was used to trace and map the rivers from source to sink, and this information was compared with known patterns of human migration in the region.

"We decided to conduct this research because the presence of Acheulean artifacts [hand axes] within one of those rivers suggested their sedimentary record would potentially yield interesting data about humid periods during the middle Pleistocene 800,000 years ago, an important climatic window with links to human expansion 'out of Africa' through the Nile corridor," explained Abdallah Zaki, a Ph.D. researcher in the Department of Earth Sciences at UNIGE and lead author of the study.

## Reconstructing Rivers

To reconstruct the paleohydrology of the entire region, researchers started small—by measuring pebbles.

Coarser clasts and "large pebbles indicate a high water discharge" because only high volumes of water could transport them, explained Sébastien Castelltort, an associate professor at UNIGE and a coauthor of the study.

Geologists also had to determine the surface area of the drainage basin, the area that connects water flowing upstream to the main stem of the river itself. "By combining these figures, we obtain the precipitation rate responsible for transporting the studied sediments," Castelltort explained.

The age of the rivers was calculated using two different techniques. The first was carried out in collaboration with the Swiss Federal Institute of Technology in Zürich using carbon-14 dating of organic matter from the fossil rivers. The second technique was optically stimulated luminescence, which measures the most recent time a quartz sediment was exposed to light. These calculations were made with specialists from the University of Lausanne.

## Human Migrations

"The most significant surprise was to find that the ages of gravel deposits in these rivers clustered in the period of time corresponding to the so-called African Humid Period," said Zaki. "We found that our paleohydraulic estimates indicated rainfall intensities in the range of 55–80 millimeters per hour—3–4 times more than before and after the African Humid Period."

Such extreme conditions seemed to have forced people to abandon the Nile area for 3,000 years, said Zaki. The migration itself is well documented in analyses of archaeological occupation of the Nile Valley during the African Humid Period. The push and pull factors for this migration are debated.

The current "results suggest that the Nile was perhaps not a mere conduit for people fleeing Africa during the middle Pleistocene but also a source of the population that fled away into a greener Sahara during the African Humid Period," Zaki said.

The results were published in *Quaternary Science Reviews* (bit.ly/flooding-nile).

## Documenting "Some Very Wild Rivers"

Reaction to the study has been mixed. "This is an important study, because we knew that there were some very wild rivers in the Sahara during the African Humid Period, but we had until now no estimation of flow rate or rainfall intensity," said Cecile Blanchet, a sedimentologist at the Helmholtz-Centre Potsdam–GFZ German Research Centre for Geosciences who was not involved in the study.

"And these numbers tell us that the tributaries of the Nile that [Zaki and coauthors] studied were under similar rainfall regimes to what we know in the Mediterranean region, prone to generating flash floods. So one can well imagine that people might not deem the Nile banks a nice place to live if they experience flash floods on a regular basis while being surrounded by a lush Sahara," Blanchet said.

If temperature and extreme rainfall events both increase (as forecasted by climate models in the most recent Intergovernmental Panel on Climate Change report), we can envisage the Nile River and its drainage area as a hazardous place to live once again, she continued. Some hints of this change may have been given by the huge flooding in Sudan in 2020, she added.

### Unprecedented Warming

Overall, the study is interesting, as it brings in additional information regarding the African Humid Period, said Francesco S. R. Pausata, director of the master's program in atmospheric science at the University of Quebec in Montreal, who was not involved in the research.

"It's an important study, as it advances our understanding of past human response to climate change," he said. Pausata was surprised, however, at the authors' use of the Clausius-Clapeyron relation in explaining changes in precipitation at the regional scale. Although the Clausius-Clapeyron relation shows that the water-holding capacity of the atmosphere increases by about 7% for every 1°C rise in temperature and may be applied when considering global precipitation, he explained, it is not applicable to changes in rainfall at the regional scale that are, rather, driven by large-scale circulation changes. Therefore, Pausata said, the authors would have benefited from incorporating climate models instead of the Clausius-Clapeyron relation to explain rainfall changes.

Furthermore, "while this study tells a narrative of a multimillennial experiment in human ecodynamics, the sedimentary record cannot be used to infer anything about future climate. What we are experiencing does not have any precedents, and the warming is currently global, while in the African Humid Period it was confined to one hemisphere," Pausata said.

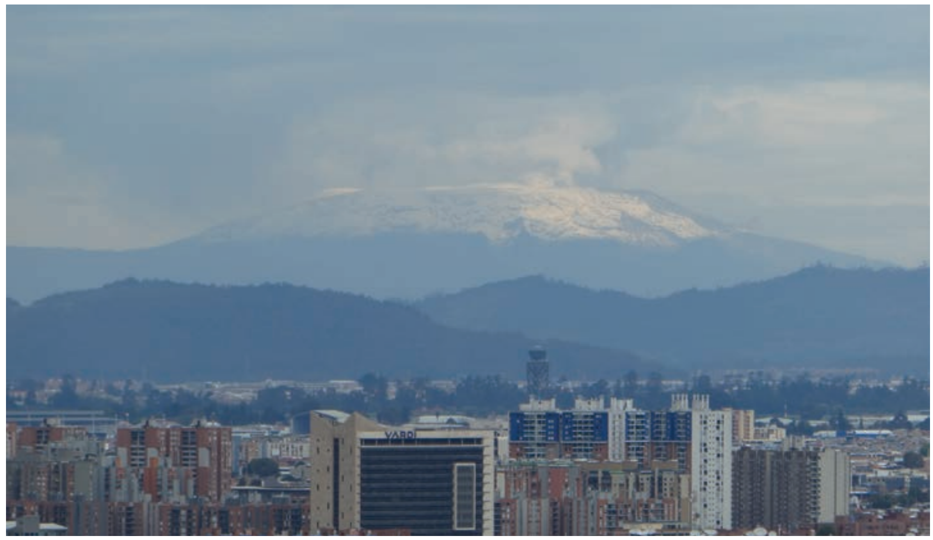
Zaki said this study can be used to illustrate the tangibility of the impact of climate change on populations, as it conveys the risks and challenges associated with global warming.

He does not anticipate similar internal migration from the Nile, however. "Actually, I wouldn't expect a [modern] migration like what happened during the African Humid Period because the Sahara is currently hyperarid with no other water resources in the deep Sahara to sustain life."

Instead, Zaki said, the findings ring true to Richard Pancost's 2007 commentary in *Nature Geoscience* that "the past does not necessarily predict risks associated with climate change but it assures us that they are real" (bit.ly/climate-narratives).

By **Munyaradzi Makoni** (@MunyaWaMakoni), Science Writer

# How the Armero Tragedy Changed Volcanology in Colombia



*The Nevado del Ruiz volcano, seen here on a recent cloudless morning from the western hills of Bogotá, was the site of the worst natural disaster in Colombia's history. Credit: Santiago Flórez*

On 13 November 1985, Nevado del Ruiz volcano erupted, killing more than 25,000 people in Armero—a town of 30,000 inhabitants—making it the worst natural disaster in the history of Colombia.

Marta Lucía Calvache Velasco, technical director of the Colombian Geological Service (SGC), was studying the volcano 1 month before the eruption. She and her colleagues had submitted a report to the Colombian congress describing the geological history of the site and warning of the likelihood of an eruption within the next months or years.

The warnings were mostly ignored. The documentary *El Valle Sin Sombras* (the *Valley Without Shadows*) by Colombian filmmaker Rubén Mendoza compiled the experiences of some survivors. Resident Gabrielina Ferruccio says in the film that when ash started falling on Armero on the eve of the eruption, she went to church to ask for advice; the priest told her to "enjoy this beautiful show; it will never be seen again." Edilma Loiza remembers how at 6:00 p.m., "a fire truck went through town telling everybody to stay at home, to not leave home or panic." The catastrophic lahars (avalanches of volcanically induced landslides and debris flows) occurred 5 hours later.

The second volume of the book *Forecasting and Planning for Volcanic Hazards, Risks, and Disasters* (2020) includes a chapter written by a group of Colombian geologists led by Calvache. They describe how geologists in the country have worked to avoid future disasters by improving monitoring, creating a legal framework, and raising awareness in at-risk populations. The text clarifies how Colombian volcanologists realized that studying natural phenomena was irrelevant if they could not share their knowledge in a way that made policymakers and the public understand the urgency to avoid predictable tragedies.

### Monitoring and Studying Volcanic Hazards

Colombian volcanology grew rapidly and exponentially, thanks to international aid that arrived after the disaster and helped establish a network of observatories. Today 600 stations monitor and investigate 23 active volcanoes. In addition, 14 hazard maps have been produced for local authorities to use. "The fact that there is a volcanic eruption should not be a synonym of disaster," said Calvache. Policymakers and scientists learned that they could protect the nearby communities as long as they understood what was happening geologically.

In June 1989, Nevado del Ruiz had an eruption similar to the one that destroyed Armero. As soon as one of the new monitoring stations detected an increase in seismic activity, SGC started to produce daily updates on the status of the volcano. On 30 August, SGC told the local community that an eruption was imminent and evacuations were necessary.

Just 4 years after the Armero tragedy, when Nevado del Ruiz erupted again, there was no loss of human life.

## Legal Framework

"In 1985, Colombia didn't even have an institution in charge of volcanoes," remembered volcanologist Diego Mauricio Gómez Martínez of SGC. Geologists advocated for the passage of decree 919 of 1989, which created the first legal and institutional framework for risk management in the country. The agency it created, Ingeominas, was put in charge of assessing and preventing volcano risk; in 2012 the agency changed its name to SGC.

The legal framework has brought new and unforeseen problems, as well as ways to address existing ones.

Lucio Figuero, an Indigenous leader who has lived more than 60 years near the Galeras volcano (named *Urkunima* by locals, meaning "mountain of fire" in the Quillasinga language), argued that the risk management strategy has been negative for his community, for example. When the volcano reactivated in 2004, the locality of Mapachico, where Figuero lives, was designated a risk zone. With the new designation, "all possibilities of construction or investment stopped, condemning us to poverty.... The price of land devalued so much that if we sell it, we won't have enough money to move anywhere else," said Figuero.

*Students who live in at-risk zones around Colombia's Azufral volcano attended the Second Volcano Biennial in 2019 with members of the Colombian Red Cross and the country's Civil Defense. Credit: Colombian Geological Service*

Several families from the region brought a lawsuit demanding to be relocated outside the risk area of Galeras, which has erupted 25 times in the past 30 years. After their request was denied by several regional courts, the Colombian Constitutional Court ruled in their favor, arguing that resettlement was necessary because of "the fundamental rights to life and dignified housing."

According to Figuero, studies are being conducted to determine a new hazard map for the region—almost 10 years after the Constitutional Court ruling. He hopes that when the new hazard map is completed, his community will be able to stay in their territory and "learn to live with the *volcan*," although he acknowledged that there is a possibility they will have to be relocated. If that happens, he hopes the government will be able to provide some economic support.


*This map was created by the Colombian Geological Service to teach about volcanic phenomena and risk management. Credit: Colombian Geological Service*

## Raising Awareness in At-Risk Populations

Monitoring and the legal framework are useful tools to prevent disasters. However, Calvache believes that community awareness of volcanic phenomena will ensure that if an eruption occurs, there will be no disaster. SGC has partnered with local universities and schools to produce videos, posters, radio spots, and an online teaching module (bit.ly/SGC-awareness)). "We have to do science that can be shared," said Calvache.

Gómez believes that for the awareness to be effective, "communities need to be able to appropriate scientific knowledge." This belief is the reason Gómez organized the first youth conference in Pasto after a visit to Japan in 2011, where he was inspired by the way risk prevention focused on the experiences of youth living in volcanic regions. He organized an event in which more than 150 children from all over Colombia shared their stories with peers, learned about volcanoes, and studied risk management.

The goal of such projects is to allow local communities to share their experiences and promote volcanic risk management for new generations in Colombia.

By **Santiago Flórez** (@rflorezsantiago), Science Writer, with additional reporting by **Camilo Garzón** (@CamiloAGarzonC), Science Writer

# Roman-Era Millstone and Mixer Makers Knew Their Rocks

*Ancient inhabitants of Volubilis chose stones to fit the functions of their tools. The limestone ring on the left was part of a rotating milling tool, as was the basalt ring on the right that may have ground grain. Credit: Jared Benton*

Thousands of years ago in the Roman city of Volubilis, mills crushed olives or grain and bakeries mixed dough in stone vats. Volubilis, in modern-day Morocco, still bears evidence of these activities today in the form of enormous mixers and millstones that sit on the ancient site's ruins. Now, a study of these stone tools' geochemistry suggests a local source for the stones—and that ancient people knew which rocks were best suited to each task.

Mixers and millstones would have held significance for the people who lived in Volubilis because of their roles in daily life and the economy, said igneous petrologist Derek Weller. "We can actually use them to understand something about the culture," said Weller, who engaged in the study while at the Earthquake Research Institute at the University of Tokyo. He is now at Yachay Tech University in Ecuador.

Weller and his colleagues examined the mineral makeup of samples from 16 millstones and mixing vats from the Roman era, between the 1st and 8th centuries CE, including some collected from areas that once were bakeries, mills, and homes. Some tools were made of limestone, and others were basalt.

## Locally Quarried Basalts

The team focused on the basalt. Basalt is an igneous rock, and the tectonic environment in which magma forms influences basalt's chemical composition, including trace elements that can link a rock to its region of origin. For example, Weller said, volcanic rocks from sites in Sardinia and Sicily have well-known geochemical signatures. Researchers have been able to reconstruct trade routes by sourcing millstones and mixers made from those Mediterranean rocks. But there's been comparatively little work on tools from Volubilis.

The researchers compared ratios of trace elements, such as titanium, niobium, and vanadium, in the Volubilis basalt tools with those of volcanic rocks from places in Europe and the Mediterranean. This ruled out many potential sources but left locales in France, Sicily, and Spain, along with the Middle Atlas mountain range in Morocco. The team then applied an algorithm that compared samples' compositions with ones reported in the literature for those sites. Each Volubilis basalt had a high probability of originating in the Middle Atlas, the researchers reported in the *Journal of Archaeological Science: Reports* (bit.ly/volubilis-basalt).

"The power of this paper is to give a lot of chemical analysis" confirming that the basalts came from the Middle Atlas, said Abdelilah Dekayir, a geologist at Moulay Ismail University in Meknès, Morocco, who was not involved with the new research. Because of the essentially identical compositions of the Volubilis basalt tools, their stone likely came from a single quarry, Weller noted.

