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SCIENCE NEWS BY AGU

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A Coral Reef in the Australian Desert

Mercury Pollution Goes Deep

Subsea Cables Get SMART

SCIENCE AT THE SEAFLOOR

Researchers are taking long looks at the bottom of the ocean.

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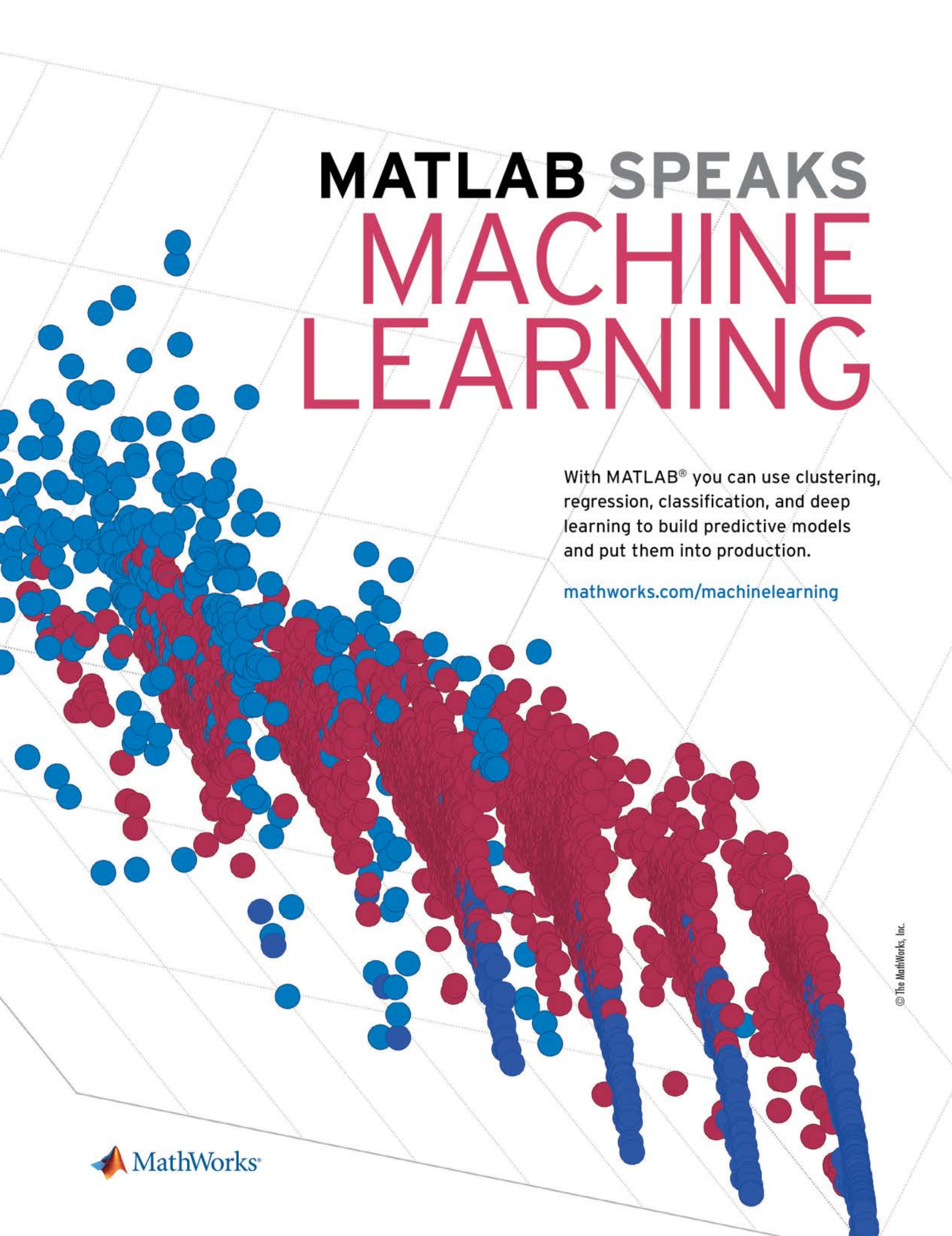
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What's Up at the Bottom of the Ocean?

The seafloor is not as serene as it seems. In fact, it's a busy, flexible hub of scientific activity.

Our changing climate and the crucial nexus of ocean and atmosphere are driving scientists to collate and curate a centralized database of seawater oxygen isotope data. Such isotopes can inform us about processes related to ocean circulation, riverine input, ocean-atmosphere water exchange, and continental ice sheet volume on timescales spanning glacial–interglacial periods and longer, write Kristine DeLong, Alyssa Atwood, Andrea Moore, and Sara Sanchez, but efforts to create a machine-readable, metadata-rich database consistent with findability, accessibility, interoperability, and reusability (FAIR) standards has been a challenge for more than 30 years. Still a work in progress, the new database has already revealed discrepancies between tracked and modeled estimates of coral-derived isotope variability, as well as enormous swaths of the ocean that lack any isotope data at all. Read "Clues from the Sea Paint a Picture of Earth's Water Cycle" on page 38.

Far from having a lack of data, scientists tracking the origin of a 2021 oil spill in the eastern Mediterranean had to grapple with the (literal) chaos of eddies and currents, multinational ship traffic, and satellite-derived radar imagery. Using innovative mathematics to better resolve geometry in the ocean's dynamical systems, they developed a model "to keep turbulence from serving as a cover for environmental pollution." Learn more about "Seeing Through Turbulence to Track Oil Spills in the Ocean" from Guillermo García-Sánchez, Ana M. Mancho, Antonio G. Ramos, Josep Coca, and Stephen Wiggins on page 32.

Lack of data, arrays of data: In "Grains of Sand: Too Much and Never Enough," Alka Tripathy-Lang explores sand mining and its discontents. Sand is second only to water as an exploited natural resource (used in everything from concrete to smartphone screens), but scientists, engineers, and industry officials are quick to note that the sands that anchor seafloors and deserts are not created equal: "The crisis that exists around sand is mostly a crisis of sand sustainability, not of availability," said Daniel Franks of Australia's Sustainable Minerals Institute. Dig deeper on page 24.

Seafloor stories also appeared at AGU's Fall Meeting 2022. Some scientists are investigating how benthic amphipods are providing clues to marine mercury pollution ("A Potent Pollutant Comes to Rest in the Deepest Ocean Reaches," p. 5), whereas others are considering how the subsea cables that transmit cat videos and financial transactions could also contain temperature, pressure, and seismic sensors ("Making Underwater Cables SMART with Sensors", p. 17). Finally, we are reminded that the seafloor can define regions millions of years after the actual sea has disappeared, as we learn in "A Mysterious Dome Reveals Clues to Australia's Miocene History" on page 14.

So what's "Happenin' on the Ocean Floor" (see this issue's crossword puzzle on p. 49)? A lot of science, and *Eos* is happy to delve deep.

Caryl-Sue Micalizio, Editor in Chief

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Randy Fiser, Executive Director/CEO

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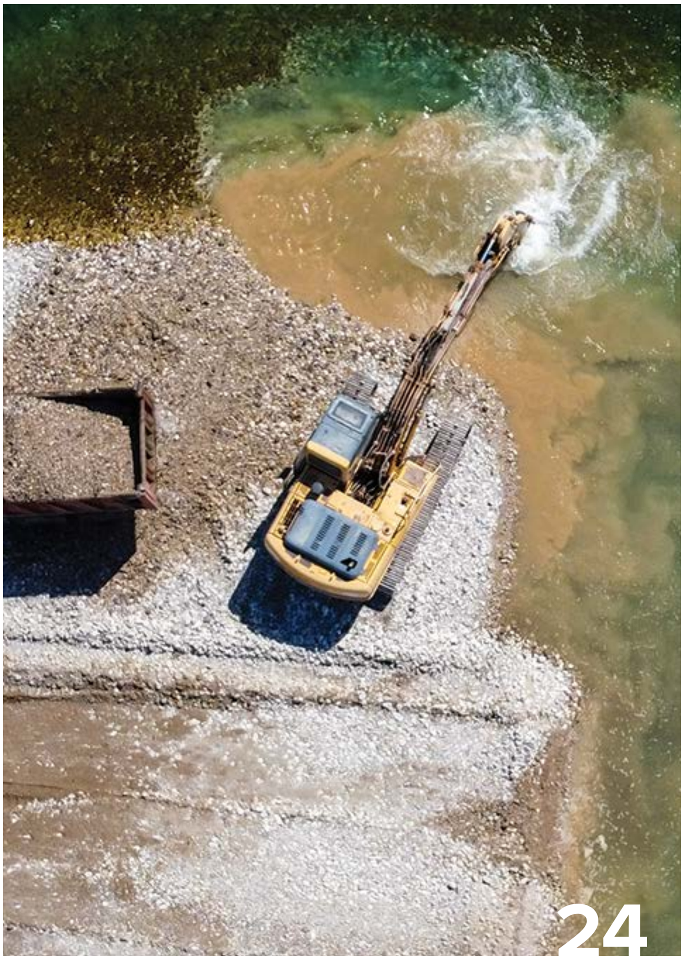

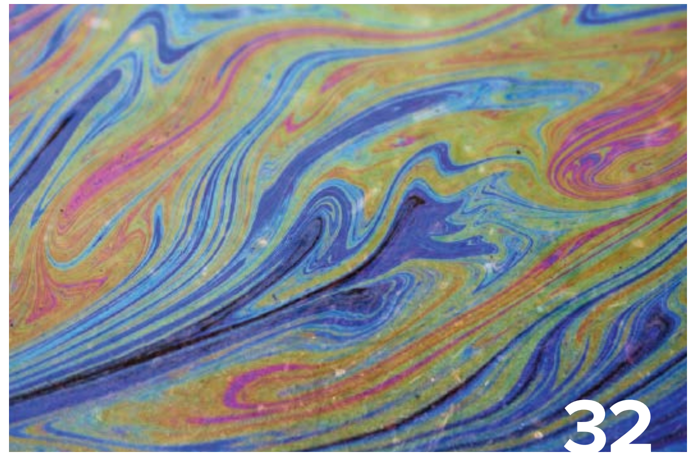

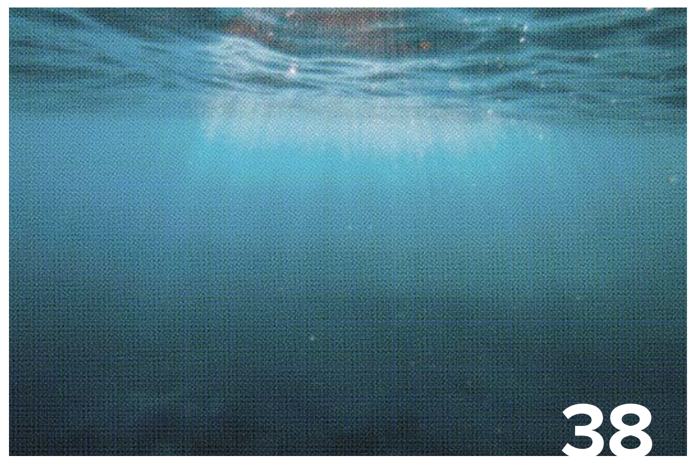

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By Alka Tripathy-Lang

Sand is the second-most exploited natural resource on Earth, but not all sand is created equal.

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Sand drains from an unnamed river into Murchison Sound close to Qaanaaq in northwestern Greenland. Credit: Nicolaj Krog Larsen

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Social Media Posts Reveal Human Responses to Deadly Tongan Eruption

The January 2022 eruption of Hunga Tonga–Hunga Ha'apai was among the most powerful ever recorded. It generated atmospheric shock waves that circled the globe, and its impacts claimed the lives of six people, including two in Peru, 9,600 kilometers away from the volcano in Tonga.

In the aftermath of the eruption, social media videos depicted the nation of Tonga inundated by ashfall and tsunami waves. Now, scientists are examining these videos to quantify human responses and improve warning systems; they presented their research at AGU's Fall Meeting 2022 (bit.ly/Tonga-social-media).

"Gauging the social response to events as complex as this [is] difficult, other than through interviews after the fact," said Jacob Lowenstern, a volcanologist with the U.S. Geological Survey (USGS) and chief of the Volcano Disaster Assistance Program who was not involved in the study. Quantifying that social response, however, could improve disaster preparedness in the future.

Hunga Tonga–Hunga Ha'apai erupted on 15 January 2022, releasing the colossal ash plume seen above. Credit: NASA/Kayla Barron, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

Predicting Unpredictable Reactions

People behave unpredictably during disasters, said Dare Baldwin, a psychologist at the University of Oregon who contributed to the study. "It's important to understand the diversity of reactions so we can tailor education and early warnings to different people."

"Knowledge of what people actually do, rather than what they report they do, informs improved education and preparation for such events."

To improve messaging and warning systems in hazard-prone regions, Sara McBride, a social scientist from USGS who presented the research, used closed-circuit television footage and social media clips to gauge how people responded to the Tongan eruption.

"A lot of physical scientists talk about how unique this event was," McBride said. "We also wanted to understand people's behavior during the crisis, whilst respecting the enormous challenges they faced."