Weller and his team were unable to confirm an origin for the limestone tools. Limestones don't carry a geochemical fingerprint as basalts do, Weller said. Previous researchers reported several quarries in the area near Volubilis, which may be the source of these stones, the researchers wrote. But such limestone can be found across northern Africa, and this study doesn't confirm a source near Volubilis, Dekayir said. Isotopic analysis would be more helpful in sourcing these stones and determining whether there were few quarries or many, he added.

Though the Middle Atlas quarries are closer than European sources, bringing the basalts to Volubilis would still have been difficult work. Many of the millstones were large objects—a meter tall and 40–50 centimeters wide, Weller said.

"They must have had a good system of infrastructure to sustain the commercialization of these materials," said Elisabetta Gliozzo, an archaeological scientist at the University of Bari Aldo Moro in Italy who was not part of this study. Ancient people would have used rivers and streets to transport stone, she explained.

**"They must have had a good system of infrastructure to sustain the commercialization of these materials."**

## Fitting Form to Function

For each of the three tool types—millstones for making olive oil, millstones for making flour, and mixers for dough—researchers found that only one stone type was used, suggesting that artisans matched the qualities of each stone to its function. "This tells us that they were very smart," said Gliozzo.

For instance, the impermeability of fossil-poor limestone makes it ideal for blending wet ingredients in a dough, whereas the rough, porous surface of basalt worked well for grinding grain. These people chose exactly what stones they needed to make the right tools for processing a variety of materials, Gliozzo said.

By **Carolyn Wilke** (@CarolynMWilke), Science Writer

# Quit Worrying About Uncertainty in Sea Level Projections

*An ice cliff at Thwaites Glacier towers over the Southern Ocean in West Antarctica. Credit: Rob Larter*

As ice sheets lose mass at increasing rates, scientists are growing increasingly concerned that portions of these massive reservoirs of frozen water are poised to begin irreversibly retreating [*Cornford et al.*, 2015; *DeConto et al.*, 2021]. To adapt to the ensuing changes along shorelines, authorities responsible for coastal planning and climate mitigation efforts need actionable sea level rise projections. However, recent studies using climate and ice sheet models are more often coming to very different conclusions about future rates of sea level rise and even about the sensitivity of ice sheets to future warming [*DeConto et al.*, 2021; *Edwards et al.*, 2021].

How can climate scientists help decisionmakers navigate vague or conflicting information to develop practical response strategies in the face of large uncertainties? One solution that may provide needed clarity is to change our emphasis from what we do not know to what we do know.

Large discrepancies among model projections of long-term sea level rise have spawned calls among the scientific community for scientists to work on reducing uncertainty. However, focusing on uncertainty is a trap we must avoid. Instead, we should focus on the adaptation decisions we can already make on the basis of current models and communicating and building confidence in models for longer-term decisions.

**Planning for shorter-term sea level rise doesn't mean ignoring the specter of more substantial sea level rise farther down the road.**

### The Folly of Focusing on Uncertainty

Emphasizing uncertainty is misguided for two main reasons. First, a growing body of research shows that providing uncertainty estimates to decisionmakers actually decreases the usability of climate projections [*Lemos and Rood*, 2010]. This is partly because it isn't always clear how best to incorporate uncertainty into planning. Do we plan for the most likely projection of sea level rise, knowing the protections we put in place may be inadequate, or do we plan for the most extreme sea level projection despite the additional cost to do so? The planning process is complex, with uncertainty in global sea level projections being just one of many factors decisionmakers must consider. For example, investing in protections against sea levels that won't be experienced for 70 years may not seem pressing when people can't leave their homes because of air quality concerns or can't drink tap water because it is contaminated. Furthermore, future planning and infrastructure decisions must directly confront the inequitable practices that have long disadvantaged vulnerable and marginalized populations.

Second, although models provide a murky picture of the magnitude of sea level rise that will occur by the end of the century, estimates of what will happen in the next few decades are much clearer. This clarity is important, because the most pressing adaptation decisions facing communities now—related to addressing both climate vulnerabilities and historical inequities—primarily reflect needs on decadal, not centennial, timescales. So rather than focusing on distant targets that are elusive and evolving, communities need help to be successful in adapting to near-term climate risks.

Planning for shorter-term sea level rise doesn't mean ignoring the specter of more substantial sea level rise farther down the road, and there is still a need for longer-term climate and sea level projections. For example, adaptation decisions such as where to place infrastructure designed to last more than a century (e.g., new sewer lines) call for information about long-term and short-term change and involve significant immediate costs.

But committing to adaptation measures across the board on the basis of unclear long-term projections is like planning a dinner party years in advance: It's good to think ahead, but it's premature to buy the groceries. Moreover, sea level rise is not like a tsunami that will suddenly inundate coastlines (although it may seem that way when sea level rise conspires with storm surges to flood communities). Rates of sea level rise, even at the extremely high end, are measured in centimeters per year. Given the reality that sea levels will rise in the near term, plans today can focus on changes expected over the next decade or two and can then be adapted as more nebulous longer-term changes come into focus.

### Uncertainty, Confidence, and Skill

Climate and ice sheet model projections increasingly diverge from one another farther in the future—reflecting uncertainty—as physical processes and conditions that we have not observed before occur in climates far different from those we have experienced in modern times. The inherent problem with

**It's thought that under certain conditions, marine ice cliff instability could cause a runaway domino effect of ice loss and rapid sea level rise. However, this process has not been observed in nature.**

this divergence, however, is not the magnitude of the uncertainty but the resulting lack of confidence that the models have the necessary skill to represent the underlying physics responsible for change, especially rapid change.

A common method for estimating uncertainty used by climate and ice sheet modelers is to examine the spread in sea level rise projections associated with a suite of different ice sheet models driven by the same input climate forcing. Each model simulates the same system but varies slightly in how it is constructed and initialized. This approach is a little like looking at the varying answers to an exam question by a group of students. The students may take different approaches to the question, resulting in a range of answers, but the hope is that most of them get something close to the right answer.

But what happens if the question asked involves material that wasn't taught? Well, students (and models) can still figure out the right answer if it is based on physical principles that the students (and models) have learned. In the case of climate and ice sheet models, some of these principles, like conservation of mass and of momentum, are established and always apply. But others are simply working hypotheses called parameterizations.

Parameterizations attempt to represent complex processes using simpler representations that rely on tunable numerical values (parameters) to define a system and how the system evolves. But many parameters can take on a range of values that are poorly constrained, giving rise to a wider spread of potential model outcomes. For example, part of the uncertainty around the projected fate of the Antarctic Ice Sheet involves a controversial recent hypothesis about a process called marine ice cliff instability, which suggests that ice cliffs that form where glaciers flow into the ocean can become structurally unstable if the cliff height becomes too tall [*Bassis et al.*, 2021; *Bassis and Walker*, 2012; *DeConto and Pollard*, 2016]. It's thought that under certain conditions, such instability could cause a runaway domino effect of ice loss and rapid sea level rise. However, this process has not been observed in nature, and current models either do not include ice cliff failure at all or rely on empirical parameterizations based on modern Greenland glaciers [*DeConto and Pollard*, 2016].

Another way to estimate uncertainty is to explore the range of simulated model outcomes associated with different parameters or parameterizations. The challenge here is that parameterizations are often tuned to represent physical processes as they have been observed in modern times. As climate change continues to expose ice sheets to conditions outside the range for which we have modern observations, existing parameterizations may no longer realistically represent the intended process. Similarly, if processes that are yet to be observed, like marine ice cliff instability, become important, estimates of uncertainty from models may no longer represent reality. Crucially, including more processes in models—especially those for which we have limited observations—to increase model accuracy is likely to increase uncertainty in longer-term sea level rise projections, at least until the processes are better understood.

So how do we know when a model is complex enough in the physics it includes that we can rely on its projections under conditions very different from today's? Answering this question comes down to two related concepts: model confidence and model skill.

Confidence reflects an assessment (qualitative or quantitative) of whether we believe that the physics and hypotheses underpinning models are fundamentally correct. Beyond being correct, model hypotheses must be complete enough that the models still produce accurate outcomes even when pushed outside the set of conditions, or regime, for which they have been calibrated. For example, we must be able to predict reliably when and how quickly ice breaks and crumbles before we can confidently predict the role of marine ice cliff instability in future sea level rise. Building confidence in models thus requires using them to make—and then test—predictions. Model skill is a measure of how accurately models have predicted past changes. Higher model skill results in greater confidence, but boosting model skill is no easy feat.

### Building Confidence Through Failure

Our record of modern observations of ice sheet change is relatively short, dating back to the beginning of the satellite era in the 1970s, and ice sheet models don't have a long track record of predicting rapid changes. In 2002, the Larsen B Ice Shelf on the Antarctic Peninsula disintegrated in less than 6 weeks, an unprecedented—and unpredicted—pace [*Banwell et al.*, 2013]. When this happened, the flow of the tributary glaciers that fed it accelerated, providing clear evidence that the ice shelf had been buttressing the grounded ice behind it [*Berthier et al.*, 2012; *Scambos et al.*, 2004] and proving that ice shelves play a critical role in regulating ice sheet discharge. At the time of the collapse, though, ice sheet modelers were still debating whether large-scale instabilities could occur, and the potential for such a rapid process was not accounted for in models [*Hindmarsh and Le Meur*, 2001].

Significant advances continue to be made in the capability of models to re-create past sea levels, but this capability by itself provides little guidance on whether the models fundamentally represent physical processes correctly. Building confidence in models—and showing that they have the skill needed to represent rapid ice sheet change accurately—will require synthesizing a wider set of observations (beyond just past sea levels) that allows us to test models' abilities to represent key processes across many different regimes.

The growing catalog of observed Greenland glacier behavior, for example, can be used to test models [*Catania et al.*, 2020]. Ongoing changes in Antarctica, like weakening of the Thwaites Ice Shelf and retreat of floating portions of the Pine Island Glacier, may also provide opportunities to test whether current models can represent substantial ice retreat or collapse. Beyond the short modern observation period, paleorecords that show changes over much longer timescales can provide additional clues about past ice sheet instabilities and responses across a wide spectrum of climate forcing. Neither modern nor paleo-data sets are sufficient by themselves, but piecing them together provides a richer, wider scope of conditions with which to test models and ferret out where they misbehave.

And the way to test models and increase confidence in their sea level projections is not to tune them to reproduce certain observations. It is instead—though this may sound paradoxical—to find examples where the models fail to reproduce observations. Identifying model failures is key to making improvements because it highlights processes that are either incorrectly represented or absent entirely in the models. Correcting these deficiencies results in a slow and steady march toward models—whether machine learning based or physics based—that accurately incorporate more of the fundamental physics involved in influencing climate, ice, and sea level. This approach of finding and fixing failures is necessary to build confidence that models will produce realistic predictions when challenged with conditions significantly different from today's.

### Confidence on a Practical Scale

Sea level rise projections that extend to the end of this century and into the next may be uncertain. But this uncertainty isn't a bad thing for science or for adaptation planning. The current divergence among model predictions is actually a good sign, because it means that scientists are probing different parameterizations, representations of processes, and hypotheses. Some of these may eventually be abandoned, but others will evolve and become widely adopted across models because of their improved predictive capabilities.

The skill of models in predicting sea level change on decadal timescales is high, and we already have actionable projections on these timescales. We should be emphasizing that fact in discussions with community members, stakeholders, and decisionmakers so they can move ahead with important adaptation and mitigation planning. These adaptation decisions need to be initiated now while scientists simultaneously continue to work toward model improvements.

In the short term, making these improvements is likely to increase uncertainty in projections of future sea level rise as we probe a wider suite of processes and conditions. But the increase in uncertainty will come with increased confidence that models aren't missing critical physics. And this increased confidence is far more useful in developing long-term strategies for adaptation than worrying about all the things we still don't know.

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**▶ Read the article at bit.ly/Eos-quit-worrying**

# A New *Mayflower*, Named for the Past, **Autonomously Navigates the Future**

By Alka Tripathy-Lang

*The* Mayflower Automomous Ship (MAS) *undergoes sea trials in April 2021. In 2022 the* MAS *will sail the same path that the original Mayflower charted in 1620, collecting data along the way. Credit: IBM and ProMare*


**To commemorate the 400th anniversary of the Pilgrims' crossing, a ship guided by an AI captain will embark on the same journey, doing science along the way.**

On 6 September 1620, the *Mayflower* set sail from Plymouth, England, bearing 102 passengers and about 30 crew members. After a perilous 66-day journey across the North Atlantic and a harsh winter, the surviving Pilgrims and crew of the *Mayflower* encountered the Wampanoag, who were familiar with Europeans as traders, kidnappers, and agents of plague. The Wampanoag have lived in what is now southeastern Massachusetts for more than 12,000 years, and the two communities coexisted for about 50 years before war began.

The European immigrants prevailed in that war, as well as in a long series of conflicts with other tribes. On this land taken from Indigenous Peoples, a new nation was eventually born, largely built by those whose ancestries traced back to the Old World via immigration and slavery.

As the country grew, inventions like the telephone, airplane, and Internet helped usher in today's interconnected world. But the inexorable march of technological progress has come at great cost to the health of the planet, particularly because of global dependence on fossil fuels. The United Nations declared in 2017 that a Decade of Ocean Science for Sustainable Development would be held from 2021 to 2030. This Ocean Decade calls for a worldwide effort to reverse the oceans' degradation.

**The AI Captain must make and execute educated decisions to avoid collisions.**

The dawn of this decade, 2020, also marked the 400th anniversary of the *Mayflower's* journey. Plymouth 400, a cultural nonprofit, has been working for more than a decade to commemorate the anniversary in ways that honor all aspects of this history, said spokesperson Brian Logan. Events began in 2020, but one of the most innovative launches is still waiting in the wings—a newfangled nautical craft, the *Mayflower Autonomous Ship*, or *MAS*.

Built and tested over the past 5 years, *MAS* will chart a new path by retracing an old one. This year it will travel from Plymouth, England, to Plymouth, Mass. Throughout the journey, it will collect data that might provide insight into ocean and marine mammal health while gathering information about a sustainable energy source—the ocean's waves—that could help power our world.

## Aye, AI, Captain!

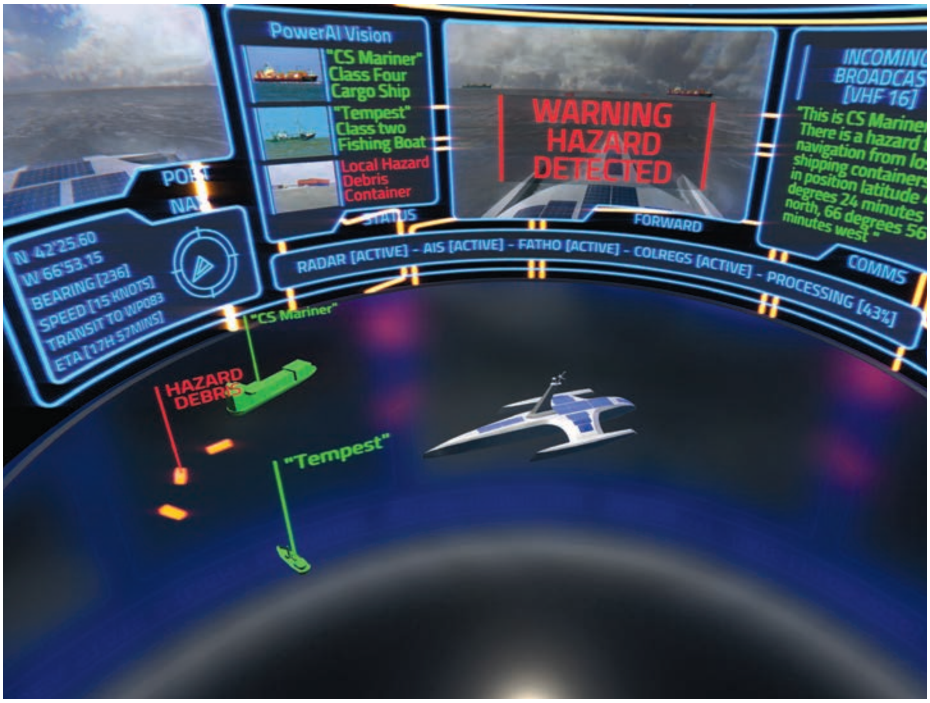
When discussion began about what a new *Mayflower* might look like, Brett Phaneuf, cofounder of the marine research nonprofit ProMare, advocated for designing and building an innovative ship instead of a replica. At the time, militaries, private companies, and research agencies were all focusing on uncrewed systems, he said. "Everybody was looking at what the next iteration of technology [would be]…and it's autonomy—true autonomy."

Phaneuf remembered watching the IBM supercomputer Deep Blue defeat world chess champion Gary Kasparov in the 1990's. With the opportunity to build a new *Mayflower*, he thought, "we must be able to bring some of this technology to bear…how hard can this be?" Pretty hard, as it turns out. Creating an artificially intelligent captain to navigate the ocean proved trickier than navigating the famously difficult strategies demanded by chess. The ship must have agency to make decisions by itself, said Phaneuf, "so even when you don't have communication with it…it can still function safely and achieve a goal."

To navigate coastal waterways and open oceans alike, *MAS* uses artificial intelligence (AI) developed by IBM and ProMare. The AI Captain uses its camera-based vision system to recognize potential hazards (learned from perusing pictures ranging from ships to seagulls). Two weather stations on board, plus a link to IBM's The Weather Company, provide the AI Captain with real-time meteorological information. Sensors that notice how waves roll by inform the AI Captain of sea conditions. With all these inputs, the AI Captain must make and execute educated decisions to avoid collisions and stay upright and safe.

To help with those decisions, *MAS* uses IBM's Operational Decision Manager, a tool used by financial institutions to determine, for example, whether certain people qualify for loans. In this case, the rules aren't financial but, instead, focus on avoiding impacts. The International Regulations for Preventing Collisions at Sea (COLREGs), published by the International Maritime Organization, serve as the "rules of the road" for the ocean, according to Lenny Bromberg, program director for automation, intelligence, and decision management at IBM. Because the COLREG framework bounds the Operational Decision Manager, he said, the AI Captain can decide how to safely and legally proceed when anything from dolphins to debris to destroyers appears within its sights.

A diesel generator combined with batteries and solar panels drives these systems and




MAS's *AI Captain must detect hazards and make decisions to avoid collision. Credit: IBM and ProMare*

sensors, as well as the ship itself, said Phaneuf. When the batteries are low, the diesel-powered engine starts, charges the batteries, and shuts itself off, allowing the ship to run via battery and solar. "If you want to cross an ocean, we could probably build a [totally] solar-powered ship," he said. "But then you'd need to take out about 99% of all the science."

### "My Humans May Want This!"

Without a physical captain or crew, there's no need for sleeping quarters, a galley, or anything else humans may require. Eliminating these compartments freed ProMare and its partners to design a lightweight trimaran whose innards can be devoted mostly to science. The energy-efficient payload sits in a space of about 2 cubic meters—slightly larger than a refrigerator box, said James Sutton, a software engineer at IBM who helped build the systems running the *MAS* science package. The ship can hold 700 kilograms (1,500 pounds) of scientific equipment.

To sample seawater, said Sutton, the ship has an intake pipe that sucks water out of the ocean and into one of several sensor systems. To keep the intake from getting clogged with large detritus like seaweed, grills and filters armor this crucial entrance. Flowmeters ensure that tubing inside the ship remains clear. With this design, he said, "we don't have to worry about sticking lots of sensors on the outside of the ship."

One slug of water heads into a fish tank–like box equipped with sensors that test for temperature, salinity, pH, and oxygen content. A fluorometer optically observes whether anything in the seawater fluoresces, which can be used as a proxy for quantifying chlorophyll-rich algae, said Sutton. A satellite link uploads data from the fish tank to the cloud in real time whenever possible, he said.

Also on board is a version of HyperTaste, IBM's AI-assisted "tongue" designed to rapidly test the chemical composition of liquids. This system, based on a tool originally used to identify counterfeit brandy, according to Phaneuf, includes four separate sensors that measure the presence of various molecules and ions in seawater. The brandy-sniffing version takes about a minute to test, whereas the *MAS* version takes about 15.

HyperTaste begins each cycle by sampling from a bucket of artificial seawater on board that serves as a baseline reading, followed by a rinse of deionized water and a taste of the ocean, said Sutton. When it's done, like a wine connoisseur, the system spits the seawater back into the ocean and cleanses its palate for the next sip. HyperTaste will measure quantities of calcium, magnesium, and other markers of the ocean's biogeochemistry about every 15 minutes, said Sutton.

A holographic microscope will photograph water samples from several different directions to build 3D images of any microbes or microplastics present in the water, said Sutton. Unfortunately, because the photographic data sets are too big to send over the satellite link, they will be saved on the 12 terabytes of solid-state hard drive storage available on board, he said.

To complement the holographic microscope, a robotic sampler will collect and refrigerate about 20 liter-sized flasks of seawater that will be given to a local university upon arrival in Plymouth, Mass., said Phaneuf. To choose where water samples come from, he said, the hope is to teach the AI system to recognize anomalies and say to itself, "My humans may want this!"

> **"Wave energy harvesting is global, sustainable, nondepletable, and emission free."**

Chemical oceanographers take these same kinds of measurements—temperature, salinity, oxygen, pH, fluorescence, and others—not only at the surface but also in vertical depth profiles, said Hilairy Hartnett, an oceanographer at Arizona State University. These metrics help scientists monitor water density, nutrient content, and the ocean's health. "What we lack in oceanography is lots and lots of coverage," she said. "The oceans are freaking huge!"

That *MAS* can collect such detailed information about the surface ocean is appealing, Hartnett continued, but "until we see the data, it's going to be hard to know what we can do with it."

### The Next Wave of Sustainable Energy?

*MAS*'s inertial measurement unit records acceleration in all three axes 300 times per second, painting an incredibly high-resolution picture of how waves rise and fall in the open ocean, said Sutton. Six cameras mounted around the central mast of the ship keep watch as the waves come toward *MAS*, allowing researchers to use the pixel velocity to calculate the size and speed of

Opposite: IBM and ProMare


MAS *attempted its first transatlantic crossing in June of 2021. Credit: IBM and ProMare*

each wave. By linking inertial measurements to individual waves, said Sutton, researchers can calculate how many joules of energy each wave carries. Such information could eventually help place wave energy harvesting systems in the ocean.

Wave energy harvesting, said Michael Webber, a professor of mechanical engineering at the University of Texas at Austin, "is global, sustainable, nondepletable, and emission free." To get usable electricity, Webber said, you need either rotational motion or an electrical potential—a difference between charges. The most basic way to make electricity is by burning fossil fuels to turn water into steam, which spins a turbine like a backward fan, he said. That turbine rotates a shaft, which rotates magnets in a generator. "That's the basis for just about all of our electricity," he said.

In the ocean, the rise and fall of waves can be converted into rotational motion, for example, via a buoy that bobs up and down or a gate on the seafloor that rocks back and forth, Webber explained. "Earth does the heavy lifting for you," he said. However, as powerful as waves can be, "it takes a lot of equipment to convert that into useful energy, and you have to worry about marine ecosystem impacts."

"I would be interested to know what the wave structures are like around the oceans," said Webber, but mapping wave energy by boat is difficult because the oceans are large and constantly changing. Satellite imagery, he said, could be very helpful. Data from *MAS*, said Jyotika Virmani, executive director of the Schmidt Ocean Institute, can help verify and calibrate such satellite data. "It'll be interesting to see how this autonomous ship's information meshes with what we can do from satellite data," said Hartnett.

## Bigger Ships, More Science

Choosing which aspects of the ocean *MAS* would explore for its inaugural voyage, "was kind of organic," said Phaneuf. At some point, "I went, 'Stop! We have enough stuff right now.'"

The science team had to focus on what could be done without the watchful eye of a crew, said Sutton. For example, a single hydrophone mounted on a pipe near the center of *MAS* pokes out from the bottom of the ship to listen for songs of marine mammals like whales and dolphins. In a typical marine acoustic experiment, however, "the gold standard would actually be to have it tethered on a line behind the ship, quite some distance," he said. "But we didn't want to risk the line getting caught."

When Scripps Institution of Oceanography geophysicist Vashan Wright goes to sea, his goal is to image the subsurface as he searches for faults, submarine slides, and paleoseismic deposits. "I can't imagine [an autonomous vehicle] dragging a 5-kilometer streamer behind it, and an air gun array, and having no problems," he said. Doing this type of science autonomously "would take a lot of creative thinking."

A notable absence in the *MAS* science suite is sonar, especially considering that one of the goals of the Ocean Decade is a comprehensive digital atlas of the ocean. "Right now, we have first-order bathymetry for the world oceans from orbital gravity [data], but that's pretty coarse compared to what you get from a hull-mounted sonar," said Robert Stern, a professor of geosciences at the University of Texas at Dallas. Sonar helps scientists map the bathymetry of the ocean in exquisite detail, but current coverage is patchy. "[Autonomous ships] would be perfect for mapping large swaths of the oceans," said Stern.

However, mapping bathymetry many fathoms deep with sufficient resolution would require equipment that simply can't fit on *MAS* as it is currently configured, said Phaneuf. Plus, he said, the power requirement for such equipment is extreme. The ship is simply too small.

The autonomous *Mayflower* descendants are already on their way, said Phaneuf, speaking of the next two ships in the pipeline. The first will be named after Oceanus Hopkins, born to the Pilgrims during the *Mayflower*'s crossing. The second child born on the original *Mayflower*, Peregrine White, will give his first name to the second of *MAS*'s offspring. Construction of *Oceanus*, expected to be nearly twice the size of *MAS*, is scheduled to begin in late 2022 or 2023. These future vessels will have more endur-

**"It's more important for us to provide that portal to people, so they can experience the sea without having to physically be on the ship themselves."**

ance, said Phaneuf, "and much more payload for science."

### Accessible Oceans

Autonomous research ships could help bring the oceans to those who cannot currently access the world of oceanography. At the moment, admitted Hartnett, "it's not a super accessible field."

"[Autonomous ships] would expand access to people who don't know how to swim or are afraid if something goes wrong," said Wright. "Sometimes, those are people from historically excluded groups," he added.

Stern knows this better than most. "I've got a degenerative nervous disease called Charcot-Marie-Tooth syndrome, and it affects my motor nerves," he said. "I get around on a scooter, and I don't do any fieldwork anymore." To maintain involvement with marine research, he relies on ships with Internet, which have become more common in the time of COVID-19.
"I can't handle any rocks on the ship, obviously, but I can participate in a much better way than just waiting until [my team gets] back."

Other life circumstances may not allow people to devote weeks at a time to an expedition, said Allison Fundis, chief operating officer for the Ocean Exploration Trust. This group includes parents and expectant mothers. "For that reason, it's more important for us to provide that portal to people, so they can experience [the sea] without having to physically be on the ship themselves."

Some scientists simply don't have the funding or time to go to sea, said Virmani. With *MAS*, they could potentially get the data they need to continue their work.

*MAS* also presents tremendous teaching opportunities, said Hartnett, especially for landlocked universities. "I love being able to find ways for students in my oceanography classes to deal with real-time oceanographic data," she said. "The ability to help [students] see the kinds of data that we collect and use…is very powerful."

### An Uncertain Future

Uncrewed research vessels like *MAS* may expand opportunities for scientists but complicate the careers of people who work indirectly with science. "Many people make their livelihood at sea," said Wright. They are the cooks, the able seamen, and technical staff whose careers require going to sea. "When we think about automation, we have to think about…what happens to them."

MAS *will listen for the songs of marine mammals, like these dolphins playing in the swell. Credit: Schmidt Ocean Institute*

Fundis acknowledged this concern but said that replacing crewed missions with autonomous ships "is very much not the case." Instead, she described autonomous vehicles taking on tasks not suitable for crewed ships,

**"An autonomous ship is like Sputnik. It doesn't really have to do much, as long as it can do what it's designed to do."**

like sailing during risky weather windows and making long transits across remote regions.

Virmani noted that uncrewed vessels could greatly expand the ability to monitor particularly dangerous situations, like the 2011 Fukushima nuclear power plant meltdown in Japan that resulted in radioactivity contaminating parts of the Pacific. "You don't have people on board, so it's pretty safe to send something like this to assess what's going on," Virmani said of *MAS*.

### A Sputnik Moment

In October 1957, when the Soviets launched Sputnik into orbit, walking on the Moon a mere 12 years later may have seemed like an outrageously unattainable target. Early competitors in the Space Race may never have imagined astronauts living in space or tourists popping into orbit. Similarly, said Stern, *MAS* may be a Sputnik moment for oceanography.

After its 2020 launch was rescheduled because of the COVID-19 pandemic, *MAS* attempted its first transatlantic voyage on 15 June 2021. However, a mechanical failure forced Phaneuf and his team to recall the ship to England after 3 days. It's now back in the water and ready to try again in spring.

"All Sputnik did was, it went around the Earth, and it beeped," said Stern. "It didn't collect any data at all but still revolutionized humans' relation to space." An autonomous ship, he said, is like Sputnik. "It doesn't really have to do much, as long as it can do what it's designed to do, which in this case is roam the oceans."