The researchers collected 480 videos that were posted to Reddit, Twitter, TikTok, and YouTube following the event, including 180 videos filmed in Tonga itself, plus tsunami footage from 11 countries across the Pacific.

McBride and a team of geoscientists and social scientists—including Tongan researchers and those involved in the Pacific tsunami response—watched the videos to identify what people did during and after the event.

They analyzed the videos using a method previously established to quantify earthquake response. This included noting whether people evacuated, took cover, or protected others, for example.

Shirley Feldmann-Jensen, a professor of emergency services administration at California State University, Long Beach and a pioneer of the video analysis method, said she is pleased to see other researchers apply the technique to different natural disasters. "Knowledge of what people actually do, rather than what they report they do, informs improved education and preparation for such events," she said.

One Eruption, Multiple Hazards

The videos captured an ash cloud burgeoning over Tonga. This was closely followed by at least 13 separate shock-wave-type booms around the archipelago that coincided with tsunami waves that lurched across the Pacific.

Baldwin said the eruption's onset and early shock waves may have warned nearby communities of the devastating effects to come. "What was hopeful was that we saw quite a few videos where people seemed to have proactively taken protective action, like filming from up high and a fair distance from shore," she said. Similarly, McBride noted that people tended to evacuate once they saw tsunami waves breaching seawalls.

But scientists have found that when faced with multiple hazards, such as earthquake and tsunami effects, the response is more

Ashfall and tsunami waves damaged islands throughout Tonga following the Hunga Tonga–Hunga Ha'apai eruption. Credit: New Zealand Air Force/Wikimedia Commons, CC BY-4.0 (bit.ly/ccby4-0)

haphazard. Under these circumstances, people tended to congregate with others rather than protect themselves by taking shelter or moving to high ground. "We saw that exposure to cascading hazards like this can really confound people, and understandably so," said McBride.

The findings highlighted the growing need for multihazard drills, McBride said. Every year, millions of people across the world practice earthquake drills by taking part in the Great ShakeOut, but multihazard drills are much more rare. Currently, New Zealand is leading the way with its multihazard ShakeOut, which includes an earthquake drill and a tsunami hīkoi (an evacuation walk).

It makes sense to combine these drills, McBride said, both to save time and to better simulate simultaneous hazards. Multihazard drills could prepare communities to respond and clarify dizzying hazards that might otherwise muddle life-and-death decisions.

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

A Potent Pollutant Comes to Rest in the Deepest Ocean Reaches

Since the Industrial Revolution, tens of thousands of tons of mercury have entered the world's oceans, traveling through marine food webs and into the fish we eat. And each year, an estimated 200–600 metric tons of the toxic metal settle beneath sediments on the seafloor, where they can no longer affect human health. A lack of data, however, has prevented scientists from understanding just how much mercury gets locked away in the deepest parts of the oceans.

An international team of researchers braved those depths. Using seafloor landing rigs to snag sediments and bottom feeders from trenches in the western Pacific, they found accumulations of mercury far beyond what researchers had expected for the deep ocean.

"This knowledge can help us develop more effective mercury management targets and measures based on a complete understanding of the global mercury cycle," wrote Maodian Liu, one of the researches and a postdoctoral fellow at the Yale School of the Environment, in an email.

The group presented its findings, published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/deep-ocean-mercury) and *Environmental Science and Technology Letters* (bit.ly/mercury-bioaccumulation), at AGU's Fall Meeting 2022.

An Impossible Lift

Harvesting sediments from such depths was a Herculean challenge.

Liu's colleagues sailed the Chinese research vessel *Zhangjian* over the Bougainville, Mariana, Massau, and New Britain trenches. At each site, the researchers deployed autonomous landers—"basically a metal frame that

"This knowledge can help us develop more effective mercury management targets and measures based on a complete understanding of the global mercury cycle."

supports a host of scientific instruments," wrote Yunping Xu, director of marine science and technology at Shanghai Ocean University and a coauthor of the study, in an email to *Eos.*

One lander included cages stocked with stinky mackerel to lure amphipods—shrimplike animals that crawl along the trench

Researchers measured mercury levels in amphipods collected from deep ocean trenches. Credit: Jiulin Chan

Yunping Xu (left) and a colleague collect sediment retrieved from the seafloor. Credit: Zhilian Cen

floors, scavenging the mercury-tainted organic matter that drifts down from above.

The landers plummeted to the seafloor—almost 11 kilometers for one trench—where they gathered cylinders of sediment, or cores, before resurfacing after 2–3 hours. When trapping amphipods, the researchers' wait grew to 12 hours.

"You've got to admire the technical skill," said Peter Outridge, a research scientist with the Geological Survey of Canada who was not involved in the study. "You're on a ship bobbing around the ocean, and you're trying to bring a core back up to the surface from six and a half kilometers down, intact. That's pretty spectacular." Outridge belongs to the only other group to have measured mercury accumulation in deep-trench sediments.

To add to the challenge, a storm greeted the researchers over the Mariana and Massau trenches. "Our biggest feeling was 'dizzy,'" wrote Xu. "We even waited for almost 1 week until the weather was temporarily suitable."

High Numbers at Low Depths

The researchers collected nine cores and 12 amphipods. Back in the lab, they analyzed the sediments and dissected the animals to determine how much mercury they had ingested. Through the layers of sediment, the scientists found mercury burial rates up to 400 times higher than earlier estimates suggested for the deep ocean.

The amphipods, on average, harbored more than twice as much methylmercury—a particularly toxic form of the metal—as their counterparts in shallower water. Biologists have not yet examined how the toxin might affect the crustaceans' health, Liu said.

"You're on a ship bobbing around the ocean, and you're trying to bring a core back up to the surface from six and a half kilometers down, intact. That's pretty spectacular."

The team estimated that up to 17,000 metric tons of mercury could have settled into deep-sea trenches since 1900—equivalent to 28% of the amount in the entire ocean from human activity. This amount makes the trenches a significant sink because they occupy less than 0.5% of Earth's seafloor area. Their V shapes, the researchers believe, concentrate sinking material the way valleys on land funnel rainwater.

Outridge cautioned that data from one or two cores per trench may not be enough to determine exactly how much mercury is locked away. But overall, he said, the team's findings agree with those of his own group.

Mercury buildup in the sediments accelerated over the past 120 years as industries released greater amounts of the metal, the authors said. Their analysis suggests that most of that mercury floats down from the atmosphere, hitching a ride to the deep sea on bits of sinking organic matter.

But whereas some mercury makes the trip in decades, the bulk of it takes centuries—sometimes millennia—to finally nestle into the seafloor, Outridge noted. He compared its lingering presence in the water column to carbon dioxide emissions in the atmosphere: "Most of it's still going to be around in a hundred years," he said. "It takes a while."

By **Sean Cummings** (@SciNonficSean), Science Writer

Could Floating Solar Panels Help Mitigate Climate Change?

In 2022, a floating solar photovoltaic (floatovoltaic) power generation system with an installed capacity of 1.972 megawatts was installed in the Neipuzi Reservoir, located in Minxiong Township, Taiwan. Credit: Ministry of Economic Affairs Water Conservancy Agency

Many countries bet on solar panels when engaging in the switch to cleaner energy. But the technology requires much larger areas than conventional fossil fuel plants to generate the same amount of electricity. An emerging solution to save space is to float the panels on bodies of water: floatovoltaics. Scientists believe this new approach could help solar energy to scale globally and fight climate change, but its environmental impacts are largely unexplored.

The world's first commercial floatovoltaic system was installed on an irrigation pond at a California winery in 2008. Since then, bigger plants with a capacity of hundreds of megawatts have been built on lakes and hydropower reservoirs in China, and more are planned in Southeast Asia and Brazil.

"Floatovoltaics is one of the fastest growing power generation technologies today and a promising low-carbon energy source," said aquatic ecosystem ecologist Rafael Almeida, an assistant professor at the University of Texas Rio Grande Valley.

Almeida explained that ideally, floating panels are placed in human-made bodies of water, such as irrigation channels and the reservoirs of hydropower plants, not taking up land that could otherwise be used for nature preserves or food production. Reservoirs at hydropower plants, especially, have the advantage of already having the infrastructure to distribute electricity.

Almeida and his colleagues calculated the potential of countries worldwide to use floatovoltaics on the basis of the area of their hydropower reservoirs. They found that countries in Africa and the Americas have the highest potential of generating energy through the technology. Brazil and Canada, for example, could become leaders in the sector because they require only about 5% reservoir coverage to meet all their solar energy demands until midcentury. The scientists presented their results at AGU's Fall Meeting 2022 (bit.ly/AGU22-floatovoltaics).

Assessing the Environmental Impact

"We have to seriously consider all possibilities to increase low-carbon energy production while minimizing land use intensities," said Almeida. "But we also need to understand how to reduce unwanted social and ecological repercussions," he added, explaining that we still know little about the impacts of covering large swaths of water with solar panels.

Regina Nobre, a freshwater ecologist at Paul Sabatier University in Toulouse, France, agreed. Nobre was not involved in the recent research but is part of a group that has just started a pioneering effort to monitor the environmental impacts of floatovoltaics in old gravel pit lakes in Europe. These pits were originally created for mining but naturally fill with river water when abandoned and host diverse aquatic life. Nobre doesn't have results yet but believes the evidence of the groups environmental impact study will be crucial for policymakers.

"This technology is growing fast, and we urgently need more data to understand the impacts and give a better direction for environmental agencies and public policies," she said.

For one thing, extensive panel coverage could block light from penetrating the water, Nobre said, altering the feeding and reproduction patterns of algae, which could lead to oxygen depletion in the lake and have cascading effects on the whole ecosystem, harming local fisheries and other wildlife.

Another possibility is that the panels could interfere with the exchange of greenhouse gases such as methane between the water and the atmosphere, perhaps offsetting decarbonization benefits. But the real consequences are unpredictable without studies and will likely vary with different panel designs, area coverage, and landscapes, both scientists pointed out.

"We need to take a precautionary approach," said Almeida. "On one hand, we can't put too many barriers to this potentially important sector to advance, but, on the other hand, we need to understand the trade-offs and fill our prevailing knowledge gaps with more studies."

By **Sofia Moutinho** (@sofiamoutinhoBR), Science Writer

How Climate Change Is Affecting Women in the Amazon

According to the United Nations (U.N.), the effects of climate change are not gender neutral: Women and girls are hit the hardest, as the climate crisis deepens already existing gender inequalities.

This is especially true in the developing world. According to a 2022 U.N. report, women experience lower survival rates when faced with environmental disasters. They are also highly vulnerable to gender-based violence in the aftermath of extreme events. Agriculture, a deeply weather-dependent activity, is still the largest employer of women in low- and lower-middle-income countries. Though they are almost half of the agricultural workforce globally, women own less than 13% of agricultural lands, according to the U.N.

In the Amazon, changes in hydrological cycles pose a special threat to traditionally organized groups. Women bear a good part of the brunt, according to Luisa Viegas, an ecology researcher at the Federal University of Bahia in Brazil. "The change in river levels affects riverine communities, and when extreme events happen, women are especially affected, as they are usually home and take up most of the domestic work," Viegas said.

Research has consistently pointed to increasing changes in rain cycles and drought in the Amazon. One study suggested that areas deforested for more than a decade receive less rainfall than others during the dry season (bit.ly/Amazon-precip-deforestation). NASA released another study in which researchers concluded that the atmosphere over the rain forest has been increasingly dry as a result of deforestation and the burning of forests (bit.ly/drying-Amazon). A review found that changes in land use, especially in the southern Amazon, affect atmospheric circulation: The regimes of dryness and rainfall are quickly changing (bit.ly/Amazon-hydrology).

"When extreme events happen, women are especially affected, as they are usually home and take up most of the domestic work."

Traditional communities that work the land, especially women who care for small family farms, are feeling those changes already. A primary impact is on food security, observed Mônica Vasconcelos, a sociobiodiversity researcher at the State University of Amazonas. In the Negro River region close to Manaus, capital of Amazonas state, rising temperatures decrease outdoor working hours. Nearer the Juruá River (in the west), flooding extremes mean reduced cassava production.

"The result of both flood and drought is increased food insecurity and less revenue for local communities. For women it is even worse, as they have a double work journey and do not receive twice the compensation," Vasconcelos said.

In Brazil, women are a powerful workforce behind family farming—according to Brazil's National Supply Company (CONAB), female participation was 80% higher than male participation in family farming in 2019. Family farms in the Amazon are particularly vulnerable to flooding and drought. "Soils in the Amazon are really acidic, so the overflow of rivers helps balance the soils' pH," said Marcela Vecchione, an Amazonian studies researcher at the Federal University of Pará. Women usually sow the floodplains after the rainy season, but the lack of [accurate precipitation forecasting] harms the management of small agricultural systems," she said.

This limitation not only confounds the agroecological calendar but also harms the collection of seeds for future production seasons, Vecchione said.

Finding Solutions

Challenged with the current scenario, women in the Amazon are working on solutions. One project addressing the issue is Amazonian Agroecological Logs (Cadernetas Agroecológicas na Amazônia), in which women keep track of the food they produce, consume, exchange, donate, and sell. Created in 2011 at the Center for Alternative Technologies of the Zona da Mata region in the eastern part of Brazil's Minas Gerais state, the log system is familiar to rural communities in Brazil.

This year, the Federation of Organs for Social and Educational Assistance (FASE), a nongovernmental organization, together with the nonprofit Dema Fund, is undertaking a project in Pará state, in the Amazon region. According to Beatriz Luz, an educator at FASE and the Dema Fund, the organization is following about 90 women in Pará state.

"Every day, women write down all they do with their production and account for what they would pay or get, so they have an idea of their work's worth—something that has been historically made invisible," said Luz.

Leila Mafra Conceição is one of the women involved in the agroecological log project in the rural area of Camiranga, Pará state, Brazil. Conceição is filling a log in a workshop that took place in May 2022. Credit: Suelany Sousa da Silva/FASE/Fundo DEMA, All rights reserved

In a previous round of the project, the logs revealed that women made an average of 400–600 reals ($80–$120) a month—about half of Brazil's current minimum wage. Even that value, according to Luz, is an underestimate, "as women do not always note the seeds they exchange, for example."

The project sheds light on invisible work, fosters food security, and highlights local biodiversity, Luz explained. (One log documented 246 species in a single backyard garden plot.) The logs have also cataloged rural work, allowing the women to apply for retirement benefits from the government.

By keeping effective records, women farmers are able to scale their production—some family farms manage their crops in a way to sell to local schools or businesses, for instance, and others diversify to extend growing seasons or include animal husbandry.

*Medicinal plants, along with food, are cultivated by women on family farms in Brazil. Coerama (*Kalanchoe brasiliensis*), kiss-me-quick (*Portulaca pilosa*), and wax mallow (*Malvaviscus arboreus*) are among the herbs most commonly cultivated and have been extensively used during the COVID-19 pandemic. This image was taken at a workshop in July 2022 in Jacarequara, Pará state. Credit: Suelany Sousa da Silva/FASE/Fundo DEMA, All rights reserved*

In another project, this one close to the Negro River in São Gabriel da Cachoeira, Amazonas state, members of the Indigenous Women's Association of Alto Rio Negro are working to pass on and preserve their Traditional Knowledge of agricultural production. Older women lead workshops in which they teach younger generations to grow beans, cassava, and other crops. It has been a challenge to follow the tradition by the book as rainfall patterns change, said Elizângela Costa, a Baré Indigenous leader who directs the Women's Association.

"We're looking for new alternatives at the same time we want to protect our Traditional Knowledge and value our fellow women. It hasn't been easy, but it's important to care for our community, our territory, and our future generations," Costa said.

By **Meghie Rodrigues** (@meghier), Science Writer

Protecting Poor Neighborhoods from Landslide Risk

A 2017 landslide in Freetown, Sierra Leone, killed an estimated 1,100 residents, largely in informal settlements. Credit: Mark Stedman/Trocaire, CC BY 2.0 (bit.ly/ccby2-0)

Landslides adversely affect low-income regions, killing an estimated 4,600 people and causing $20 billion in damage each year. Those grim numbers are expected to grow, thanks to the clash of climate change and urbanization.

The risk of damage is especially elevated in the tropics, where poverty rates are high and informal settlements creep up steep hillsides. The tropics also face more intense weather systems under climate change, with extreme rainfall further slackening the soil. Landslide disasters have become 10 times more frequent in the past 50 years, with 80% of fatal landslides occurring in the tropics.

To measure the growing threat, researchers have developed a new model to quantify the interplay of climate change and urbanization. They recently applied the model to five tropical cities and found that, residents in informal settlements are up to 500% more exposed to landslide risk than their more urbanized neighbors. These results, which were shared at AGU's Fall Meeting 2022, suggest that landslides aren't just physical processes but economic, political, and social ones, too (bit.ly/AGU22-landslide-risk).

Tropical Models

According to the United Nations, most of the world will live in the tropics by 2050. And as the population climbs, more people will crowd onto steeper slopes circling tropical cities. These unplanned neighborhoods increase the likelihood of landslides by carving away a slope's natural stability, adding weight to the surface, removing vegetation, and improperly draining rainfall.

> **"People might have no other choice than living in hazardous zones."**

Despite the risk, "people might have no other choice than living in hazardous zones," said Ugur Öztürk, a landslide researcher at the University of Potsdam and lead author of the study.

The new model works at both global and local scales, identifying regional hot spots of landslide risk as well as individual risk factors. Users can adjust typical landslide considerations like soil and slope, plus elements of urbanization like drainage and deforestation. The research team hopes the tool can guide future development and prevent disasters in the poorest corners of the tropics.

In the past, researchers separately assessed factors including the hazard itself, exposure, and vulnerability to ascertain risk, Öztürk explained. "In our approach, we combine them."

"Low-Regrets" Solutions

In the study, recently published as a commentary in *Nature,* researchers applied their model to five tropical cities: Antipolo and Baguio, Philippines; Bukavu, Democratic Republic of the Congo; Freetown, Sierra Leone; and Port-au-Prince, Haiti (bit.ly/landslide-study). Across all locations, informal settlements were more likely to appear on steeper slopes. In Freetown—where a 2017 landslide killed an estimated 1,100 people—65% of neighborhoods with the least access to roads ("most informal") were on slopes of 10° or steeper.

Next, the scientists explored the effects of rainfall in their model. They found that disturbed hillslopes in Freetown started to slide at a lower angle (18°) than natural slopes (26°) and that rainfall triggered slides on even gentler slopes. Settled slopes were 5 times more likely to slide than natural slopes, with climate change increasing the risk by another 50%.

By pinpointing problems, the model can also recommend specific prevention tools, researchers said. Policymakers can identify which neighborhoods are at greatest risk and target specific solutions. "In the optimum case you should decrease the landslide hazard," said Öztürk.

The authors recommend "low-regrets" solutions—methods that provide both immediate benefits and long-term security. For instance, "if you have informal urbanization, very often there's no water management," explained Thorsten Wagener, a hydrologist at the University of Potsdam and a coauthor of the study. Simple features like roof gutters and water tanks "might be beneficial for the household and at the same time reduce the landslide risk," he said.

"Local knowledge can be really critical for translating this into meaningful action."

A Need for Local Knowledge

The threat of landslides isn't news in the tropics. Residents know the risks, and many mitigation strategies are already in place, said Sandra Catane, an engineering geology professor at the University of the Philippines Diliman.

"These are great ideas, but the challenge is the implementation," she said. "The politics, the economic factors—it's easier said than done."

The researchers recognized that in many regions both inside and outside the tropics, decisionmaking is siloed. City planners try to enforce building codes, engineers focus on stabilizing slopes, and social scientists study the factors forcing residents onto dangerous hillsides. Their study suggests more integrated ways to approach landslide mitigation.

Sharing knowledge with the local population can also be a challenge. Modeling can demonstrate the problem, Wagener said, "but getting that information to the people is a very, very complicated issue.... Local knowledge can be really critical for translating this into meaningful action."

Catane agreed, adding that nongovernmental organizations often have a unique capacity to assist at the local level. She's happy to see attention focused on the tropics and looks forward to further research on the socioeconomic pieces of the puzzle. "There has to be a long-term plan," she said, but "I'm not pessimistic. It can be done."

By **J. Besl** (@J_Besl), Science Writer

Could Jupiter's Heat Waves Help Solve a Planetary Energy Crisis?

Jupiter has been unusually prominent in both headlines and the night sky over the past year—not only because the gas giant made its closest approach to Earth in 59 years but also because it's been surprisingly hot. Researchers recently announced the discovery of an unexpected heat system measuring 700°C in the planet's upper atmosphere. The finding could shed light on why the giant planets in our solar system are surprisingly warm.

Planetary "Heat Wave"

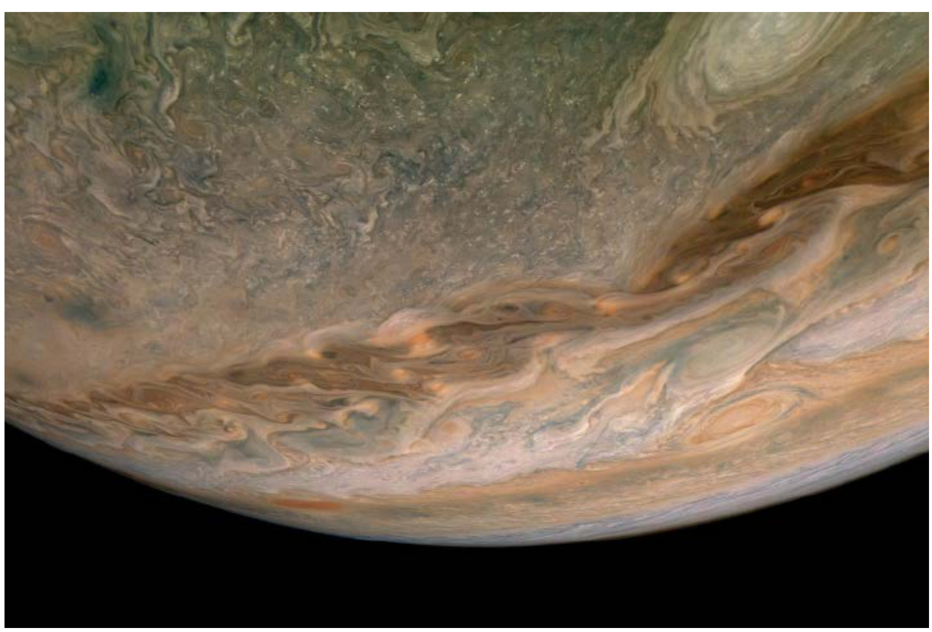
Jupiter's churning atmosphere is famous for its many cloud bands, storms, and the Great Red Spot. Close-up observations began only with the Pioneer probes of the 1970s, and the planet can still surprise.

Because it's so far from the Sun, receiving less than 4% of the sunlight that Earth gets, temperature models predict that the highest part of Jupiter's cloud layers should be -70°C. Researchers who presented findings at the Europlanet Science Congress 2022, however, measured them at more than 400°C. The conference was held in Granada, Spain, in September.

The researchers described the disparity between modeling and measurement as an "energy crisis," adding that the nonauroral upper atmospheres of Jovian planets (Jupiter, Saturn, Uranus, and Neptune) are "hundreds of degrees warmer than expected based on solar heating alone, motivating a search for missing heat sources." In the case of Jupiter, they believe the heat is being generated by solar wind exciting auroras at the poles. Unlike the transient auroras of Earth, Jovian auroras are always present and can raise polar temperatures to more than 700°C.

"While the auroras continuously deliver heat to the rest of the planet, these heat wave 'events' represent an additional, significant energy source," the team wrote in the presentation. "These findings add to our knowledge of Jupiter's upper atmospheric weather and climate, greatly helping to solve the 'energy crisis' plaguing the giant planets" (bit.ly/Jupiter-heat-wave).

James O'Donoghue, a planetary scientist at the Japan Aerospace Exploration Agency who presented the results, has spent about 10 years trying to unravel the mystery of why giant planets are hotter than they are expected to be. He and his colleagues used observational data from the high-resolution Near Infrared Spectrometer on the Keck II telescope on Hawaiʻi's Mauna Kea to analyze



Temperatures in Jupiter's northern hemisphere soared to up to 400°C, according to recent studies of infrared data. Credit: NASA/JPL-Caltech/SwRI/MSSS the heat gradient between Jupiter's poles and its equator. They examined emissions of triatomic hydrogen (H_3^+) ions, electrically charged molecules that are everywhere in Jupiter's upper atmosphere, and used a model to derive temperature values.

They found a smooth gradient between the poles and the equator, suggesting the aurora was causing heating, but also found what they call a "heat wave" extending from the poles to the lower latitudes. The heat wave, which measured more than 130,000 kilometers across (about 10 Earth diameters), was observed traveling toward the equator at speeds of thousands of kilometers per hour.

"It was kind of a chance discovery that happened to be in that data set."

During an earlier quiet period, Jupiter's magnetosphere was being populated, as usual, with plasma originating from the volcanic moon Io. A dense pocket of solar wind likely activated the system, leading to charged-particle precipitation in the aurora getting accelerated into the atmosphere, apparently heating it dramatically.

"It took this event of compressing Jupiter's magnetic field with the solar wind to shake it up like a snow globe," said O'Donoghue. He described "a large dumping of heat in the aurora" with nowhere to go. As a result, the heat "will firmly expand the atmosphere, spilling over to the equator and the pole.... Around the planet, you see this giant heat wave."

A Chance Discovery

The researchers focused on only the northern hemisphere on the particular day studied (25 January 2017), but O'Donoghue speculated that they might have seen a similar feature in the south. Asked why our understanding of Jupiter's atmospheric temperature has been poor, O'Donoghue offered two reasons. One reason, he noted, is that relatively few scientists focus on the subject. Another is that few telescopes are large enough for such high-resolution observations, so data are lacking. His team was lucky because it happened upon evidence of a large, dense pocket of solar wind hitting Jupiter at just the right time.

"It was kind of a chance discovery that happened to be in that data set," O'Donoghue said.