### Author Information

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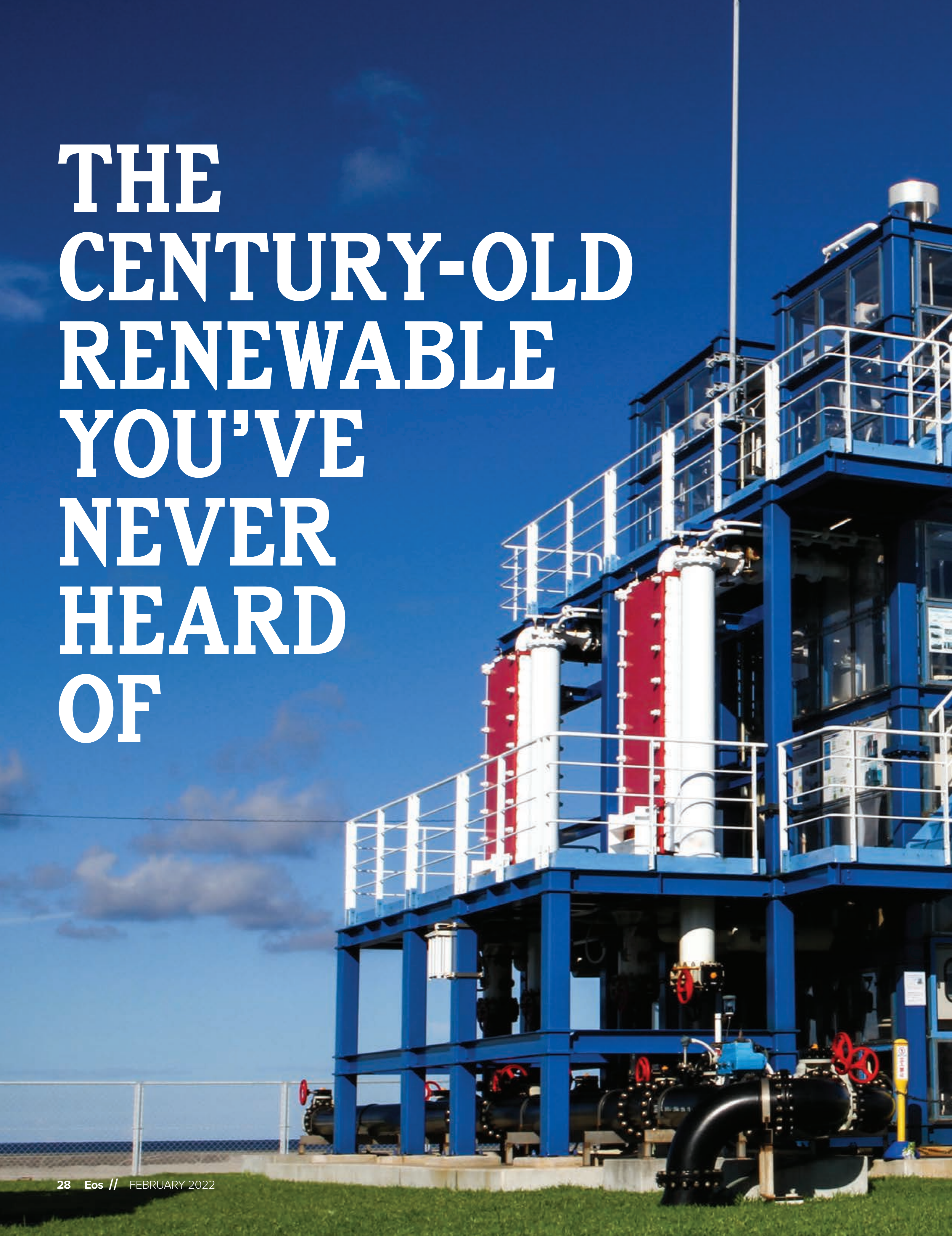
**▶Read the article at bit.ly/Eos-MAS**

# THE CENTURY-OLD RENEWABLE YOU'VE NEVER HEARD OF



BY MARK BETANCOURT

# Ocean thermal energy conversion could power the world's tropical islands, if it ever gets out of the "innovation valley of death."


*The ocean thermal energy conversion (OTEC) demonstration plant on Kume Island in Japan generates roughly 100 kilowatts of electricity. A 10-megawatt plant could power the entire island. Credit: Okinawa Prefecture Industrial Policy Division*

Benjamin Martin came to the tiny Japanese island of Kumejima to work as an English teacher after graduating from a business school in landlocked Arizona. Now he runs a power plant fueled by ocean water. "I don't have an engineering degree, and I do all the maintenance for our electricity," he said. "It's relatively easy."

The plant, which looks like a cross between a lighthouse and a jungle gym, generates a negligible amount of power, only about 100 kilowatts. It was built in 2013 to demonstrate a process called ocean thermal energy conversion, or OTEC. The idea behind OTEC isn't new, and it's deceptively simple. Like most power plants, the facility uses vaporized liquid to spin a turbine and generate electricity. The difference is that instead of burning fuel, the plant gets its energy from Sun-warmed water from the ocean's surface. Cold water pumped up from a depth of several hundred meters cools the vapor again, creating a heat engine.

For now, Kumejima depends mostly on diesel fuel, shipped in at a premium, to provide electricity for its 8,000 residents. But residents of the island hope someday to sever that dependency by building a 5-megawatt OTEC plant that with a bit of solar, could cover all of its energy demand.

Such an endeavor would be expensive, and the plan is to help pay for it by sharing the cold-water intake pipe with the various cold-water industries already thriving on the island—from prawn farming, to a deep-sea water spa, to greenhouses in which the water chills the soil so that it's the optimum temperature for growing spinach. Cold seawater can even be used for air-conditioning.

**"OTEC CAN BE COST COMPETITIVE, IT'S JUST NO ONE'S DONE IT YET."**

"Our research center is cooled by deep-sea water, which reduces the amount of power we need for cooling by about 90%," said Martin, who also serves as secretary general for the Ocean Thermal Energy Association, a group with members from around the globe who want to see OTEC deployed and expanded in the power sector.

On paper, they're right to be optimistic. The theoretical potential of OTEC is vast. It could produce at least 2,000 gigawatts globally, rivaling the combined capacity of all the world's coal power plants on their best day. And unlike many renewables, OTEC is a baseload source, which means it can run 24/7 with no fluctuation in output.

But the conditions necessary to make the process viable—at least a 20°C difference between surface and deep water—occur only near the equator, far from most of the world's power demand and much of its wealth.

That's why, despite its simplicity and decades of small, successful demonstrations, OTEC has yet to take hold in the renewable power industry. Its high initial capital costs have kept investors away, especially as other renewables like solar and wind get cheaper by the minute.

But places like Kumejima and dozens of small island states, many of them among the poorest countries in the world, could benefit enormously from ocean thermal power. If they can raise the money to get started, energy independence and carbon neutrality may be literally at their doorstep.

"The island hopes to be 100% carbon free by 2040," Martin said of Kumejima. "But we need OTEC to get there."

### More of a Warmth Engine

The universe runs on contrasts and the forces of entropy. Thermal power, for instance, isn't generated by heat but by its ability to do work as it cools. Even a modest amount of heat can do the job, as long as there's a temperature gradient to be exploited.

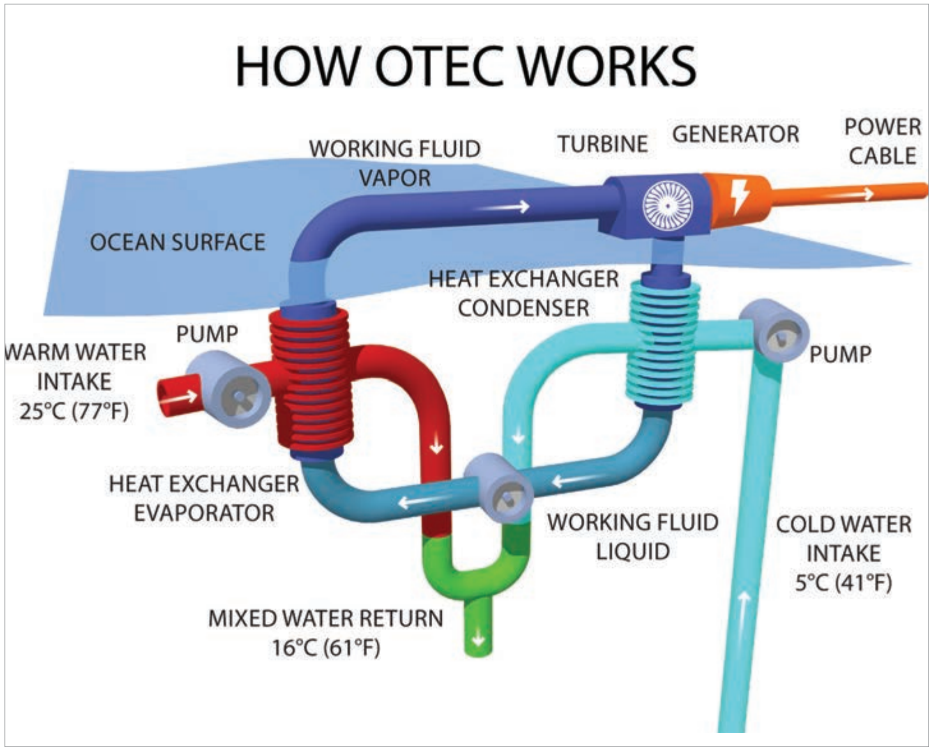
Most OTEC systems use liquid ammonia, which has a very low boiling point, as what's called the "working fluid." Warm water from the ocean surface flows into a heat exchanger, where it causes the ammonia to evaporate. (Other "open" systems use the seawater itself as the working fluid, first exposing it to a vacuum to lower its boiling point.) As the vapor expands, it flows around the blades of a turbine. The vapor then enters another heat exchanger, where cold water pumped up from the deep ocean causes it to condense again. The pressure differential between the two chambers on either side of the turbine pulls vapor from one to the other, spinning the turbine and generating electricity. Some of that electricity is used to run the pumps. What's left can feed the grid.

At first glance it looks like a painfully inefficient process; only about 2%–3% of the energy in the seawater is converted to electricity. But the fuel is free and virtually infinite. Output is limited only by how much water you can pump at a time.

And there's the rub. For OTEC to be viable—that is, for it to be competitive with other renewables like wind and solar—the plants need to be huge. To get anywhere near wind's or solar's average cost of 0.02–0.06 cents per kilowatt-hour, an OTEC plant would have to keep the equivalent of four Niagara Falls flowing through its heat exchangers at all times.

A 100-megawatt OTEC plant (the equivalent of about 500 acres, or 202 hectares, of solar panels) would need a cold-water intake pipe that's 7–10 meters in diameter to work efficiently. Just to scale up to a modest 1-megawatt plant, Kumejima expects to spend between $60 million and $80 million on a 1.5-meter pipe.

So far, funding for that kind of leap of faith has proven to be elusive. "OTEC can be cost competitive," Martin said. "It's just no one's done it yet."




*A "closed" OTEC cycle uses warm seawater to evaporate ammonia and cold seawater to condense it again. The vapor moving from higher to lower pressure spins a turbine, generating electricity. Credit: Makai Ocean Engineering Inc.*

## The Curse of the First

The concept of using warm and cold ocean water to generate electricity is about as old as the generation of electricity itself. French scientist Jacques-Arsène d'Arsonval theorized the process in 1881, just as the notion of using a steam engine to rotate coils of copper wire around a magnet was emerging as a source of commercial and industrial power. His student Georges Claude, a rebellious and hardheaded entrepreneur who got rich selling neon lights, built the first OTEC plant in Cuba in 1930. At first cockily optimistic, he eventually admitted that running it cost about 4 times more power than it generated.

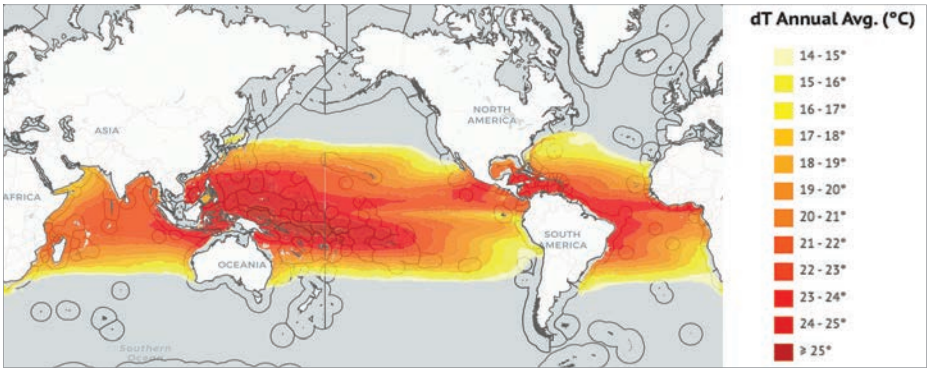
And Claude had a lot of trouble with the cold-water pipe. He sank a handful of failures in Matanzas Bay, losing a million dollars with each attempt. The one that finally worked was destroyed by a hurricane.

The moral of Claude's story is that when it comes to big, novel machines, failure is expensive. And before Claude had even begun his less-than-convincing demonstration, coal had become ubiquitous as the fuel for large-scale power plants. Unlike two-temperature seawater, coal (and, later, oil and natural gas) was perniciously easy to ship anywhere in the world.

Predictably, global interest in OTEC has followed oil prices. After the crises of the 1970s, President Jimmy Carter signed a bill calling for 10,000 megawatts of OTEC capacity to be up and running by 1999. Then oil prices stabilized, administrations changed, and other than a few demonstration projects, nothing happened.

OTEC projects began to crop up again after the 2008 financial crisis, coupled with growing concern over climate change. Makai Ocean Engineering, based in Hawaii, was the first to connect an OTEC plant to the U.S. power grid. But like Kumejima's facility, it was a temporary demonstration, generating only enough electricity to run about 120 homes. The cold-water pipe is still operating, though, allowing a local fishery to grow and sell Maine lobsters.

Plans for a score of small-scale OTEC projects have been announced, including in Bora Bora, where one resort is already using deep-sea water for air-conditioning; China; Martinique; and Puerto Rico. But this time, the meteoric rise of wind and solar power has simply overtaken marginal renewables like OTEC.




*The optimal surface-depth temperature differential for OTEC power generation is concentrated in the tropics, especially in the western Pacific, where most of the ocean falls within the exclusive economic zones of small island nations. Credit: DOE/NREL/ALLIANCE*

The main advantage of wind and solar is their modularity. The technology can be proven at full scale with a single turbine or panel; scaling up is a matter of simply manufacturing more of them. OTEC, on the other hand, requires a huge investment—and the risk that goes with it—before even the first kilowatt is generated.

The potential pitfalls of installing a true commercial OTEC plant can come from unexpected quarters. The Korea Research Institute of Ships and Ocean Engineering plans to install a 1-megawatt, shore-based plant on Tarawa atoll in Kiribati, smack in the middle of the Pacific. The plant components were successfully tested on a barge off the Korean coast in 2019, generating the largest OTEC current to date—about 338 kilowatts—even in suboptimal conditions. But the project stalled when the COVID-19 pandemic drove up the cost of shipping the components to Kiribati.

George Hagerman, a senior project scientist at Old Dominion University's Center for Coastal Physical Oceanography, questions whether OTEC itself is quite ready for its moment. The main reason hasn't changed for nearly a hundred years.

"The big risk, the big unknown, the big killer for OTEC—and it's what actually destroyed George Claude's plant in Cuba—is the cold-water pipe," said Hagerman.

## The Kilometer-Long Thorn in OTEC's Side

Most OTEC enthusiasts agree that large shore-based plants would be too expensive, mostly because the cold-water pipe would have to be too long. Go down about a kilometer pretty much anywhere in the world, and you'll feel an icy 4°C, but running the pipe from shore adds to that distance and exposes a fixed pipe to the battering of waves and currents.

To keep the pipe shorter and avoid this exposure, the plant could instead be mounted on a barge or platform and parked where a flexible pipe could be suspended straight down to cold water. Power could be run ashore via the same kind of cable currently being used by offshore wind facilities.

There's still the problem of making the pipe wide enough to efficiently draw massive amounts of water. OTEC believers say that's mostly a matter of tweaking the designs and materials currently being applied in other industries that move large volumes of water.

But Hagerman, who's been researching and developing ocean energy technology for 40 years, knows it's not that easy. Even designs that seem straightforward can run into unexpected and expensive challenges, especially in the chaotic environment of the sea. "When people actually have to build stuff that's got to survive in the ocean and be insured, costs double. Insurance premiums triple," he said. "And all of a sudden, what looked good when you announced it, you can't actually get finance to build."

Hagerman thinks it would be better to forgo the suspended intake pipe entirely, replacing it with a tunnel beneath the ocean floor. A tunnel would be easier to design as wide as necessary to make OTEC cost-efficient and could bring cold water ashore to a fixed plant (where it could also feed cost-sharing ventures like aquaculture and air-conditioning) or to a movable barge that could detach from the tunnel and move out to sea in the event of a storm.

"Elon Musk is doing tunnel boring all over the place right now," said Hagerman, who suggested that OTEC is the perfect project for a climate-conscious billionaire. "You would have basically a permanent cold-water intake conduit on an island or a coastline, and it would be there for the life of the planet."

According to Hermann Kugeler, Makai's business development manager, the cold-water pipe is an inherently expensive part of the OTEC system. "We've done what we can, but that's kind of the one cost [for which] we don't see much more reduction," he said.

Instead, Makai's recent focus has been on building cheaper heat exchangers that won't rust. The relative acidity of deep-sea water is hard on aluminum, which com-poses most off-the-shelf components, so the second heat exchanger must be made of expensive titanium. Kugeler said that his team has been working out a design that uses much thinner plates to separate the seawater and working fluid and therefore requires less titanium to build. It's also significantly smaller and lighter, which lowers the cost of mounting it on a platform.

Although a 100-megawatt plant may still be only theoretically possible, "a commercial scale of 10 megawatts is probably commercially feasible today using this technology," said Kugeler.

### A Niche Market

That may be enough to sneak OTEC into the commercial space. Dan Grech, the young and exuberant CEO of a U.K.-based start-up called Global OTEC, challenges the idea that an ocean thermal plant has to be enormous to be viable. Instead of making plants bigger, he wants to keep them relatively small and rightsize the market, namely, scattered island nations that don't need much power but need to spread it over a vast area.

"Our plan is to standardize as much of the OTEC platform as possible so it can be mass-produced for the widest deployment possible," Grech wrote in an email. He's worked out that a few dozen small island nations have a combined installed capacity of about 12,000 megawatts—barely 1% of the installed capacity of the United States alone—and most of it's generated by fossil fuels.

"Annually, we spend more than $20 billion a year on oil imports," said Albert Binger, secretary general of the Small Island Developing States (SIDS) Sustainable Energy and Climate Resilience Organization (SIDS DOCK), a climate- and energy-focused coalition of 32 developing small island states. More than $6 billion of that collective oil is burned for energy. It's an expense they can little afford. Binger added that many small island nations still haven't recovered from the debt they incurred during the oil crisis that began in 1979. That's partly because oil costs more for tiny, remote places; suppliers see modest orders with astronomical shipping costs and raise prices.

And the volatility of oil prices stunts small island nation economies, Binger said, because businesses can't rely on consistently affordable electricity to produce their goods. "If we [SIDS] had taken a lot of that money and put [it into] OTEC system[s] previously, we would be in a completely different situation," said Binger. "We need an energy source that is secure, reliable and has a pretty good price."

Many of the archipelagos that make up island nations are the exposed peaks of submerged mountain ranges of extinct volcanoes called seamounts. Their shorelines are more like cliffsides, and kilometer-deep water can be found within a few kilometers of shore. This bathymetry makes them ripe for OTEC.

"We have more ocean than the EU [European Union] has land," said Binger of small island nations—in fact, it's about 16 times more. So by definition, there's very little building space for land-based renewables. Most of the V-shaped atoll that comprises Kiribati's capital, for example, is less than a kilometer wide. "Every megawatt of solar that we put up means about 2 acres of land taken out of something or not available for something," said Binger.

In 2021, SIDS DOCK signed an agreement with Global OTEC to develop ocean thermal power, starting with a small 1.5-megawatt barge in São Tomé and Príncipe, off the central African coast. The plan is to use that first barge to prove the model, then scale up to a larger one or more barges over the following few years. Like Kiribati, many islands are also considering shore-based plants—the associated secondary cold-water industries like those on Kumejima could bring much-needed jobs. Open OTEC systems, which desalinate seawater as it's vaporized, could also yield fresh water on islands where it's becoming increasingly scarce.

**"THE BIG RISK, THE BIG UNKNOWN, THE BIG KILLER FOR OTEC…IS THE COLD-WATER PIPE."**

And despite their limited resources, all of the SIDS DOCK countries are signatories to the Paris Agreement. That's ironic given that many of them are net carbon sinks; their ocean water and tropical biomass absorb more carbon dioxide than their human population emits. But, Binger said, island countries are at the forefront of converting to renewable energy out of self-preservation—some could be swallowed entirely by the rising sea if climate change isn't slowed.

"If you can't speak up for yourself when you're vulnerable, you can't blame anybody else," he said.

### "A Tipping Point"

Researchers at the University of Hawai'i at Mānoa have been working out the environmental impacts of OTEC, should it ever gain a real foothold in the market. One OTEC plant, they found, would have a negligible effect on the physical environment in the ocean around it. But what about thousands of plants all over the world?

On a massive global scale with high plant density, OTEC systems would mix up enough seawater to nullify the thermal gradient that makes the process work. "The core idea is that OTEC is self-limiting," Gérard Nihous, who recently retired from the University of Hawai'i, wrote in an email, "and could have, at sufficient scale, unintended and unwelcome consequences."

The ocean is vast, however, and there's room for quite a few OTEC plants. In a 2018 paper, Nihous and two other colleagues from the University of Hawai'i wrote that as many as 15,000 plants, spaced 30 kilometers apart and within 100 kilometers of land, would avoid any large-scale disruptions (even if they were all plopped down in the ocean at once, which they wouldn't be). These plants would generate more than 2 terawatts of electricity, making OTEC a viable way, with other renewables, to help power the world.

Of course, all of that is theoretical. Like Kumejima and every other place looking to take advantage of ocean thermal energy, SIDS DOCK and Global OTEC are still searching for funding to even begin their modest projects. It's a frustrating catch-22: Investment would almost certainly follow a successful OTEC plant that generates commercial-scale power, say, 10 megawatts. A recent report by Ocean Energy Systems, part of the International Energy Agency, suggests that even 2.5 megawatts would be enough to quell investors' fears about the cold-water pipe.

But that can't happen without investment. Entrepreneurs call it the "innovation valley of death."

There's a chance OTEC's ticket out of the valley could be as a complement to its rivals, wind and solar. "As the grid penetration of those increases, there's going to be a pretty significant need for energy storage or something to provide baseload power, which OTEC does," said Kugeler. If the cost of storage is factored in, he said, OTEC's price per kilowatt hour looks competitive.

But it remains to be seen how much global capital will be spared for a technology that not everyone in the world can use.

Tim Ramsey, program manager for marine energy at the Water Power Technologies Office with the U.S. Department of Energy (DOE), said that OTEC's potential may not be realized until it's free from geographical constraints. That prospect isn't as far-fetched as it may seem.

The same electricity storage technologies being developed to stabilize intermittent renewables like wind and solar could light a fire under OTEC, too. Picture ships shuttling massive, charged batteries from remote ocean plants to the mainland. Or self-propelled plants (grazing barges) could hunt out the best temperature gradients and use OTEC power to produce hydrogen fuel, then ship it around the world. That would open up a whole new lane within the energy market, to the benefit especially of developing nations that control the lion's share of the warm ocean.

Ramsey said that's part of why OTEC is still on DOE's radar. "It's one of those things that there will just potentially be a tipping point where all of a sudden the economics makes sense and it just blows up and you see it everywhere," he said.

That may be of little comfort to the millions of islanders currently living under the thumb of expensive and destructive diesel power. All the clean energy they need stretches out in every direction, as far as the eye can see. But without investors who are willing to take the plunge, it's out of reach.

Having watched how seawater has sustained his little island community on Kumejima, Martin feels certain OTEC's day is coming; people just need to understand it. That's easy if they can see it work. When local schoolchildren come to tour the 100-kilowatt test plant, he invites them to touch the two intake pipes that snake up from the ocean.

"You feel the cold, you feel the hot," he said. "It's simple."

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# THE 2-YEAR COUNTDOWN TO DEEP-SEA MINING

BY JENESSA DUNCOMBE

*Deep-sea mining machines owned by Nautilus Minerals are parked on shore. Note the people in yellow jackets next to the machine on the left for scale. Credit: Nautilus Minerals*

**A small island nation is forcing the hand of international regulators to finalize rules for deep-sea mining, but scientists say the environmental consequences are not yet clear.**

Nauru, the smallest island nation in the world, invoked a legal provision last June that started a countdown clock for deep-sea mining in international waters. The move is essentially an ultimatum to speed up the completion of deep-sea mining regulations so that commercial enterprises can begin exploiting the seabed.

In a letter to the president of the council of the International Seabed Authority (ISA), the United Nations (U.N.) body that oversees mining in international waters, Nauru president Lionel Aingimea stressed the "urgency" of finalizing regulations so that industry can move forward.

The prospect of mining in the deep sea has attracted criticism because of the damage it could inflict on marine ecosystems. Supporters, however, claim it is less harmful than terrestrial mining and necessary to supply materials for renewable technologies, such as lithium-ion batteries for electric vehicles.

ISA has been deliberating regulations governing commercial mining of the deep seafloor, called the Mining Code, since 2014 and planned to finish them in 2020, but the COVID-19 pandemic sidelined the process. The "2-year rule" that Nauru triggered compels ISA to finalize the rules by mid-2023. If it doesn't, ISA may accept applications for exploitation even in the absence of formal guidelines, with many questions about the long-term effects of mining likely still unresolved.

The deep sea is the largest habitat on Earth. Still, we know very little about it. ISA has issued 31 exploration contracts to companies interested in conducting baseline studies. Data from these studies have fueled basic science in the deep sea—one deep-sea mining company, UK Seabed Resources, even keeps a list of research that grew from its environmental surveys.

Until commercial exploitation permits are issued, however, mining will remain illegal in international waters.

In the meantime, public scrutiny of ISA's governance plagues the nascent industry. Scientists and international organizations have voiced criticism about the scope of scientific oversight of ISA's various projects and technologies, and observers have drawn attention to the ethics of scientists funded by corporate dollars.

**MINING APPLICATIONS COULD BE CONSIDERED—WITHOUT OFFICIAL GUIDELINES—AS EARLY AS 2023.**

### Cobbles on the Seafloor

Deep-sea mining targets rare earth elements (REEs) and other metals and minerals thousands of meters below the ocean surface. Three types of resources have caught the eyes of prospectors.

The first, seafloor massive sulfide (SMS) deposits, precipitate around hydrothermal vents as they emit sulfide-rich fluids into seawater. SMS deposits are rich in copper, gold, silver, REEs, and zinc. The second resource considered for deep-sea mining is a type of rocky crust that coats seamounts. The coating, which precipitates over millions of years, is rich in iron, manganese, and cobalt and can be up to 26 centimeters thick. The third mineral resource is polymetallic nodules, sometimes called manganese nodules after their most abundant metal.

Most countries, including Nauru, are interested in mining these nodules, which don't require drilling to collect. The dark, potato-sized mineral masses, or concretions, form slowly by the precipitation of metals from seawater and the sediment underneath. They grow several millimeters every million years and sit on the seafloor like "cobbles on a street," said Diva Amon, a marine biologist at the University of California, Santa Barbara and director of SpeSeas, a nongovernmental organization in Trinidad and Tobago.

Although the nodules appear in various places around the deep ocean, the primary target of potential mining is the Pacific's Clarion-Clipperton Zone (CCZ), a 5,000-kilometer stretch of seafloor between Hawaii and California that extends 4,000–5,500 meters deep. The CCZ hosts trillions of mineral-rich nodules.

Reaching the nodules involves a three-stage process: First, a support ship lowers a remotely operated vehicle to the seafloor. Next, the vehicle—like a Roomba vacuum for seafloor mining—drives around through the soft sediments scooping up nodules. Last, a large pipe sucks the nodules to the ship above. Cobalt, copper, iron, manganese, and nickel can then be extracted from the nodules during onshore processing and refining.

A dozen European and Asian countries and several island nations have sponsored companies for exploration permits so far. The United States cannot apply for permitting through ISA because it has not ratified the treaty that presides over it, the U.N. Convention on the Law of the Sea. However, a subsidiary of the U.K. arm of the American company Lockheed Martin, UK Seabed Resources, has two permits for exploratory mining.

In early 2021, the Belgian company Global Sea Mineral Resources (GSR) and the German Federal Institute for Geosciences and Natural Resources (BGR) ran a test in the CCZ with a one fourth–scale 25-metric-ton prototype mining vehicle named Patania II. It was the first mining trial of any kind in the CCZ since the late 1970s, when commercial interest first flared for deep-sea mining during a metal market crunch.