Solar wind was not thought to play a role in Jupiter's magnetosphere, but scientists have been wondering about the relationship since the Pioneer 10 observations decades ago. The recent findings show that the "solar wind does indeed alter the properties of Jupiter's magnetosphere, at least during events when the planet is hit by a dense stream of solar wind particles," said Sushil Atreya, a professor of climate and space sciences and engineering director at the Planetary Science Laboratory at the University of Michigan in Ann Arbor, who was not involved in the study.

The findings do not fully resolve the question of the energy crisis on big planets, Atreya added, noting that space probes and other observations have found even greater temperature differences with predicted values. "Any coordination between future telescopic observations of H_3^+ from Earth and the Jovian Infrared Auroral Mapper observation of the same from the Juno spacecraft at Jupiter, together with joint analysis employing also the magnetospheric and auroral data collected on Juno," he said, "would go a long way in satisfactorily resolving the question of [the] energy crisis at the giant planets."

O'Donoghue and his colleagues hope to work with Juno operators to have a companion data set that can show when and to what degree Jupiter was affected by solar wind events. Hard data could serve as a backup for the solar wind model that the team has been using. As the Sun enters a more active phase, researchers hope to find more heat waves and gather detailed readings on their magnitude, frequency, and other variables, as well as whether a similar phenomenon is happening on other Jovian planets.

"We'll try to track down future waves—it's difficult to plan for those things," O'Donoghue said. "We need the Sun to be kicking off a coronal mass ejection or something like that, and hopefully we can time our observation to be on Jupiter then."

By **Tim Hornyak** (@robotopia), Science Writer

Warmer Winters Keep Crops Sleepy into Spring, Hurting Yield

There's a reason sci-fi stasis pods are often icy: Biology tends to slow down when it's cold and speed up when it's warm.

By this logic, higher temperatures should boost plant growth. But the warmer winters brought on by climate change actually seem to hurt yields for many crops. And scientists now have a better idea why.

Annual crops need frosty periods to break out of their winter dormancy, reveal results published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/winter-warming). Researchers grew winter oilseed rape, or canola, in temperature-controlled chambers and farm plots and found that the plant goes through a hibernation-like state that "breaks" only if the plants are sufficiently chilled.

The new results highlight how climate change can shake up the finely tuned feedback systems linking life and the environment.

"One of the main footprints of climate change is…the timing of biological events, like flowering in this case," said ecologist Johanna Schmitt of the University of California, Davis, who was not involved in the new research. Such events are "a big deal for ecosystems, the fitness of plant populations, and in this case for crop yields."

Getting the Timing Right

Perennial plants like trees and bushes stay in the ground for more than two growing cycles (usually measured in years). To protect their developing buds from winter frosts, perennials enter a dormant state once their surroundings start getting chilly. This state is called bud dormancy, and it's a critical adaptation to seasonal climates.

But there's a catch: Plants need to be very careful not to "wake up" from bud dormancy too early. Mistaking a few warm autumn days for spring could have deadly consequences.

For plants to get bud dormancy right means working against biophysics. Generally speaking, warmer temperatures speed up biology and boost growth, whereas colder temperatures do the opposite. But bud dormancy works against this tendency, explained plant biologist Steven Penfield of the John Innes Centre in Norwich, U.K., who led the new study.

"The normal relationship between temperature and plant growth is completely reversed" during bud dormancy, Penfield said. "This is the trick plants have evolved."

During bud dormancy, plants slow down when it's warm and speed up when it's chilly. Dormancy breaks only after plants spend enough time at cold enough temperatures. This keeps them safe until spring actually arrives.

Bud Dormancy in Annual Crops

Annual plants stay in the ground for only 1 year or less, so many don't bother surviving the winter at all. But "winter annuals," planted in late summer or early autumn, delay flowering until spring and need cold to develop properly.

Previous studies had linked warmer winters to lower yields in winter annual crops like winter wheat and winter oilseed rape, but the relationship wasn't clear (bit.ly/yield-instability). Penfield and his team wondered whether bud dormancy might be the answer.

Scientists conducted field experiments with temperature-controlled plots to test the bud dormancy of winter crops. Credit: Phil Robinson

To find out, they grew winter oilseed rape and watched what happened when they put the plants through simulated warmer winters.

In the lab, the researchers grew their plants in climate-controlled growth chambers about the size of an office, which they programmed with weather station data to mimic a real farm in northern England. They also ran experiments in the field with temperature-controlled plots.

The results in both cases were the same: The plants that experienced warmer winters had worse yields.

A closer look at the plants, including an analysis of how they turned key dormancy-related genes on and off during the winter, revealed that the lower yield really was linked to flower bud dormancy, a life stage not previously recognized in annuals.

The new results don't "just show a direct correlation between a measured increase in temperature and reduced yield" but also explain why the correlation exists, said plant developmental biologist Pilar Cubas of the National Centre for Biotechnology in Spain. "It could give us some ideas of how to sort out this problem."

Climate Change Scrambles Environmental Signals

Bud dormancy is just one of many ways plants have evolved to perceive and respond to cues in their environments. Being able to notice those cues helps plants survive, but climate change is scrambling the signals.

In a warmer climate, some events that plants use to time their growth aren't coming at the expected time. They sometimes don't even come at all.

"What's happening with climate change is now there's a mismatch, so a formerly adaptive cue is no longer adaptive," said Schmitt. "I saw this actually in our nectarine trees in our backyard in Davis one year: They just didn't accumulate enough chilling units, and they didn't really do much that spring. They [only] had a few deformed buds."

Penfield said his group's experiments in growing diverse varieties of oilseed rape offer hope that breeding plants better suited to warmer winters may be possible. Understanding dormancy could help.

It's less clear how wild plants will cope.

"The really big question," asked Schmitt, "is, Are our natural plant populations going to be able to keep up with climate change?"

By **Elise Cutts** (@elisecutts), Science Writer

A Mysterious Dome Reveals Clues to Australia's Miocene History

On the dry, barren Nullarbor Plain in southern Australia, researchers have uncovered a remnant of the continent's deep past. A massive, fossilized dome of coral sits atop the vast limestone plateau.

Australia's remote Nullarbor Plain was once a shallow sea, where a reef similar to the Great Barrier Reef may once have thrived. Credit: Fiona Smallwood/Unsplash

The dome is likely a remnant of an ancient reef that once stretched across this landscape, a vestige of a time when shallow seas invaded what is now mainland Australia. Imprinted inside the dome are countless corals and other marine invertebrates, which give researchers valuable insights into how ancient reefs waxed and waned and could offer a more robust understanding of Australia's Great Barrier Reef today.

The ancient coral formation, which appears something like a massive bull's-eye in satellite images, is just one of many structures from the Miocene, which stretched from 23 million to 5 million years ago, still visible on the Nullarbor.

"You can find landforms that are really old," said Matej Lipar, head of the Department of Physical Geography at the Research Centre of the Slovenian Academy of Sciences and Arts and lead author of a new study describing the reef published in *Earth Surface Processes and Landforms* (bit.ly/coral-dome). "This is spectacular because in normal environments you've got glaciers and a lot of rain [that leave] all of these geomorphological landforms washed away or denuded."

But on the Nullarbor, untouched by glaciers and tectonic activity, researchers are able to see 10 million or more years of history. The courses of rivers, dry now for millions of years, can be found on the plain, along with evidence of ancient sand dunes that long ago were fossilized into limestone.

"Nothing much happened to it," said Lipar, who also noted a lack of rain in the region. "You can really see what was going on back in the past."

From Ocean to Desert

Although the Nullarbor today is arid and bare, it was once a shallow, thriving sea. The plain's bedrock, which covers almost 200,000 square kilometers and can be more than a hundred meters thick, was created bit by bit as ancient sea creatures died and left their remains on the floor of the ocean. Over time, the shells and skeletons were bonded together into limestone, which reacted with water to form a karst landscape, riddled with holes and cave systems.

"It's a dangerously remote area," said Michael Archer, a paleontologist at the University of New South Wales who was not involved in the study. "You can be beetling along in your four-wheel drive and suddenly disappear into a hole."

But thanks to new technologies, more details of the Nullarbor are beginning to emerge. Using ground-mapping radar data from the TanDEM-X satellite operated by the German Aerospace Center, Lipar and his coauthors were able to create detailed elevation maps of the remote plain, revealing forms invisible from the ground.

One of those newfound details is a mysterious structure consisting of a large dome more than 1,200 meters across, surrounded by a slight trough and a raised ring.

After discarding a number of other theories (including a meteorite impact, volcanism, and tectonic activity), the researchers came upon an explanation for the feature rooted not in geology but in biology. The formation is probably a fragment of a massive reef, they thought, that once stretched across the Nullarbor.

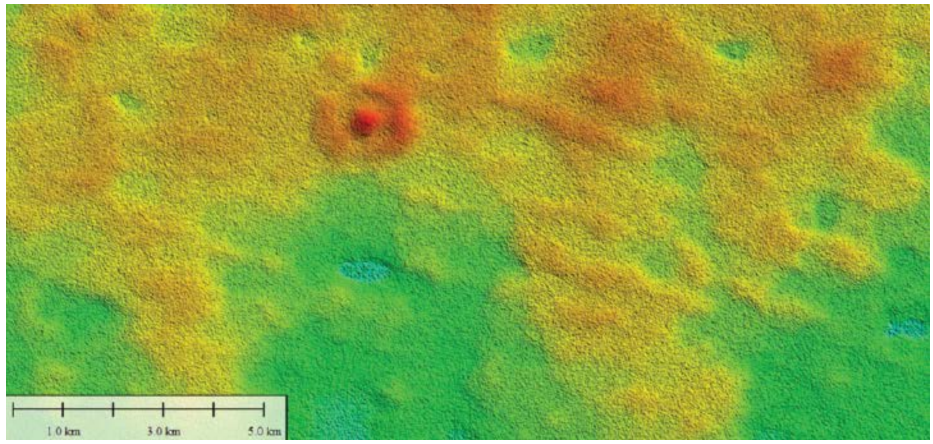
Although coral fossils previously have been found in the region, this is the first evidence of an actual reef on the Nullarbor, said John Webb, an environmental geoscientist at La Trobe University in Australia who wasn't involved in the study.

He said the dome looks similar to other so-called bioherms, hills of calcium carbonate found on the ocean floor where coral reefs exist.

Studying the structure could yield new insights into the biology of coral reefs during the Miocene, Archer said. "There could be fossil fish deposits there that would tell us a lot about what the marine life—not just the invertebrates, but the vertebrates that were in those shallow marine seas—was doing."

Those insights in turn could prove useful to scientists studying the Great Barrier Reef

On the Nullarbor, untouched by glaciers and tectonic activity, researchers are able to see the signs of 10 million years of history.



A satellite image with false color for elevation reveals a domed, ring-shaped structure. Credit: Curtin University

today. The Miocene saw a period of warming similar in scale to what contemporary climate change may bring to the region; looking to how ecosystems reacted more than 10 million years ago might help us understand how modern reefs might fare.

The find also revealed that the ocean that once covered the Nullarbor was relatively warm, Webb said. This discovery may indicate that the currents that wrap around the west and south coasts of Australia were stronger back in the Miocene.

Millions of Years of Data

The dome feature is not the only clue to the Miocene the Nullarbor has for scientists. Inscribed into the entire landscape are records of typically ephemeral processes. For instance, in some places, the limestone is rippled, a feature that records the presence of millennia-old dunes sculpted by wind.

"You basically have the shape of the dune imprinted into that rock," Lipar said.

The dunes reveal wind patterns that look very different from those experienced on the plain today, Webb said. Paired with other clues left on the surface of the Nullarbor, discoveries like this may shape a far more detailed picture of landscapes that are long vanished but not entirely forgotten.

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

U.S. Streams Are Drying Up

For millennia, communities throughout North America have adapted to the ebb and flow of waterways. Water infrastructure provides reservoirs for periods of drought and flood control for instances of deluge.

Drought is a way of life in some parts of the United States, said Jeffrey Mount, a geomorphologist and senior fellow at the Public Policy Institute of California. "What you worry about is whether you're picking up a trend." Long-term shifts in streamflow could signal a fundamental change in climate that scientists believe the country's infrastructure is not designed to endure.

Unfortunately, such a trend is emerging. In the first comprehensive picture of streamflow in the United States, scientists reported that streams in the South and West have gotten drier in the past 70 years. Though unsurprising to many, the result is worrisome. The finding was published in the journal *Water Resources Research* (bit.ly/drought-trends).

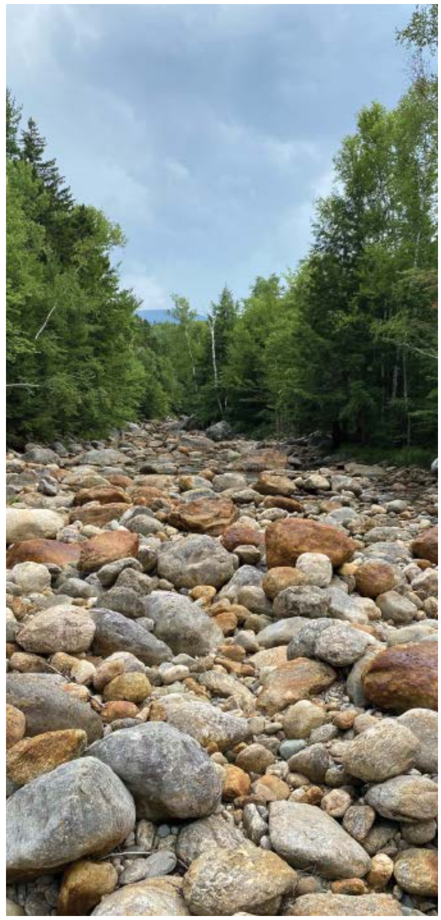
What Is a Drought, Anyway?