Independent scientists, funded by European public science agencies, observed the trial by placing more than a hundred sensors around the simulated mining activities. "It was by far the most extensive suite of monitoring equipment for any trial that's ever taken place for deep-sea mining technologies," said Massachusetts Institute of Technology's Thomas Peacock, a physical oceanographer who attached a novel deep-sea sediment-monitoring sensor to Patania II.

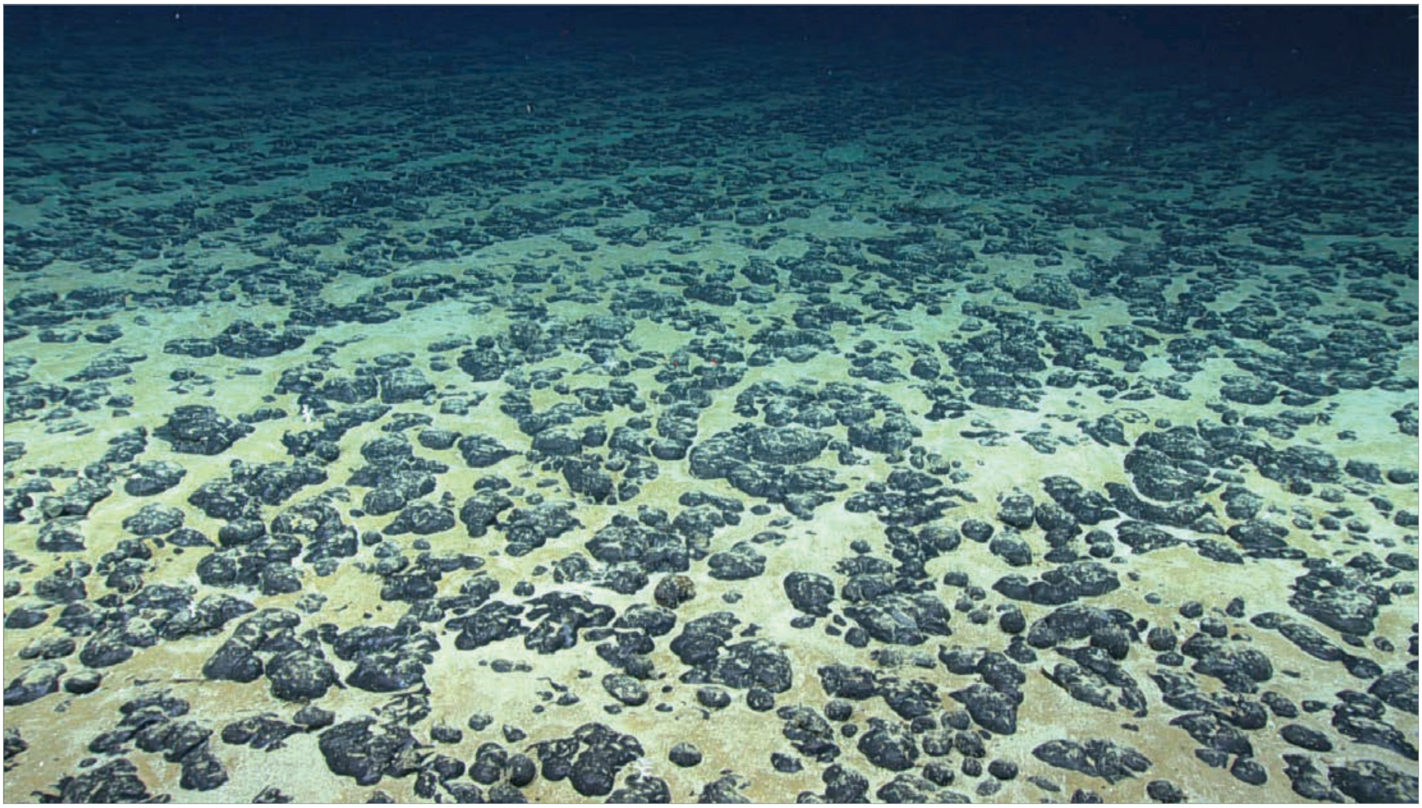
As the industry gathers speed, opponents are sounding the alarm.

More than 600 scientists and policy experts from more than 44 countries have signed a petition calling for a ban on deep-sea mining "until sufficient and robust scientific information has been obtained." And the Patania II expedition was observed by protestors on board the Greenpeace ship *Rainbow Warrior III*.

Separately, BMW, Google, Samsung, and Volvo signed a call from the World Wildlife Fund for a temporary ban on deep-sea mining. The companies promised to keep deep-sea minerals—which are not currently commercially available—out of their products, supply chains, and financial activities.

### The Possible Toll of Mining

Opponents of deep-sea mining say that without a better understanding of its consequences, the risk of environmental damage it poses to the seafloor could be too great.



*Black, potato-sized polymetallic nodules scattered on the seafloor are drawing prospectors for their cobalt, nickel, copper, and manganese. Credit: 2019 Southeastern U.S. Deep-sea Exploration/Office of Ocean Exploration and Research/NOAA*

Although research into the effects of mining on deep-sea ecosystems is scarce, one significant attempt to simulate the long-term effects uncovered some damning clues.

In 1989, German scientist Hjalmar Thiel led a test of deep-sea mining off the coast of Peru. The expedition, funded by West Germany's Ministry of Science and Technology, towed an 8-meter-wide plow harrow on 78 passes through an 11-square-kilometer section of seafloor. The plow disturbed the sediment enough to bury most of the nodules—simulating their removal by mining.

Twenty-six years later, scientists on the R/V *Sonne* visited the site for the first time in decades and found long-lasting damage, said ecologist Erik Simon-Lledó from the National Oceanography Centre in the United Kingdom.

The nodules still sat under a blanket of sediment, and the critters that usually live among the nodules hadn't returned. "Nodules act like trees in a forest," said Simon-Lledó. "If there are no trees, there are no squirrels."

In other research, a group in the Netherlands and Germany simulated the deep-sea food web and showed that removing the nodules resulted in a 31% loss of links in the ecosystem's food chains.

The deep ocean is so poorly understood that in a 30- x 30-kilometer area on the seafloor, a typical research survey might identify hundreds of species living on the nodules themselves—and likely between 70% and 90% would be new to science, Amon said. That doesn't include the multitudes of single-celled organisms living there.

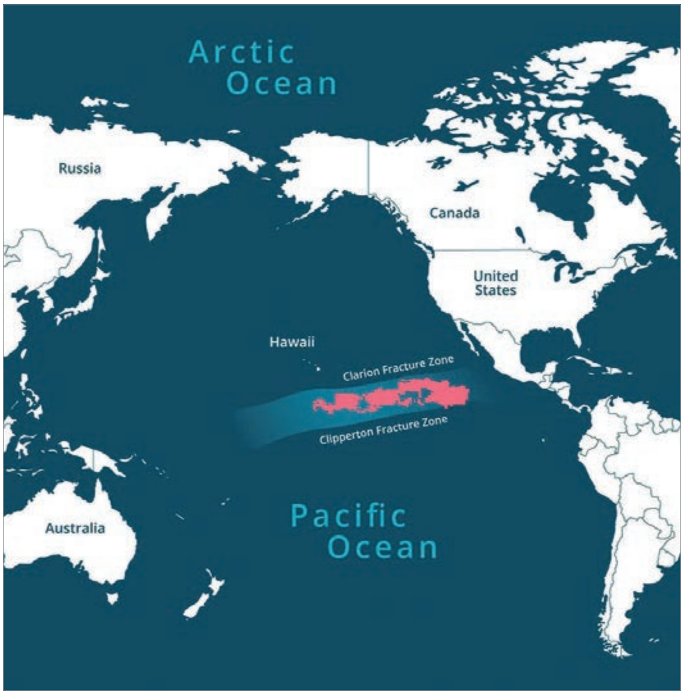
**ETHICAL QUESTIONS ABOUT SCIENTISTS FUNDED BY CORPORATE DOLLARS PLAGUE THE NASCENT INDUSTRY.**

Deep-sea mining could potentially kill microbes in the seabed that sequester carbon dioxide and trigger the release of carbon dioxide stored in deep-sea sediments.

Moreover, many marine animals use sound to avoid predators or find prey, and loud noises from deep-sea mining could impair them, said oceanographer Craig R. Smith from the University of Hawaiʻi.

"Just like you and I get on with our jobs every day, every species in the deep ocean has this role that it plays," Amon said. These jobs are "all linked to services that you and I rely on," like drawing carbon out of the atmosphere, storing heat, and supporting fisheries.

To safeguard vulnerable ecosystems, ISA excluded 1.6 million square kilometers of the CCZ from mining, singling out areas for




*The Clarion-Clipperton Zone spans approximately 4,500,000 square kilometers. Credit: Horizon, CC BY 4.0 (bit.ly/ccby4-0)*

their biodiversity and the presence of seafloor features like seamounts.

Simon-Lledó believes that the biggest open question about deep-sea mining relates to the effects of sediment kicked up during the extraction process. Mining vehicles will muck up bottom waters with fine particles as they roam around sucking up nodules, and operators will discharge sediment carried up in pipes back into the ocean.

Muddy water could clog delicate mucus filters of animals like the giant anemone *Relicanthus sp.* or obscure light that species like the vampire squid *Vampyroteuthis infernalis* and the barbeled dragon fish *Idiacanthus antrostomus* use to mate and hunt. The bottom waters of the CCZ are some of the clearest in the world; sediment collects on the seafloor at only a few millimeters per millennium.

In one modeling study, researchers calculated that a cloud of sediment could travel a maximum of 4–9 kilometers from a study site depending on deep-sea currents. Data from the GSR test with Patania II could provide much-needed field observations.

"There could be very grave consequences for these activities," said Amon, who signed the petition for a moratorium on deep-sea mining. Amon worked on baseline surveys for UK Seabed Resources between 2013 and 2016. "I think we as scientists have a responsibility to connect the dots between our research and informing policymakers, decisionmakers, and, ultimately, humankind," she said.

"I have mixed feelings about the moratorium," said Smith, who has also worked with UK Seabed Resources in the past. Smith has not signed the petition and worries that the moratorium doesn't detail specific research goals for tackling mining impacts or the resources needed to achieve those goals. Because research into the deep sea and mining effects is often funded by private companies and governments keen on mining, he believes research could plummet if a moratorium is enacted.

*These nodules from the Cook Islands in the South Pacific Ocean come in many shapes and sizes. Credit: USGS*

Simon-Lledó, who did not sign the petition, thinks that scientists must only inform others. "As researchers, we have the obligation to provide clear, unbiased information so that an open debate can be held on whether deep-sea mining should go ahead or not." Simon-Lledó's employer, the National Oceanography Centre, has received funds from industry partners, including deep-sea mining companies.

More than half of deep-sea biologists have worked with mining companies or governments for research, biological oceanographer Lisa Levin from the Scripps Institution of Oceanography told *Mongabay* in 2021. Financial support sometimes comes with nondisclosure agreements and can raise ethical questions about scientific independence. Jeff Drazen, an oceanographer at the University of Hawaiʻi, was reportedly at risk of losing his funding after commenting negatively about deep-sea mining, according to the *Wall Street Journal*. Drazen declined to comment on the matter for this article.

Two of the leading mining companies are taking different approaches when talking publicly about potential environmental harm.

GSR managing director Kris van Nijen told Reuters last year that "GSR will only apply for a mining contract if the science shows that, from an environmental and social perspective, deep seabed minerals have advantages over the alternative—which is to rely solely on new and current mines on land."

Chief executive officer of The Metals Company, Gerard Barron, on the other hand, has called the abyssal plain a "lifeless desert" where the effect of mining would be minimal.

### Prospecting Mining's Potential

Although major mining companies have different takes on the possible environmental damage of mining, they promote a shared vision of the industry as an answer to climate change: "The biggest risk to the ocean right now is global warming," van Nijen told *Time*. Barron calls the nodules "a battery in a rock" and "the easiest way to solve climate change."

Unlike most land-based ores, nodules on the seafloor contain several valuable minerals in one package and produce better yields overall. Rich with cobalt and nickel, nodules could supply metals for batteries used to power today's electric vehicles and energy technologies.

A widely cited study by the World Bank and the International Energy Agency estimated that global demand for cobalt will increase by more than 450% by 2050 if the world adopts green technology to cut fossil fuels and limit warming to 2°C. Demand will shoot up by more than 50% for nickel over the same time frame and by 100% for copper.

Mineral economist Ian Lange from the Colorado School of Mines said that the World Bank's analysis involves simplified projections, however, because it assumes that technologies like batteries won't change over time. Battery technologies are evolving to use cheaper metals in place of cobalt, for instance.

However accurate these estimates turn out to be, supporters of deep-sea mining claim that these operations will be more environmentally responsible than those on land.

"I am confident we will be able to show that extracting polymetallic nodules will have a lower impact on the environment than will be the case with the opening of new mines on land or the expansion of existing ones," Chris Williams, managing director of UK Seabed Resources, told the *Guardian*.