"There are a lot of flavors of drought," said Adam Ward, a hydrologist at Oregon State University who was not involved in the study. Abnormally dry stream conditions, a collective phenomenon termed streamflow drought, tend to follow prolonged meteorological drought, which is brought about by a lack of precipitation; the length of the lag depends on such factors as the size of the basin.

"The larger question is, Can you use this to help develop policy that adapts to these changing conditions?"

Previous anecdotal evidence and empirical data from some locations have shown that streamflow droughts have gotten more severe in recent decades.

Stakeholders define streamflow drought differently, often considering daily, seasonal, or long-term average flows. However, a barge moving through the Mississippi River doesn't care what time of year it is, just whether there's enough water flowing, said John Hammond, a hydrologist at the U.S. Geological Survey (USGS) and lead author of the new streamflow study.



Parts of New Hampshire's Peabody River were dry in August 2022. Credit: John Hammond

In the study, researchers looked at measurements of streamflow between 1921 and 2020, gleaned from USGS gauges in 555 watersheds throughout the continental United States. To reveal any long-term changes arising solely from shifts in climate, they focused on streams without dams or other management systems. They evaluated the history of drought on these streams, considering several thresholds of fixed long-term average and variable seasonal average flows.

The data showed that in the South and West, streamflow droughts got longer between 1951 and 2020, regardless of threshold. Worse yet, droughts in these regions are becoming more intense. "[Recent] droughts have caused there to be a lot more missing water from the system," Hammond said. Conversely, streamflow droughts generally got shorter and less intense in the East and North. These trends track with increasing aridity in the West, signaling that as the climate continues to dry out, streamflow drought will get worse.

The study's scale "helps us see that the future of New Hampshire and the future of Sacramento can be very different," Ward said. "It helps us understand why the EPA and Army Corps [of Engineers] have regions instead of one-size-fits-all policies."

The results are useful for policymakers because they confirm that there is a long-term trend in drought, said Mount, who was not involved in the study. "The larger question is, Can you use this to help you develop policy that adapts to these changing conditions?"

Day of Reckoning

The study highlighted that understanding big-picture climate trends is critical in developing sound water policy. "The implications of changing streamflow are going to cascade through some of our regulations in a way that we don't necessarily appreciate," Ward said.

The changing climate is forcing the United States to evaluate the scope and efficacy of the Clean Water Act, for instance. Legal battles (including an upcoming Supreme Court decision; see bit.ly/Sackett-v-EPA) have been fought over the act for 50 years, with some policymakers questioning, "What does it mean to count as a waterway?" Ward said.

"When you get more frequent droughts, waterways go from flowing all the time to flowing sometimes," he explained, a situation leading to a gray area regarding what features should be protected by a law written to address rivers. Ultimately, Ward said, "none of our regulations are set up for changing streamflows."

"I think we're here on a day of reckoning on drought policy," Mount said. Many of the country's major water infrastructure projects and policies date back a century, when the climate and streamflow were very different.

"All of that needs a rethink," Mount said.

By **Jennifer Schmidt** (@DrJenGEO), Science Writer

Making Underwater Cables SMART with Sensors

About 8 years ago, at the end of a long day of meetings at the University of Hawai'i at Mānoa, visiting speaker and seismologist Charlotte Rowe walked into Bruce Howe's office. "He rolled a map out... that showed all the transoceanic telecommunications cables," she recalled. He described a future in which these underwater cables could include seismic sensors every 50–100 kilometers, all around the world.

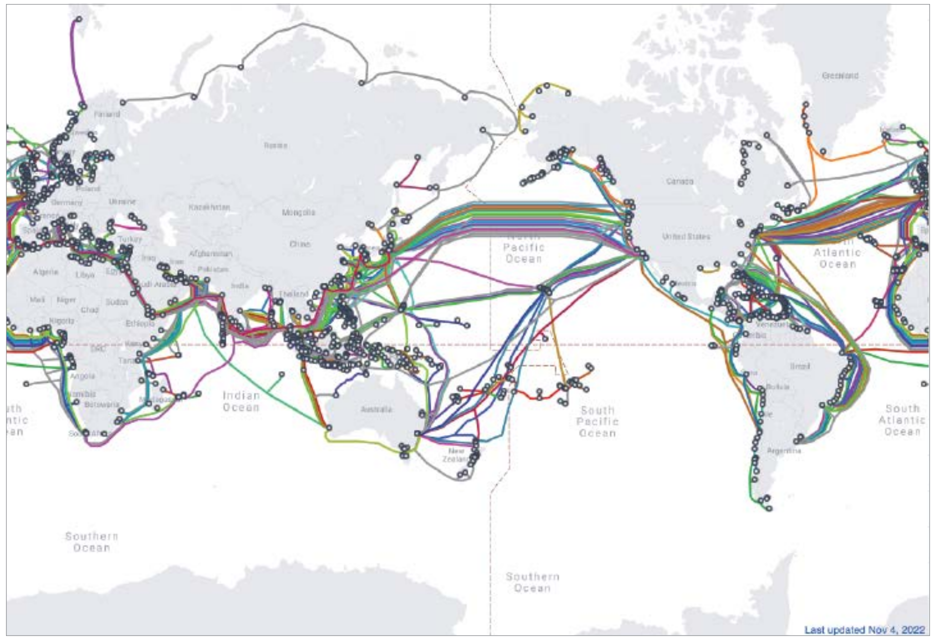
Howe, a professor in the Department of Ocean and Resources Engineering, asked, "Would this be of interest to you seismologists?"

Rowe responded, "Well, yes!"

During that meeting, Howe asked Rowe to quantify just how useful underwater cables equipped with regularly spaced seismic sensors might be for seismologists. "With a few exceptions, all of our seismic networks are on land," said Rowe. For Earth beneath the oceans, this means that "we don't do a very good job of characterizing how seismic waves propagate through it." After doing some calculations with a summer intern back at Los Alamos National Laboratory, Rowe said, "the [modeled] improvement was stunning."

Since then, Rowe has been involved with the United Nations' Joint Task Force for Science Monitoring and Reliable Telecommunications (SMART) Subsea Cables, for which Howe is chairperson. The task force is working to outfit the ocean with temperature, pressure, and seismic sensors that would help with a host of problems, including earthquake early warning, tsunami tracking, and climate change.

Rowe updated the scientific community on plans for SMART cables in various locations around the world at AGU's Fall Meeting 2022 (bit.ly/AGU22-SMART-cables).



In this map, colored lines depict the locations of subsea cables. They cross oceans and wind their way around continents, stopping at various hubs, shown as open circles, along the way. Credit: TeleGeography's Submarine Cable Map, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Transoceanic Internet

The Internet might seem like a combination of satellites, the cloud, and data flitting through the air. In fact, the cloud consists of buildings full of servers scattered throughout the world, where physical cables connect to one other. Sending data across an ocean simply requires longer, tougher, specially engineered cables.

Spanning thousands of underwater kilometers, telecommunications cables, which look like garden hoses, contain at their center hair-thin optical fibers protected by sheaths of metals and other materials, explained Howe. The optical fibers transmit data at the speed of light, and copper in the cable carries the necessary electrical power. This is how we view cat videos from other continents in real time; how we videoconference with overseas coworkers, friends, or family; and how global financial transactions take place. "Without these cables, we would not have the Internet as we know it," he said.

These cables begin and end at shore stations that provide power. About every 70 kilometers along the entire length of each cable, a long cylinder called a repeater amplifies the throughgoing signal, said Howe. These cylinders, between 1 and 1.5 meters long, have enough space for sensors to sit within the mechanically protected, seawater-flooded end sections. The current plan is to find funds to add SMART sensor packages that measure temperature, pressure, and seismicity to future cable deployments to replace aging transoceanic telecommunications infrastructure.

Portugal's Once and Future Great Earthquake

One of the first cables likely to include SMART sensors will maintain Portugal's connection to the Azores and Madeira islands. Existing cables are nearing the end of their lifetimes, said Vitor Silva, an earthquake engineer and risk coordinator at the Global Earthquake Model Foundation. "We've been lobbying the government to make sure that the next time they replace the cables, [they'll] be SMART."

Silva explained why Portugal is a good test case for the SMART sensors. In 1755, he said, the Great Lisbon Earthquake destroyed the nation's capital. The earthquake, which may have been greater than magnitude 8.0, began southwest of Portugal's coast, under the waters of the Atlantic Ocean. Following the rupture and collapse of countless structures, a tsunami inundated the coast as fires raged. Today, Portugal does not have an earthquake early-warning system akin to those in other earthquake-prone regions. In addition, many of Portugal's buildings are not seismically sound, making them, and their inhabitants, vulnerable to shaking from a future earthquake.

If the SMART cable were strategically where scientists suspect the seafloor will break, any such earthquake would be quickly detected, according to a recent paper led by Silva (bit.ly/Portugal-earthquake-warning).

"The closer you can get a seismometer to the earthquake source, the sooner you can transmit the fact that there has been an earthquake," explained Rowe.

Silva and colleagues calculated how much money SMART cables could save Portugal should another offshore earthquake strike. The new cables are likely to cost 140 million euros. Making them SMART should add about 10%, upping the expense to 154 million euros. However, the cost could be recouped by saving people's lives. By simulating various earthquake scenarios, determining how many people might die, and using estimates for the cost of losing a person's life, Silva and colleagues calculated that 170 million euros would be saved. "Including this technology could actually pay for the entire thing," said Silva.

Though Silva's calculations didn't account for tsunami warnings, both the seismic and pressure sensors on SMART cables could more quickly inform authorities of incoming ocean waves.

"Detecting the first arrival of the earthquake waves [earlier] will help us get a more rapid and perhaps more accurate location and depth of the earthquake," said Stuart Weinstein, deputy director of the Pacific Tsunami Warning Center and a member of the joint task force. An earthquake's location, depth, and magnitude factor into whether a tsunami is a possibility and guide initial tsunami alerts.

When a tsunami forms, it changes sea level as it propagates, Weinstein explained. As the crest of a tsunami wave passes, sea level rises and pressure increases on the sensor. Likewise, when the trough passes, sea level drops and pressure decreases. In this way, pressure sensors can track tsunamis (not wind-driven surface waves) and validate forecasts produced from seismic data.

Future Cables, Future Climate

Additional sensors have been considered, said Howe, but "the key problem is, many of those are not ready for 25-year life on the seafloor." Plus, he said, adding too many sensors will turn industry off because most cables are privately owned. For the plan "to get implemented on a global scale, we have to keep this concept simple."

Currently, the joint task force is exploring external couplings, particularly for certain custom cables, said Rowe. These couplings would allow later installations of additional seismic instruments that might be able to measure a greater variety of signals than the small seismic sensors planned for the SMART cables. These external instruments, perhaps installed via underwater robot, could be more solidly coupled to the seafloor, which would enhance the signal's integrity. This setup would solve two limitations of today's scant ocean bottom seismometer deployments—power and communication—which would both be supplied by the cable, Rowe explained.

In addition, the U.S. National Science Foundation is considering a cable that would connect New Zealand to McMurdo Station in Antarctica, where researchers lack high-speed Internet connections. The Southern Ocean, which surrounds Antarctica, is the worst-instrumented part of the world, said Rowe. "There's so much that we could learn" from a SMART-equipped cable, she said.

"Including this technology could actually pay for the entire thing."

Another intriguing avenue for the future, according to Rowe, involves hydroacoustic sensors (hydrophones) that listen to sounds propagating through the water. "The ocean is a very, very noisy environment," she said. Earthquakes rumble. Underwater volcanoes explode. Marine mammals splash and sing. Icebergs crack and groan. Ships clack and clang. Listening to the sea's sounds is one way to track changes and patterns in the ocean, though hydrophones aren't part of current plans for the sensor package.

SMART cables could also keep tabs on climate change. Pressure sensors would measure components of ocean circulation, and temperature sensors could inform scientists about how ocean bottom temperatures are changing, Howe explained.

Howe noted that scientists cannot trace a direct line from a person suffering from the effects of drought to a specific measurement. Nevertheless, he said, "the climate measurements [along with other observations] will affect everyone on the planet, albeit indirectly and over longer timescales."

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Looking to the Sky for Better Tsunami Warnings

A constellation of CubeSats could help map where atmospheric and tsunami waves are heading before ground-based receivers can detect them. Credit: NASA/JPL-Caltech

In late December 2004, a magnitude 9.2 earthquake near Sumatra caused a tsunami that rippled across the Indian Ocean and devastated coastal stretches of Indonesia, as well as Bangladesh, India, Malaysia, Maldives, Myanmar, Sri Lanka, and Thailand. Other sizable tsunamis have followed since, including the deadly magnitude 9.1 Tōhoku earthquake–generated event in 2011 that inundated Japan's Pacific coast and the tsunami triggered by the eruption of the Hunga Tonga–Hunga Ha'apai (HTHH) volcano in the South Pacific nation of Tonga.

Today more than 700 million people living in coastal areas are at risk from tsunamis and other extreme events like severe storm surges. And this number is likely to grow as coastal populations and oceans rise.

Advance warning of impending hazards is the most critical factor in saving people and resources—the more lead time, the more opportunity people have to evacuate and to safeguard critical infrastructure. Thankfully, the impacts of tsunamis can be forecast given the waves' relatively slow velocities (compared with, say, seismic waves) and that their propagation across the ocean can be tracked and projected. But the quality and advance timing of tsunami forecasts rely on the capabilities of sparse instruments like ocean buoys and tide gauges on Earth's surface. To increase the warning lead times for tsunamis, we suggest a disruptive idea for how to identify geohazards better and faster than current ground-based systems can.

The new solution we propose is based on low-cost satellite technology with a high readiness level that can be built and co-operated by global stakeholders. Specifically, we can use dense intersatellite links between Global Navigation Satellite System (GNSS) satellites and constellations of nanosatellites (also called CubeSats) to convert the atmosphere into a global sensing system for rapid detection of geohazard and extreme weather events, advanced early warnings, and disaster risk reduction.

Early Warnings from Atmospheric Waves

How can orbiting satellites detect a tsunami that is just beginning to propagate? These giant waves are often triggered by earthquakes or volcanic eruptions, many of which produce atmospheric effects that satellites can easily detect. For example, the recent volcanic activity at HTHH occurred as a series of events, with the most violent eruption taking place at around 04:26 UTC on 15 January 2022. The explosion ejected a volcanic plume that reached into the mesosphere (>50-kilometer altitude) and spread ash widely over distances of several hundred kilometers.

Satellite-detected atmospheric (Lamb) waves from the HTHH event propagated around the world three to four times, and about 9 hours after the eruption, residents of Alaska, some 9,000 kilometers away, heard the sonic boom. Barometric stations worldwide, including throughout the Australian continent, also recorded the Lamb waves, which propagated at about 315 meters per second and had pressure wave amplitudes of a few hectopascals [*Amores et al.*, 2022; *Matoza et al.*, 2022].

The coupling of these atmospheric waves to the oceanic basins resulted in sea level fluctuations observed much earlier than the tsunami waves themselves [*Omira et al.*, 2022]. For example, the tide gauge at Lord Howe Island, located off Australia's east coast and about 3,000 kilometers southwest of the eruption site, recorded an initial sea level fluctuation of 0.1 meter about 2.5 hours after the eruption, followed by much larger waves of up to 1 meter when the tsunami, traveling roughly 200 meters per second, arrived another 2 hours later. Such observations were initially enigmatic but now are understood as resulting from the atmospheric pressure wave [*Kubota et al.*, 2022].

Tsunamis are often triggered by earthquakes or volcanic eruptions, many of which produce atmospheric effects that satellites can easily detect.

The HTHH event and subsequent atmospheric and oceanic observations have reinvigorated interest in the idea of monitoring the atmosphere for signs of ground events. Atmospheric acoustic waves travel faster than tsunamis—about 315 meters per second at the surface and more than 1,000 meters per second at 500-kilometer altitude (Figure 1). Waves generated by extreme events such as volcanic eruptions and tsunamis penetrate the troposphere and stratosphere (roughly the bottom 50 kilometers of the atmosphere) and reach all the way to the ionosphere (100–1,000 kilometers). There, these waves produce traveling ionospheric disturbances (TIDs) by perturbing the plasma of ambient electrons [*Dautermann et al.*, 2009].

Observations of TIDs have been commonly reported after volcanic eruptions, tsunamis, earthquakes, storms, and even human-made signals like large explosions [*Komjathy et al.*, 2016]. The upper atmosphere is also an ideal place in which to detect anomalies associated with these extreme events because the amplitudes of atmospheric perturbations increase dramatically with altitude. This increase occurs because the density of air exponentially decreases at higher altitudes, leading to larger fluctuations in accordance with the law of energy conservation [*Hines*, 1960]. For example, a tsunami with a 30-centimeter wave height on the open seas induces a kilometer-scale oscillation in the ionosphere at an altitude of 100 kilometers [*Astafyeva*, 2019].

Because these atmospheric waves travel faster than ocean waves, TIDs can be detected in the atmosphere before potentially damaging hazards like tsunamis are detected or cause damage on the ground. Sensing these atmospheric disturbances is thus a way to improve warning times ahead of an impending tsunami. The fact that atmospheric waves propagate along great circles (the shortest point-to-point route on a spherical surface), whereas tsunamis must detour around landmasses, offers the potential for even more advance warning and is another advantage of atmospheric detection.

Using Spaceborne Sensors

Our proposed method for atmospheric sensing of disturbances would use measurements from a globally distributed constellation of numerous CubeSats (ideally, in the hundreds) detecting signals from the roughly 100 GNSS satellites currently operating (including those in the GPS, GLONASS (Global Navigation Satellite System), Galileo, and BeiDou constellations). These GNSS satellites, orbiting at about 20,000 kilometers in altitude, act as artificial radio sources transmitting at L band frequencies of 1–2 gigahertz. The L band radio signals penetrate and refract within the atmosphere below before reaching receivers on satellites orbiting at lower altitudes, such as those in low Earth orbit (LEO; about 350–800 kilometers), or receivers at ground stations.

Atmospheric parameters such as temperature, moisture, and electron content can be

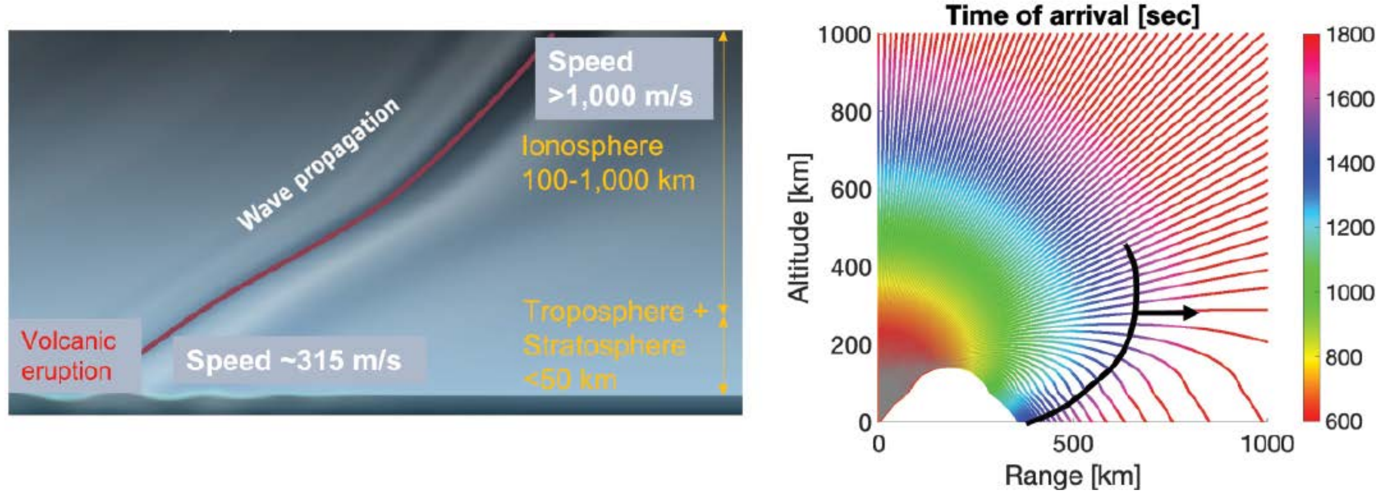


Fig. 1. The schematic at left highlights how atmospheric waves—produced by a volcanic eruption, for example—propagate faster and grow larger with increasing altitude. At right, the arrival times (color scale in seconds) of acoustic waves from the 2022 Hunga Tonga–Hunga Ha'apai (HTHH) volcanic eruption along various ray paths are shown. It takes only about 15 minutes for the acoustic waves to reach the ionospheric peak layers (200- to 300-kilometer altitude). Ray tracing computations were done using Los Alamos National Laboratory's infraGA. The black curve and arrow show the pattern of wave propagation of equal phase from the surface to 500-kilometer altitude. Credit: left: Adapted from a figure by European Space Agency/IRAP/CNES/TU Delft/HTG/Planetary Visions

mapped by detecting atmospheric refraction of the GNSS L band radio signals. With a constellation of the orbiting CubeSats collecting GNSS data, the extent that extreme events perturb these parameters over space and time can also be measured.

Ground-based GNSS receivers can measure TIDs associated with extreme events, such as earthquakes [e.g., *Heki et al.*, 2006] and tsunamis [e.g., *Rakoto et al.*, 2018], so why do we need CubeSats? The high-altitude GNSS satellites orbit slowly, so their geometry with respect to ground stations remains relatively constant, and the ionosphere pierce point (where GNSS radio signals encounter the peak electron density in the ionosphere, roughly 300 kilometers above the ground) is almost stationary. Also, a ground-based GNSS station detects atmospheric perturbations as they sweep by above the station, but it cannot detect much about what is happening at distant locations—for example, atmospheric perturbations over the ocean related to incoming tsunami waves. In contrast, CubeSats continuously orbit in LEO at a speed of 7–8 kilometers per second, detecting atmospheric perturbations (i.e., TIDs) above land and ocean. In other words, a single CubeSat equipped with a GNSS receiver can sample widely different regions, whereas a ground station covers only its immediate vicinity.

Because atmospheric waves travel faster than ocean waves, they can be detected in the atmosphere before potentially damaging hazards like tsunamis are detected or cause damage on the ground.

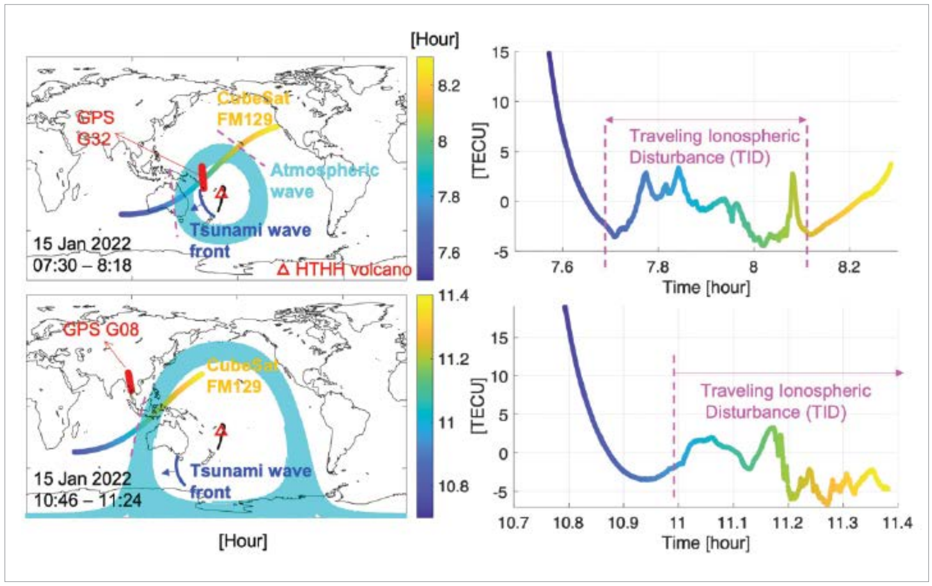


Fig. 2. The ground tracks of Spire Global's CubeSat FM129 (blue to yellow curves; colors represent the hour of flight) and the GPS G32 satellite (red line) and the atmospheric Lamb wave propagation (cyan; from a 2D simulation by Amores et al. *[2022]) are depicted during the period of 07:30–08:18 UTC on 15 January 2022 (top left). The CubeSat was orbiting from southwest to northeast. The HTHH volcano is shown as a red triangle. The position and direction of the tsunami wavefront are shown by the blue curve and arrow. The time series of traveling ionospheric disturbances (TID) data, measured in total electron content units (1 TECU = 1,016 electrons per square meter) along the CubeSat trajectory, indicates when the atmospheric disturbances (i.e., Lamb wave and tsunami gravity wave) occurred after the volcanic eruption (top right). Pink dashed lines denote the start and end of the TIDs detected and correspond to the dashed lines in the top left figure. Ground tracks for the FM129 and GPS G08 satellites, wave positions, and CubeSat data are similarly presented for the period 10:46–11:24 UTC (bottom left and right). The CubeSat thus detected the TID a few hours ahead of the tsunami arrival at both the east and west coasts of Australia.*

Measurements from many CubeSats combined can therefore offer substantially richer (i.e., having wider coverage, higher resolution, and greater speed) information about atmospheric perturbations, which will be useful to detect the events more quickly and better characterize and constrain their sources. Low-inclination Sun-synchronous orbits would be most useful, allowing for improved repeat passes covering most of the oceans and low-latitude regions, although these would ideally be complemented by polar-orbiting CubeSats to extend coverage.

Putting the Technique to the Test

To test our proposed method's technical viability, we have begun exploring GNSS tracking data from commercial CubeSats operated by Spire Global Inc. [*Han et al.*, 2021]. For example, we have processed data collected following the 15 January 2022 HTHH volcanic eruption using techniques developed to process data from ground-based receivers, focusing initially on the position and timing of resulting atmospheric and tsunami waves with respect to Australia.