**MINING COMPANIES SAY THE SOLUTION TO GLOBAL WARMING CAN BE FOUND ON THE SEAFLOOR.**

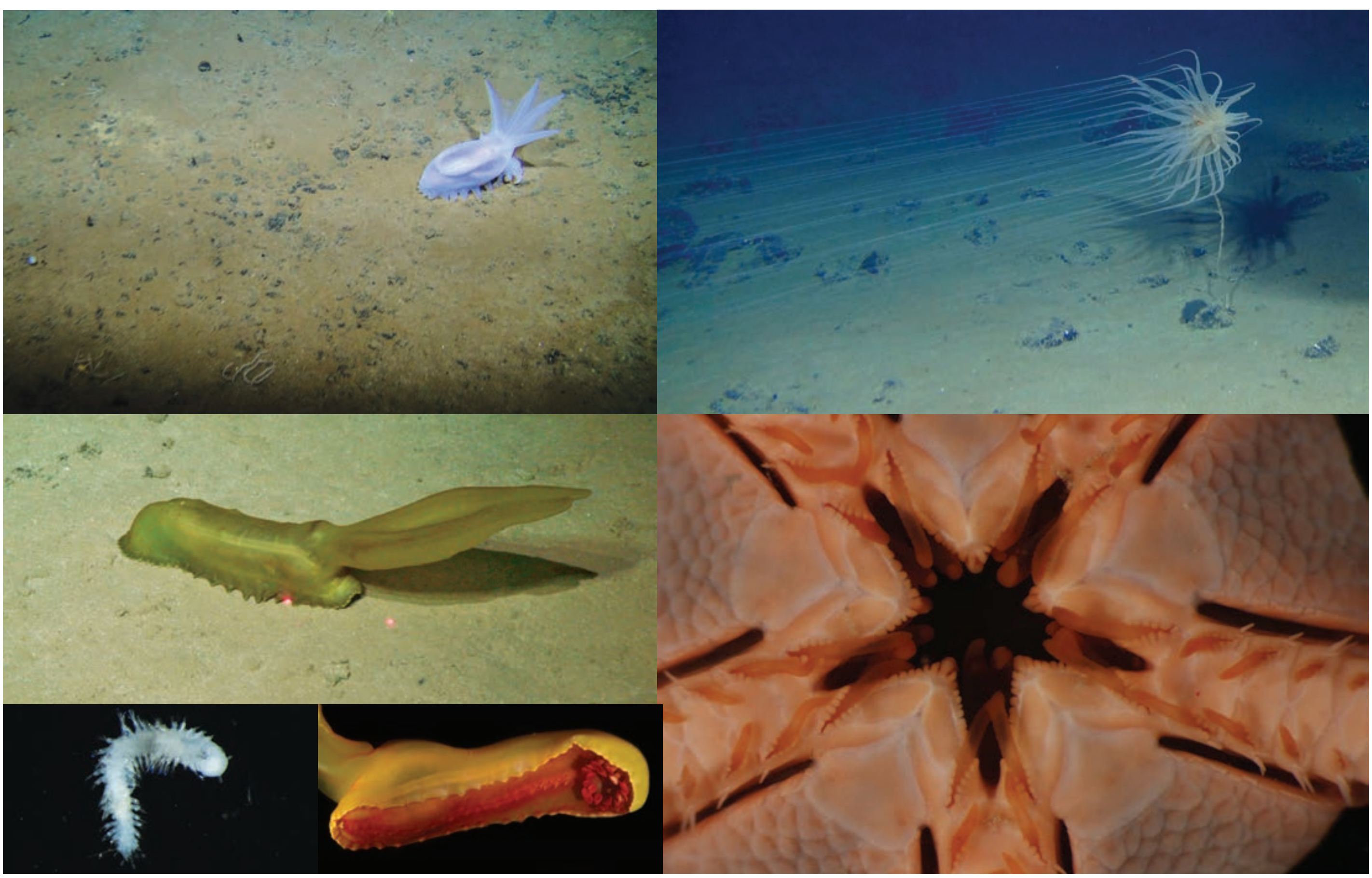
Several groups of researchers are now trying to test that claim.

Two dozen experts in sea- and land-based mining have joined together to begin comparing the two types of operations using common metrics, like biodiversity loss and toxicology. The group was convened in 2020 by the New York–based biologic science nonprofit Cold Spring Harbor Laboratory.

"What's driving us is just the discourse about the idea of deep-sea mining going ahead based on assumptions that may not be supportable," said Verena Tunnicliffe, a deep-sea biologist at the University of Victoria who co-organized the group. Tunnicliffe said she has never been supported by industry funds, but some members of the group have worked with mining companies.

Although the research is ongoing, comparing the two operations is complicated because of the lack of data from the deep sea, she said. "There are people in the group that are beginning to feel that it's just not possible to do a credible job."

Separately, energy and environmental researcher Saleem H. Ali from the University of Delaware has collaborated with industry and ocean health experts to investigate mining on land versus at sea. When it comes to the carbon footprint, the amount of waste generated, and the social impacts,



*Sea cucumbers, brittle stars, worms, and wispy new species related to jellyfish and coral make their home in deep-sea nodule fields. Credit: DeepCCZ expedition* deep-sea mining is a better option than terrestrial mining, said Ali.

"The carbon footprint of deep-sea mining is far less than terrestrial mining," Ali said. "In the case of nickel, it's about 80%. For cobalt, it's still about 30% less." The Metals Company's head of strategy and business development also participated in the research.

### Murky Waters

Nauru's 2-year ultimatum gives experts very little time to answer outstanding questions about the safety and benefits of deep-sea mining. When the countdown reaches zero in mid-2023, ISA is supposed to be prepared to properly evaluate permit requests, including having a framework for environmental impact surveys.

Pradeep Arjan Singh, a doctoral candidate at the University of Bremen, said that the Mining Code has a long list of unresolved issues and principal among them is the question of sharing income. Per the U.N. Convention on the Law of the Sea, the international seabed and its mineral resources are the "common heritage of mankind."

**"THE CONSEQUENCES OF THE COUNCIL NOT BEING ABLE TO MEET THE DEADLINE ARE SOMETHING THAT WE NEED TO SPEAK ABOUT."**

Under one interpretation, all member parties of ISA (167 countries plus the European Union) stand to get some cut of the profits from seabed exploitation. This is uncharted ground for international negotiations, however. Although fishing and whaling treaties have divvied up global ocean resources, they've never required shared revenue like this before. (Simultaneous discussions are underway about whether marine genetic resources, or marine biodiversity, qualify as the heritage of humankind.)

ISA's council, which is responsible for finalizing the Mining Code, has declined to meet virtually and instead postponed all discussions until members can meet in person.

"It's quite a crucial question on how the council is actually going to do all that with what's left of these 2 years," said Singh, who guessed that negotiations on the text of the Mining Code wouldn't resume until later this year. "We're losing time."

Singh said he hopes that members of ISA consider restarting the clock or circumventing the countdown deadline, given the disruption of the pandemic saying, "the consequences of the council not being able to meet the deadline are something that we need to speak about."

### Author Information

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

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# Seismology: A Promising Tool for Monitoring Permafrost

*Researchers used seismic waves generated by cable cars ascending Germany's highest peak, Zugspitze, to more economically observe long-term changes in the permanently frozen rock found near the mountain's summit. Credit: Marcus Rahm, CC BY-NC-SA 2.0 (bit.ly/sa2-0)*

The warming and thawing of permafrost in response to rising temperatures are increasingly destabilizing rock slopes, causing more occurrences of rockfall in recent years. This trend is expected to continue, raising concerns that these hazards could damage expensive infrastructure and disrupt settlements in permafrost regions, including the European Alps.

Obtaining the data necessary to monitor permafrost degradation, however, has been limited by the substantial costs and demanding logistics of the standard tools, such as borehole monitoring and active geophysical imaging. In a new study, *Lindner et al.* investigate the potential to use less expensive passive seismic techniques for long-term permafrost monitoring.

The researchers analyzed continuous ground vibration data from a single seismic station originally installed for earthquake monitoring atop 2,962-meter-high Zugspitze, Germany's highest peak. They analyzed seismic waves generated by cable cars ascending the peak to reveal seasonal variations in seismic velocity as well as an overall decrease in velocity during the observation period, which spanned 2006–2021.

The scientists then compared these observed changes with meteorological data, borehole monitoring data, and electrical resistivity tomography studies. The results indicate that the seasonal fluctuations were caused by freeze-thaw cycles, whereas the long-term seismic velocity decrease was the result of gradual permafrost degradation.

The findings suggest that passive seismology constitutes a promising new approach to continuously monitoring permafrost. According to the authors, future studies should investigate whether denser instrumentation can provide more detailed information about permafrost decay as well as explore additional applications of passive seismic monitoring to environmental questions of broad relevance. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL094659, 2021) **—Terri Cook,** *Science Writer*

# Shedding Light on Microbial Communities in Deep Aquifers

Underground in peridotite aquifers, rock can interact with water to produce hydrogen, which microbes can use to power their cells, research suggests. Yet much of the research on these water-rock interactions has been conducted using water samples collected from open wells or seeps that may have been contaminated by exposure to the atmosphere.

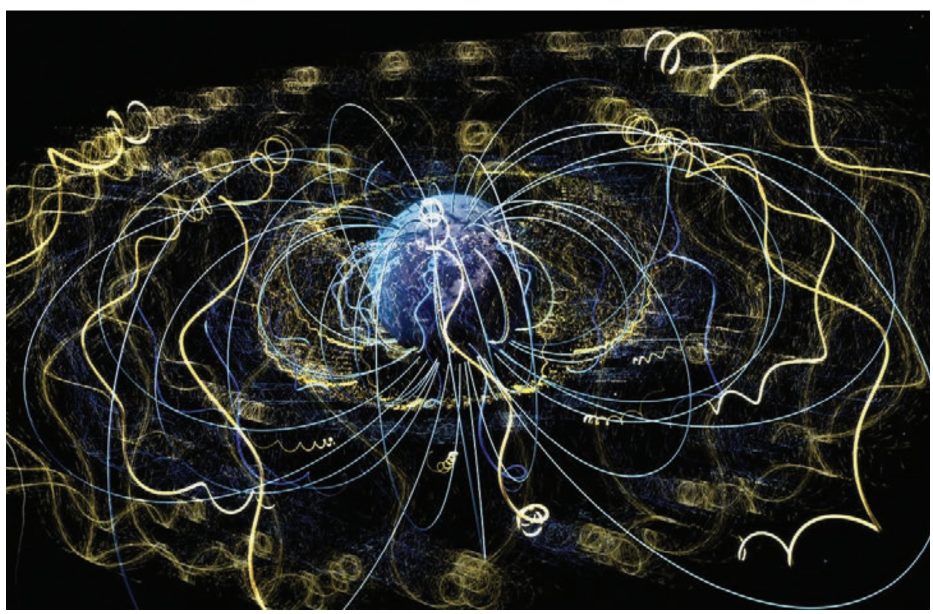
To better understand the impacts on microbial community compositions, *Nothaft et al.* studied the hydrogeochemistry of water-rock interactions in peridotite aquifers at specific depths using a packer system, which includes inflatable rubber bladders, or packers, that can be used to gather water samples from targeted areas unreachable from surface waters. The team collected samples from two 400-meter-deep wells in the Samail Ophiolite in Oman, measuring dissolved gases and microbial community compositions using 16S rRNA gene sequencing.

The analyses revealed an ecosystem teeming with chemolithoheterotrophic bacteria in the class Thermodesulfovibrionia, which yield energy by combining hydrogen oxidation with sulfate reduction and build their cells using organic carbon from the environment. More work is needed to find evidence for microbe-induced sulfurization within these boreholes in Oman, the authors note, but the study provides a new application of a methodology for understanding how hydrologic and biogeochemical processes influence microbial communities in deep aquifers on Earth and perhaps beyond. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006319, 2021) **—Kate Wheeling,** *Science Writer*

# Unifying Models of Chorus Wave Frequency Chirping

Whistler mode chorus waves are electromagnetic emissions common in planetary magnetospheres. Among other impacts, their scattering of magnetospheric electrons is one driver for the formation of auroras. An important attribute of these waves is frequency chirping, in which the frequency of the emission rises or falls nearly monotonically with time.

The existence of chorus wave frequency chirping has been known since the dawn of spaceflight, but to date, no consensus mechanism for it has emerged. Instead, the literature contains a number of mechanisms explaining both its existence and the rate of chirping. For instance, one model relates the chirping rate to inhomogeneities in the background magnetic field, an idea that has been subsequently supported by observations. Another connects the rate to the amplitude of chorus waves; this hypothesis has also received observational support.



*In this artist's conception, trapped electrons spiral about magnetic field lines in Earth's magnetosphere. Credit: NASA Goddard Space Flight Center/Brian Monroe*

*Tao et al.* propose a new model, called Trap-Release-Amplify (TaRA), that aims to unify these seemingly discordant hypotheses, and they conducted computer simulations to evaluate its implications. As in other models, TaRA describes electrons that encounter a chorus wave packet, align their phase with the packet, and then emit new chorus emissions. The electrons propagate opposite to the motion of the wave packet, meaning each interaction progresses through several distinct regions with different physical properties.

The authors demonstrate that TaRA can encompass both the background magnetic field inhomogeneity and wave amplitude hypotheses of frequency chirping. In their model, these mechanisms represent two separate stages of interaction between an electron and the wave packet. Thus, it is reasonable that both of these mechanisms can provide different estimates of the chirping rate and simultaneously agree with physical observations. Those observations, they argue, are simply measuring different stages in the chorus generation process. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2021JA029585, 2021) **—Morgan Rehnberg,** *Science Writer*

# Measuring Sea Level Rise Along Coasts

Earth's ocean is clearly rising. Between the loss of land and sea ice and warmer waters expanding, rising sea level is a global issue. But the equation governing exactly where the land meets the ocean also depends on the land itself. For instance, various forces such as the motion of tectonic plates can cause vertical land motion (VLM) that either exacerbates or mitigates the threat of sea level rise.

VLM is caused by a host of factors. Tectonic forces can drive continents up or down as plates subduct beneath others. But motion can also result from changes in the water content in an aquifer or stored in the land's surface water.

In a new study supported by NASA's Sea Level Change program, *Hammond et al.* used GPS station data from thousands of sites across the planet to create a global map of VLM along the coasts, which, the authors say can be compared with tide gauge data to forecast future sea level rise.

One particularly important cause of VLM is glacial isostatic adjustment (GIA), which describes how Earth's crust rebounds after ice melts away. Similar to how a memory foam mattress doesn't rebound immediately when you roll over, the crust takes time to rebound when large amounts of ice melt. In fact, Earth's crust is still rising in many places in the Northern Hemisphere as it recovers from the last ice age.

Thanks to GIA, the vertical land motion on Earth's continents is upward on average, meaning that the land is moving away from the core. This also means that ocean basins and ice-covered areas are, on average, subsiding. But according to the authors, if GIA were removed from the equation, the reverse would be true: The land would subside and the ocean basins and ice-covered areas would undergo uplift.

*Authors used GPS station data to create a global map of vertical land motion along the shorelines, including the coast of California, pictured here. Credit: William C. Hammond*

The global view of coastal land motion, the researchers say, should help create a reference point for measuring the threat of sea level rise as our planet continues to warm. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2021JB022355, 2021) **—David Shultz,** *Science Writer*

# Subduction Initiation May Depend on a Tectonic Plate's History

Subduction zones are cornerstone components of plate tectonics, with one plate sliding beneath another back into Earth's mantle. But the very beginning of this process—subduction initiation—remains mysterious to scientists because most of the geological record of subduction is buried and overwritten by the extreme forces at play. The only way to understand how subduction zones get started is to look at young examples on Earth today.

In a new study, *Shuck et al.* used a combination of seismic imaging techniques to create a detailed picture of the Puysegur Trench off the southwestern coast of New Zealand. At the site, the Pacific plate to the east overrides the Australian plate to the west. The Puysegur Margin is extremely tectonically active and has shifted regimes several times in the past 45 million years, transitioning from rifting to strike-slip to incipient subduction. The margin's well-preserved geological history makes it an ideal location to study how subduction starts. The team's seismic structural analysis showed that subduction zone initiation begins along existing weaknesses in Earth's crust and relies on differences in lithospheric density.