Figure 2 shows the position of an atmospheric Lamb wave relative to the position of the tsunami wavefront during two different time windows (roughly 3–4 and 6–7 hours) after the eruption from CubeSat GNSS measurements of the ionospheric electron density perturbation (i.e., the TID) caused by the eruption. Time series of total electron content measurements along the CubeSat's trajectory showed that the TID from the Lamb wave was clearly measured in both time windows and that the timings of its onset and demise coincided with when the CubeSat entered and left the domain of the atmospheric perturbation. These measurements of the TID indicate

Measurements from many CubeSats combined can offer substantially richer information about atmospheric perturbations, which will be useful to detect events more quickly.

essentially when and where the perturbation occurred after the volcanic eruption, findings that are important for determining the explosive source of the tsunami and for predicting the tsunami's propagation and impacts.

During the first time window (Figure 2, top) of the CubeSat TID measurements, the tsunami was still in the open ocean, well before it made landfall. At the time of TID detection from the orbit, the wavefront of the tsunami was still 1–1.5 hours away from the east coast of Australia, giving a sense of the advanced warning that this method could have provided to residents there.

A network of orbiting Global Navigation Satellite System (GNSS) receiver-equipped CubeSats is the ideal companion to the existing ground-based geohazard monitoring GNSS network.

Roughly 3 hours later, at 11:00 UTC, the same CubeSat detected the atmospheric Lamb wave again (Figure 2, bottom). By this time, it had propagated farther and passed Perth, Western Australia, whereas the tsunami wavefront had just passed Tasmania and would take an additional 3–4 hours to reach Perth. These examples demonstrate that the CubeSat detected the atmospheric perturbation before the tsunami arrived at the east and west coasts of Australia, by a few hours in each case.

Tiny Satellites Are Mighty Together

The recent paradigm shift in space technology toward miniaturized sensors, smaller spacecraft, and more affordable launches is opening an unprecedented level of accessibility to data collection from space-based platforms. The technology sector has realized the concept of operating numerous small satellites with science payloads for spatially and temporally dense in situ data collection. And researchers are already building their own CubeSats—with GNSS receivers routinely integrated—and launching them through commercial providers or government programs (e.g., NASA's CubeSat Launch Initiative).

Information from these platforms is becoming increasingly reliable and relevant not only to the scientific community but also to the public, for example, for rapid flood detection. At the same time, CubeSat platforms are increasingly affordable to build and deploy. With a budget of about $100,000, one can build a 2U- or even 3U-sized CubeSat (1U = 10 × 10 × 10 centimeters) with a GNSS receiver, onboard computer, power, and communication system. Another $100,000 or so can put the CubeSat into orbit (a figure that drops on a per instrument basis when "ride sharing," or launching multiple satellites simultaneously).

A direct comparison of costs to build, deploy, and maintain a CubeSat constellation for extreme event monitoring with those of existing monitoring networks (e.g., using ocean buoys) is difficult because cost estimates vary and there are many other factors involved beyond the instruments themselves. But we expect that a constellation of CubeSats would compare favorably, especially considering the improved coverage, resolution, and speed of detection it would offer, and that its use for geohazard monitoring could be piggybacked onto satellites deployed for other primary missions. Such a network of orbiting GNSS receiver–equipped CubeSats is also the ideal companion to the existing ground-based geohazard monitoring GNSS network.

Now is the time to organize an international CubeSat geohazard program to advance our capability to use this affordable technology. As first priorities, this program should set up a protocol for building CubeSats based on minimum hardware requirements for geohazard monitoring, coordinate near-real-time data downlinks from CubeSats to ground stations internationally, organize archiving and analysis centers for data collected, and develop data analysis techniques and open-source software.

We further call for international participation to initiate an intergovernmental effort to implement a real-time system for geohazard monitoring based on small satellites. Such a system could provide identification and warnings of extreme events like tsunamis, volcanic eruptions, earthquakes, large storms, and even human-made explosions earlier than what is possible with current systems. And this additional time to react could ultimately mean more lives and infrastructure saved when these events strike communities around the world.

Acknowledgments

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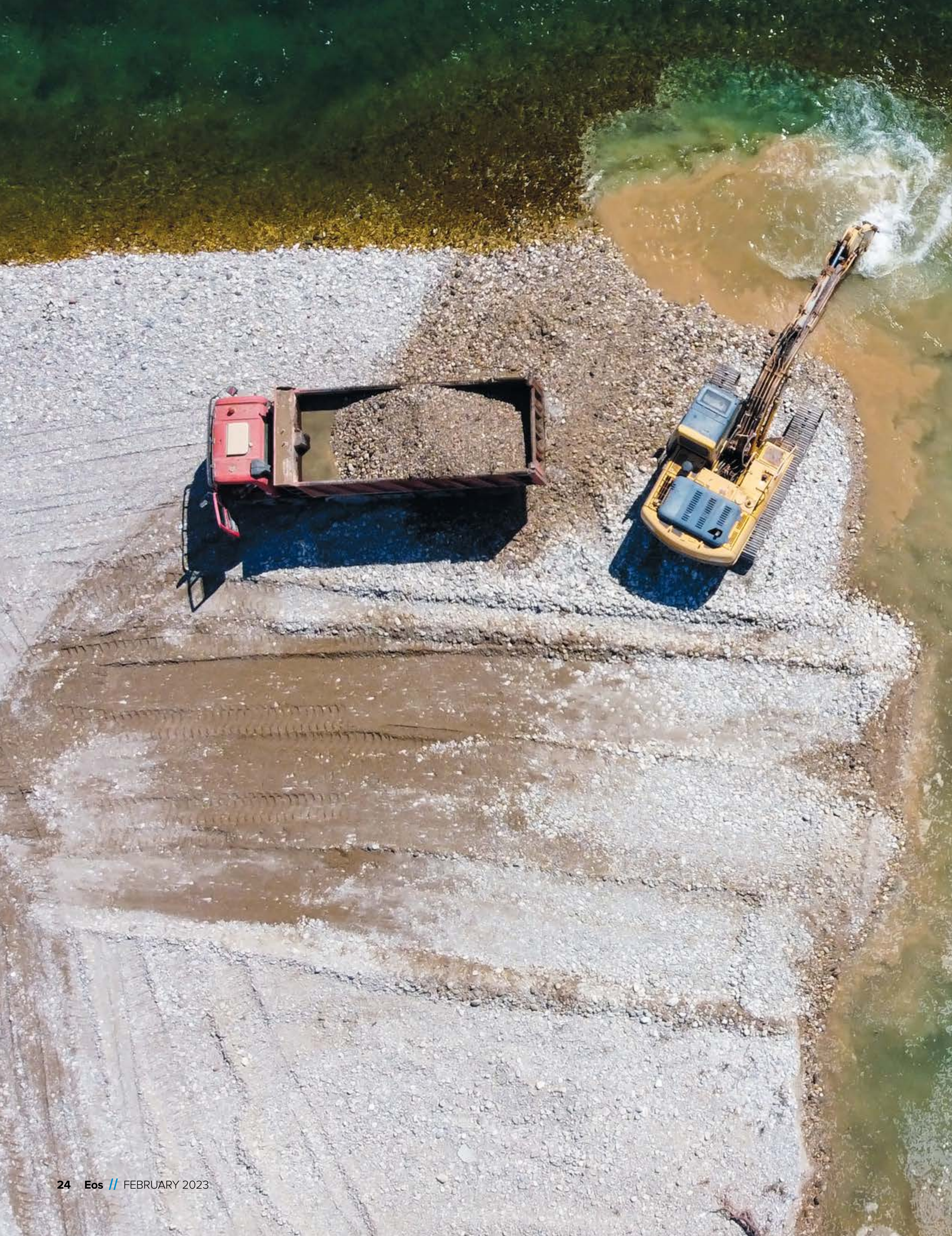
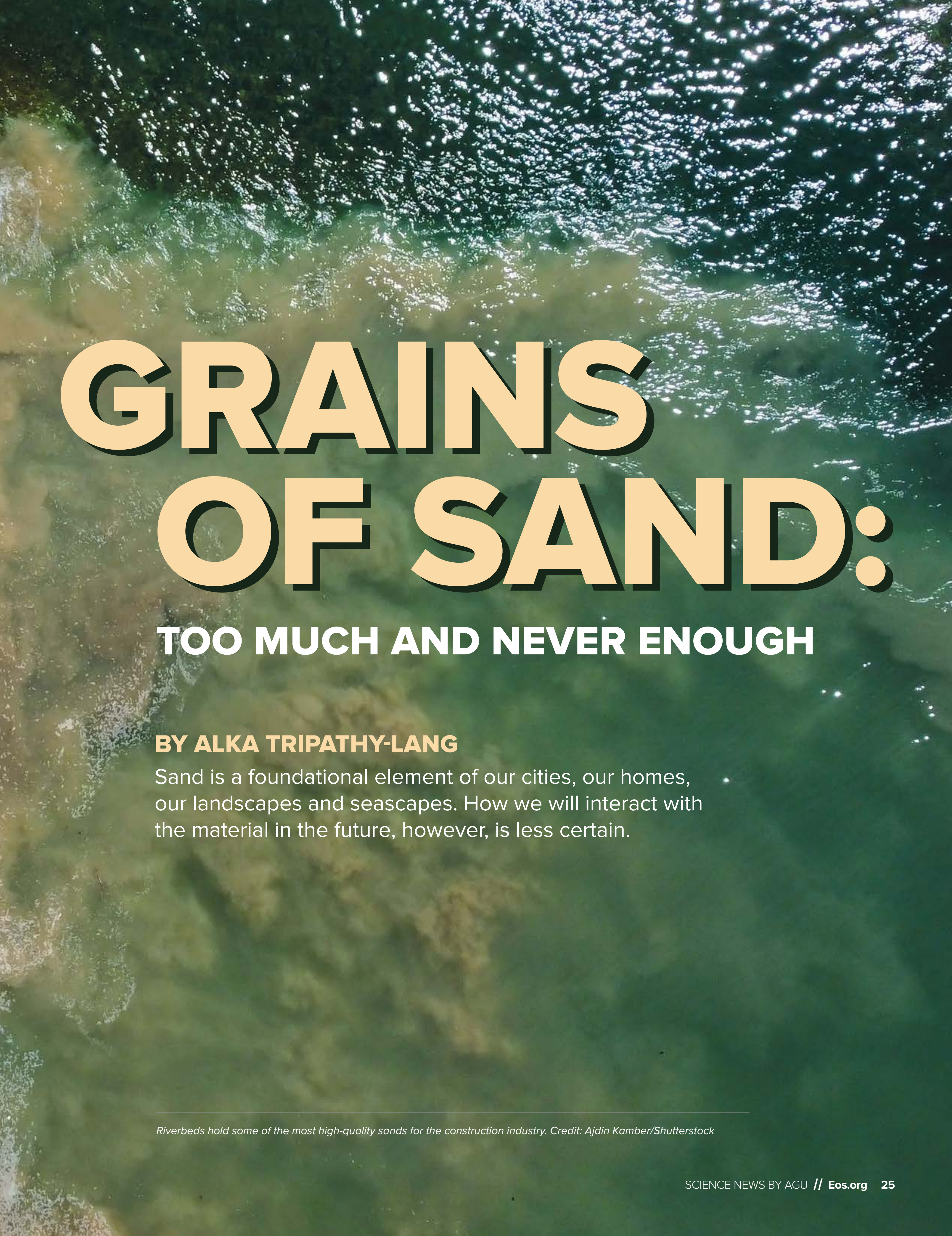


GRAINS OF SAND:

TOO MUCH AND NEVER ENOUGH

BY ALKA TRIPATHY-LANG

Sand is a foundational element of our cities, our homes, our landscapes and seascapes. How we will interact with the material in the future, however, is less certain.



Riverbeds hold some of the most high-quality sands for the construction industry. Credit: Ajdin Kamber/Shutterstock

Smartphone screens, wine bottles, and porcelain toilets share a surprising ingredient: sand. In fact, the ubiquitous material is the second most exploited natural resource on Earth, after water.

Most sand pours into the construction industry, which in turn pours much of it into concrete. "Sand is the most mined solid material on Earth, and we're using more and more sand as we're becoming more and more people," said Mette Bendixen, a physical geographer at McGill University in Montreal.

"The use of sand is now faced with two major challenges," said Xiaoyang Zhong, a doctoral student in environmental science at Leiden University in the Netherlands. "One is that it has caused enormous consequences in the environment," he explained. "The second challenge is that easily usable sand resources are running out in many regions."

Sand is extracted from the environment with irreversible impacts, the scale of which will be magnified as the world prepares for an additional 2 billion people within the next century. People will want—and need—homes, infrastructure, and livelihoods that directly or indirectly involve sand. To begin planning for this future, the United Nations Environment Programme (UNEP) issued a detailed report in April 2022 outlining 10 strategic recommendations (see the first table) for sand supply chain stakeholders (see the second table). Finding alternatives to naturally occurring sand and gravel is imperative, as are reuse and recycling-related solutions.