The conditions necessary for the subduction zone's formation began about 45 million years ago, when the Australian and Pacific plates started to pull apart. During that period, extensional forces led to seafloor spreading and the creation of new high-density oceanic lithosphere in the south. However, in the north, the thick and buoyant continental crust of Zealandia was merely stretched and slightly thinned. Over the next several million years, the plates rotated, and strike-slip deformation moved the high-density oceanic lithosphere from the south to the north, where it slammed into low-density continental lithosphere, allowing subduction to begin.

The researchers contend that the differences in lithospheric density combined with existing weaknesses along the strike-slip boundary from the previous tectonic phases, facilitated subduction initiation. They conclude that strike-slip might be a key driver of subduction zone initiation because of its ability to efficiently bring together sections of heterogeneous lithosphere along plate boundaries. (*Tectonics*, https://doi.org/10.1029/2020TC006436, 2021) **—David Shultz,** *Science Writer*

# River Ice Can Shape Watershed Ecology

*The duration of river ice cover is shrinking in most rivers, including the Little Southwest Miramichi River in New Brunswick, Canada. Credit: Antóin O'Sullivan*

River ice cover not only affects rivers during the winter but can also influence both physical and biological processes throughout the year, including the timing and duration of ecological productivity, light availability underneath ice, and the mixing and distribution of nutrients. Although many rivers around the world experience a crusting of ice during winter months, the duration of ice cover is shrinking. Researchers have been documenting the later freezing and earlier melting of river ice, but few studies have delved into what changing ice conditions might mean for river ecology, especially in smaller river systems and for ecosystem processes like nutrient cycling and productivity.

In a new study, *Thellman and Jankowski et al.* look at how ice cover and duration affect ecosystems. They found that the formation and duration of river ice cover depended on the interaction of climate, river characteristics (including flow; size; and slope, or gradient), and the connectivity of river water to groundwater systems. The breakup of ice is primarily temperature driven, with big swings of temperature leading to mechanical breakup and slow temperature changes leading to gradual melting.

The researchers also note that earlier river ice breakup appears to be most influential for productivity in small rivers. Earlier river ice breakup can increase productivity in the ecosystem, but more frequent ice breakup events during winter can have a disruptive effect on the streambed ecosystem. They note that future research should focus on river processes during the winter months, especially on ice processes in smaller river systems for which other forms of data like satellite imagery are not available. Specifically, the authors suggest studies that move beyond traditional salmonid-focused winter ecology research to include a wider variety of organisms and ecosystem processes. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006275, 2021) **—Sarah Derouin,** *Science Writer*



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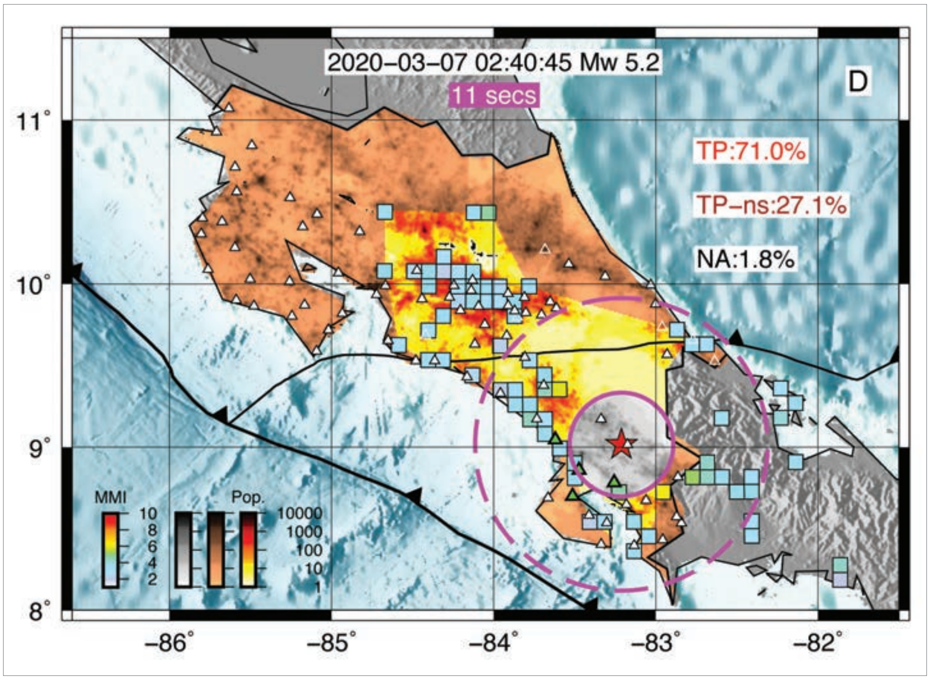
# Good, Soon, and Cheap: Earthquake Early Warning by Smartphone




*Results from the ASTUTI network in Costa Rica for a magnitude 5.2 earthquake in March 2020 are shown here. Warm colors show where and how many people in the country would have received an alert and felt shaking (TP, true positive). The copper-colored map overlay indicates where people would have received an alert but not felt shaking (TP-NS, true positive–no shaking). Gray coloration indicates where people would not have received an alert (NA, no alert) The solid magenta circle shows the estimated position of the earthquake's* S *wave when the network detected the event (11 seconds after it began), and the dashed magenta circle shows the estimated position of the* S *wave 20 seconds after detection. The figure illustrates that after allowing 5 seconds for propagation of the alert, there would still have been 15 seconds for people located near the position of the dashed circle to take protective actions. Squares indicate shaking reported through the Did You Feel It system, with color representing ratings on the Modified Mercalli Index (MMI). Triangles represent stations in the ASTUTI network that triggered the alert (green solid), were active during the event (white outline), and were inactive during the event (white empty). Credit: Brooks et al.*

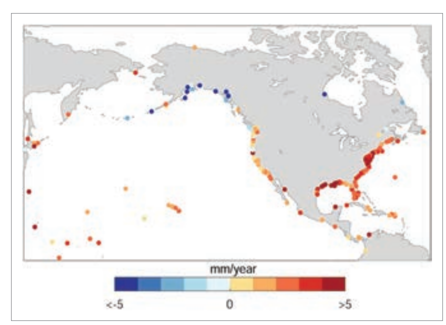
Even short warnings of earthquakes can be crucial in protecting lives and infrastructure, so there is great interest in developing earthquake early-warning systems. Any such system must be reliable and balance sensitivity for events against factors like user tolerance for false alarms in which no shaking is felt. Finding this balance is complicated by the need to have relatively dense sensor coverage not only where people reside but also in adjacent seismogenic regions, which entails high costs if typical scientific-grade instruments are used. However, such costs are prohibitive in many countries where resources are limited

*Brooks et al.* describe very encouraging results from Costa Rica, where ASTUTI (Alerta Sismica Temprana Utilizando Teléfonos Inteligentes, or Earthquake Early Warning Utilizing Smartphones) uses a fixed network of smartphones. The researchers' data indicate that such networks can be highly effective and that they can be installed and operated at relatively low cost, bringing the benefits of earthquake early warnings to a broader portion of the world's population. (https://doi.org/10.1029/2021AV000407) **—Peter Zeitler**

# Sea Level Science Coordination: A U.S. and Global Concern

Sea level rise, one consequence of the changing climate, is a global problem with direct and indirect effects on many sectors of society. As sea level rise is projected to accelerate in the coming decades, there is an urgency to make science-based information available to stakeholders to underpin adaptation measures.

A commentary by *Hamlington et al.* addresses how NASA and NOAA, two U.S. government agencies that provide sea level observations and science, can coordinate efforts to serve the needs of stakeholders. The authors recommend continued monitoring of sea level change, developing integrated science products, improved collaboration with other organizations that distribute sea level science and guidance on regional and local levels, and coordinating delivery of sea level products to stakeholders with diverse needs. Coordination across NOAA and NASA on sea level science offers the added benefit of broadening collaboration on issues related to coastal hazards and resiliency. (https://doi.org/10.1029/2021AV000418) **—Eileen Hofmann**




*The more-than-30-year record of relative sea level trends measured and computed by NOAA shows that sea levels have increased (warm colors) along most U.S. coasts. A direct consequence of this sea level rise is increased flooding in coastal communities. Credit: Hamlington et al.*

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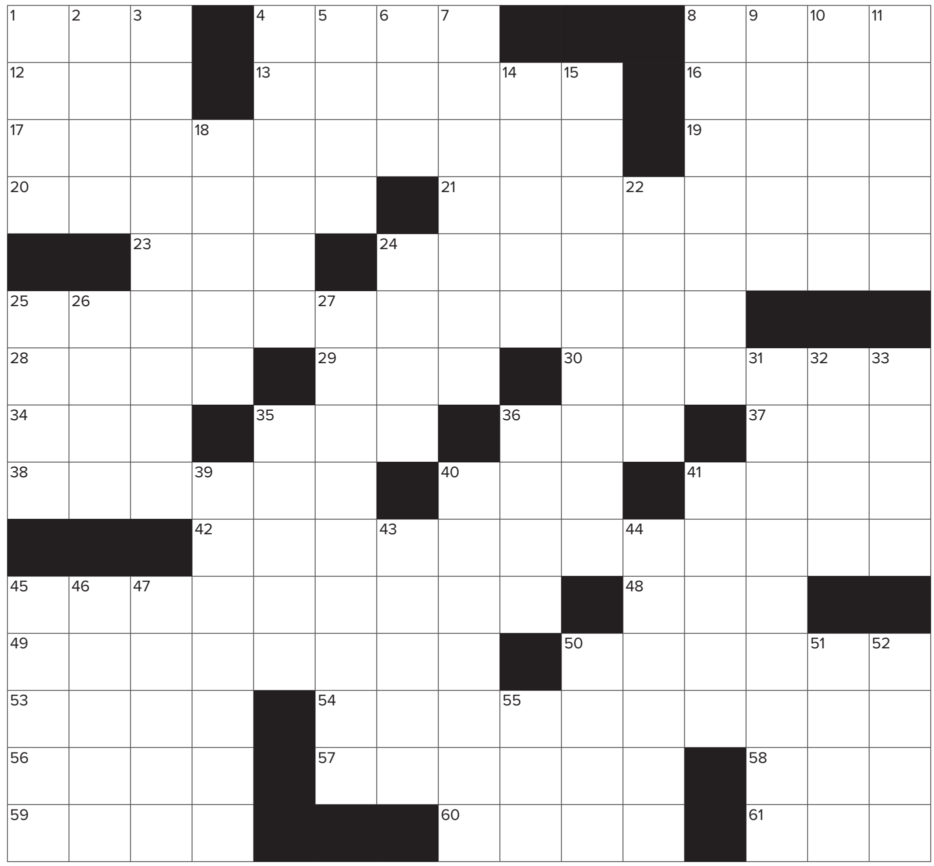
The USC Viterbi School of Engineering is among the top tier of engineering schools in the world. It counts 189 full-time, tenure-track faculty members as well as 117 full-time, research-track and teaching-track faculty. The School is home to the Information Sciences Institute and is affiliated with the Alfred E. Mann Institute for Biomedical Engineering, the Institute for Creative Technologies, and the USC Stevens Center for Innovation. Research expenditures typically exceed $210 million annually.

*The USC Viterbi School of Engineering is committed to enabling the success of dual career families and fosters a family-friendly environment. USC is an equal opportunity, affirmative action employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, protected veteran status, disability, or any other characteristic protected by law or USC policy. USC will consider for employment all qualified applicants with criminal histories in a manner consistent with the requirements of the Los Angeles Fair Chance Initiative for Hiring ordinance.*

# Treasures of the Sea

By Russ Colson, Minnesota State University Moorhead



**ACROSS**

**1** Big shot (abbr.)
**4** To torque, with no vowel
**8** A barbecue favorite
**12** The Paleozoic, for example
**13** From *The Princess Bride*: "aasss youuu ____"
**16** Nanjing nanny
**17** About 5.7 million of these are harvested from the ocean each year, perhaps unsustainably (with "t" sounds)
**19** Othello bad guy
**20** Not late
**21** Not anymore
**23** Beverage name seen in "folktales" and "chorales"
**24** A swamp, or the University of Florida?
**25** Each year the oceans absorb 2.5 trillion of these, moderating greenhouse gases (with "k" or "c" sounds)
**28** Some Canadian restaurants and, formerly, Tokyo
**29** With -pelagic, the oceanic photic zone
**30** ____ of London
**34** Constellation not visible in late August
**35** Yummy ending for "cook" or "good"
**36** Location of Christ the Redeemer statue
**37** Emergency response team (abbr.)
**38** Wash out the gangue from gold, say
**40** Type of star, in Westerns
**41** What certain wasps do to make nests of mud
**42** The ocean moves 10 trillion trillion of these every second (with "e" sounds)
**45** Heroic journey to space. Or a dance competition. Or a video game
**48** Commodity of the North Sea or Gulf of Mexico
**49** Final Fantasy XIV task, or a gender variation on a common saying, "____ ____ ____ an island"
**50** Enter text again
**53** ____, tens, hundreds
**54** Each year you use 17,000 of these produced in oceans, providing more than half your personal needs (with "o" sounds and abbr.)
**56** Shrek, for example
**57** Two playing cards with non adjacent ranking, named after particular rankings
**58** "Homemade" roadside bomb (abbr.)
**59** Information
**60** RAF ground crew
**61** Navigation tool (abbr.)

**DOWN**

**1** Reject
**2** Scarce element in ocean water since Precambrian times
**3** Half a pair of baggy breeches?
**4** Twice a million bytes
**5** Spouse
**6** You just can't stand to do it
**7** Titanic wave
**8** A downpour and what it's made of
**9** Ready here!
**10** Tag 'em and ____
**11** Edge of an ocean
**14** Environmental threats off the Turkish coast, self-defense coatings on marine hagfish, or unruly children
**15** Oceanic zone of sharply changing salt concentration
**18** Places used to store cattle feed
**22** Combined with gist, means a mountain expert
**24** Notches between hills
**25** Oceanic source for dietary emulsifiers
**26** Thought
**27** Drowned atoll or coral-capped, flat-topped submarine mount
**31** Annual job: ____ ____
**32** Pulled behind, like an ocean bottom trawl
**33** Hoping for a seat, you fly ____ (abbr.)
**35** When needed, as in "attach documents ____ ____" (abbr.)
**36** Common location for giant tube worms of the deep Pacific
**39** Above an ocean, poetically
**40** Given two, and not needing both, a conservationist wouldn't just ____ ____
**41** Yahweh, Krishna, or Zeus, for example
**43** Sounds like "seas"
**44** When the island map fails to show the location of the buried treasure?
**45** Hair holder
**46** Group of islands in the southwestern Pacific
**47** Amber or weather, for example
**50** Johnson, Gibraltar, or sedimentary
**51** Chirp
**52** They don't justify the means, some say
**55** Where the apple never falls, relative to tree location

See p. 46 for the answer key.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