"The crisis that exists around sand is mostly a crisis of sand sustainability, not of availability," said Daniel Franks, a report coauthor and professor at the University of Queensland in Australia.

Reining in Rivers

Although regional sand shortages are familiar phenomena, "we don't know if there is a global sand scarcity," said Aurora Torres, a report coauthor and Marie Skłodowska-Curie postdoctoral fellow at the Université catholique de Louvain (Belgium) and Michigan State University, because "we don't know how many global sand resources exist."

Local and regional sand shortages occur for a variety of reasons, Torres said. Sometimes, she explained, a sand shortage may occur because high-quality materials have already been extracted or never existed in that region because of unfavorable geology.

The UNEP report describes how officials and community members in Makueni County, Kenya, for example, worried that a river would run out of sand because of unsustainable mining, which would in turn decimate the water supply, thus collapsing the community's resilience.

Accessibility presents a different type of sand scarcity, said Torres. For instance, sand reserves may lie beneath something of importance, like agricultural land or the economic and social infrastructure of a city, like London, which sits atop valuable sediment. In other cases, local residents oppose sand mining for environmental or health reasons.

Quantifying the characteristics of sand resources is key to understanding where they should be preserved or could be extracted, said Arnaud Vander Velpen, a report coauthor and the sand industry and data analytics officer at the UNEP's Global Resource Information Database (GRID) network in Geneva. "Silica sand is not the same as construction sand is not the same as desert sand."

Bendixen concurred. The sands of great deserts around the world, for example, cannot be used for construction because the grains are too rounded, she said. "It's almost like building with marbles."

Size matters, too. Differently sized angular grains adhere better to make stronger con-

"THE CRISIS THAT EXISTS AROUND SAND IS MOSTLY A CRISIS OF SAND SUSTAINABILITY, NOT OF AVAILABILITY."

Sands of the Libyan desert, like those from many deserts around the world, are not usable for most construction purposes. Credit: giomodica/Wikimedia CC-BY-3.0 (bit.ly/ccby3-0) crete. "And that's exactly what you get from river sand," Bendixen said.

"You tend to get very high quality aggregate [the industry term for sand and gravel]" from river sand, said Matt Kondolf, a geomorphologist at the University of California, Berkeley. This aggregate needs minimal processing simply by taking it out of the riverbed." This straightforward process is especially clear in river systems with seasonal flow patterns, which allow miners simply to dig up and sieve sand and gravel during the dry season to sell in nearby markets. In undammed systems, the next rainy season often brings new sediment that can help fill in the holes left by the excavators.

Mining in active river channel deposits—such as streambeds and sand bars—was standard practice until the 1980s, when the method's devastating ecological impacts became apparent, said Kondolf. The gravel needed for aggregate, for example, is approximately the same size gravel that salmon need to spawn. Indeed, the features removed (or created) by mining provide critical habitat for a variety of aquatic organisms.

Regulations in the western United States and Europe began to limit extraction from rivers, but in many other regions it remains essentially uncontrolled, said Kondolf.

Vander Velpen likens this extraction process to trying to get money from a bank, a metaphor popularized by Maarten Kleinhans, a professor of geosciences at Utrecht University. "In order to [borrow] money, the bank will ask, 'OK, what's your income?' If you go to a river to take out sand, you should check the budget," Vander Velpen explained. "At the moment, we're not doing that…in many regions we have been extracting beyond the sediment budget."

Dam Complexities

Another place to find sand is in the reservoirs behind dams. Extracting sand from these spaces is more complicated than mining a riverbed. As sediment begins to fill a dammed reservoir, the coarsest material begins forming what's called a reservoir delta where the river empties into the lake, upstream of the dam. "The finer sediment tends to spread out more downstream, through the reservoir," said Kondolf. "You get a complicated stratigraphy, which is why it's not as easy to mine."

Size matters here, too: Smaller reservoirs trap gravel, larger ones hoard sand and silt, and the biggest amass even the finest sediment, said Kondolf.

Free-flowing rivers transport sediment continuously, typically from rapidly eroding mountainous areas all the way to the coasts, said Kondolf. This sediment supports deltas and beaches where a river meets the ocean. "By building a dam, you block that continuity of transport," said Kondolf.

Downstream from dams, starving rivers yearn for their lost sediment load; the hungry water erodes the beds and banks, attempting to satiate its appetite.

With the proliferation of dams throughout river basins, sand supply to coastal deltas has been cut off at a decadal scale, Kondolf noted. Many of these deltas are already retreating because of sand mining.

One solution to maintaining a steady supply of sediment throughout the course of a dammed river is to find a way to pass sediment from the upstream side of the dam to the downstream side. But dredging—suctioning sand from, in this case, the lake floor into a boat—and hauling sediment via trucks are expensive and "is a lot of [work] compared to what the river does by itself with gravity," said Kondolf.

In the United States, Great Lakes Dredge & Dock Company has successfully dredged sand from reservoirs, said Bill Hanson, the company's senior vice president of government relations and business development. However, he said, simply sending the sand downstream hasn't been feasible because of permit requirements and other regulations.

In a few places, like Japan and Switzerland, large dams have been engineered with sediment bypass tunnels that use river flows to flush sediments through steep slopes, explained Vicente Tinoco, a doctoral student at the College of Environmental Design, University of California, Berkeley. Managers can also clear smaller reservoirs by completely draining them, he said. This returns the stockpiled sediment to the river system.

"IN MANY REGIONS, WE HAVE BEEN EXTRACTING BEYOND THE SEDIMENT BUDGET."

Sand indirectly influences sex determination in many sea turtle species. Credit: USFWS, CC BY 2.0 (bit.ly/ccby2-0)

Bye-Bye Beaches

Sand can also be mined from the seafloor. Beach nourishment, also known as coastal protection, typically takes sand from the seabed and pumps it onto shore, explained Hanson. In South Florida, for example, "before we started doing regular nourishment, there was concrete and debris on the beaches," said Hanson. Beach nourishment buffers the shoreline against storms, waves, and sea level rise. Where offshore sand mining is prohibited, as is the case in South Florida, trucks bring in manufactured sand—crushed rock that's sieved and sorted to exact specifications—from elsewhere.

Dredging is cheaper and has a smaller carbon footprint than the manufacture and transportation of sand, although with seafloor dredging, "you get what you get" in terms of sediment, said Hanson. However, a substantial amount of geotechnical work prior to dredging happens with the goal of matching seafloor sand to beach sediment, he said. This matching is more than just aesthetic.

The color of the sand, said Vander Velpen, in part dictates its temperature—the darker the sand is, the hotter it gets because it absorbs more of the Sun's radiant energy. Certain animals like sea turtles, which lay their eggs in the sand, are subject to temperature-dependent sex determination. In other words, the temperature of the nest

Greenlandic fjords often expel plumes of fine, glacially derived suspended sediment. Credit: Anders Anker Bjørk

dictates whether an egg will hatch a male or female turtle. Darker, hotter sand can result in too many females relative to males, putting the population at risk.

Whether sand comes from the river itself or from people bringing it in, beaches and deltas—and the protection they offer—would disappear without regular nourishment. In Southeast Asia, "assuming no sediment management," said Kondolf, "you would only get 4% of the natural sediment load arriving in the Mekong Delta due to upstream dams trapping sediment and sand mining, which basically means there's no long-term future for the delta."

A Golden Goose in Greenland?

A potentially untapped source of sand is a curious consequence of climate change: the coastal sands around Greenland. As the world warms, Greenland's ice sheets are melting. Both water and glacial sediment drain through coastal outlets into the sea, with a single outlet delivering a quarter of all material, said Bendixen. In 2019, she and her colleagues proposed that Greenland could potentially benefit economically from this sediment exodus.

Two years after the study's release, the Geological Survey of Denmark and Greenland prepared a report on the subject. Bendixen said that it declared the recently deposited glacial sediments unsuitable for export to countries that need construction materials. "I'm a little skeptical about that report because they never went to investigate the material," she said.

Similar sands are already being dredged from the bottom of the nearshore ocean environment for use in construction projects as the capital city of Nuuk expands. Thomas Lauridsen of Greenland's Ministry of Mineral Resources and Justice explained that indeed, "a few Greenlandic companies are exploiting sand in the offshore environment for local use in Greenland."

"This is a country which wants to modernize and which wants to diversify [its] economy," Bendixen said. The survey also found that respondents want local control over extraction and export, with most saying that environmental impacts need to be addressed by any proposed mining concern. "The environmental impacts [are] one of the very biggest unknowns," she said.

Greenland sits between North America and Europe—regions that largely satisfy their sand demand from domestic sources, which include recycled demolition waste, according to a paper led by Torres. Future needs for sand are more likely to arise in places like Asia and sub-Saharan Africa. One of the challenges with mining Greenlandic sand for export, she said, "is the transportation cost and how this could significantly increase the price of sand." Both the cost and the greenhouse gas emissions associated with transport may simply be too high.

Toxic Tailings, Stronger Circularity

"The vast majority of what we call sand or aggregate that's used by humans is actually crushed stone," said Franks. But another industry already crushes rocks and produces an annual waste stream of more than 13 billion metric tons.

That industry, of course, is mining, and mining companies may be able to offer a readily available source of sand. Vale, for instance, is a Brazilian multinational corporation that generates millions of metric tons of tailings each year. Tailings are waste materials left after the target mineral is extracted from ore. Large companies like Vale have significant challenges surrounding the safe storage of tailings, said Franks. "They've had the deep learning experience of causing a major tragedy."

Vale experienced two disasters in the past decade: the Mariana dam collapse in 2015 and the Brumadinho dam failure in 2019. Hundreds of lives were lost, and hundreds of kilometers of rivers were polluted. "People in that organization are now motivated to change because they saw their work colleagues pass away from these failure incidents and also because investors and some governments have demanded reform," Franks said.

The University of Queensland and the University of Geneva worked with Vale to investigate whether sand produced *during* mineral ore processing could be a sustainable aggregate source for industry, thus reducing the amount of sand demanded from the natural environment and reducing the amount of mining waste that needs to be stored. "We're not talking about taking the tailings waste and finding a purpose for it," said Franks. In other words, the proposed process does not deal with existing tailings but instead would ensure that volumes of future tailings would be reduced by adding another set of mineral processing steps in tandem with metal ore extraction. The ore-sands report detailed these steps and the feasibility of creating sand suitable for certain construction materials.

Franks said that the tests revealed very minor concentrations of potentially toxic elements, "much lower than the environmental thresholds and background concentrations that might appear in soil."

To efficiently process ore minerals, the rocks are ground very finely, which means

"THE ENVIRONMENTAL IMPACTS [ARE] ONE OF THE VERY BIGGEST UNKNOWNS."

“IF YOU WANT TO BUILD A CITY IN 10 YEARS, YOU’RE [USING] CONCRETE, YOU’RE USING GLASS, YOU’RE USING STEEL.”

that any coproduct would also be very fine sand—useful for some construction purposes but not all. “It’s a solution that can currently contribute to the construction industry either as a blended product,” said Franks, “or also on its own…to make bricks or be used as road base.”

Many major ore-producing countries are also rapidly building infrastructure, and they cannot rely on construction and demolition waste the way economies with a mature infrastructure network (as in Europe and North America) do. Such recycling is an important component to a circular, no-waste economy, said Vander Velpen, who was also an ore-sands report coauthor. To that end, the report’s authors examined distances between potential ore-sand sites and urbanizing regions with a demand for sand, finding that the two correlated in most instances.

Built to Last

Across Africa and Asia, the demand for sand is driven by economic growth. Vander Velpen described talking to people in African countries like Mauritania and Nigeria who want modern-looking concrete homes.

Cement and concrete were first introduced during European colonization of Africa, said Doudou Deme, co-owner of Elementerre, a Senegalese company focused on using earthen materials, not concrete, to construct environmentally friendly buildings. These materials, he said, protect against tropical climate more effectively than concrete. Concrete and cinder blocks “convey heat very quickly,” whereas earthen materials provide “thermal comfort and humidity regulation.” Regardless, Doudou said, the majority of construction in Senegal uses relatively cheap and widely available reinforced concrete, which contributes to the erasure of local construction cultures that use components like clay, stone, and fiber (e.g., palm trees, straw, and bamboo).

China has erected cities of concrete over the course of years, instead of the decades or even centuries taken to build cities in North America and Europe. The statistics are staggering, with China having used more sand in 3 years than the United States did in the past century.

Materials made from sand are necessary for rapid development, explained Vander Velpen. “If you develop slowly, you use a huge variety of materials,” he said, whereas “if you want to build a city in 10 years, you’re [using] concrete, you’re using glass, you’re using steel.”

In a recently published study, Zhong and his colleagues including Paul Behrens, a professor of environmental change at Leiden University in the Netherlands, explored how to reduce sand needs through material efficiency strategies in building construction like increasing the lifetime of new and existing buildings, using different materials in new construction, and reusing building components (bit.ly/global-sand-crisis).

The need for new buildings, Zhong explained, is driven by increasing populations and gross domestic products (GDP). In general, as GDP goes up, so does area per capita. By estimating how much concrete and glass are required per square meter based on building practices, he calculated how much sand the world would need to construct the majority of its buildings every year between 2020 and 2060.

Using these material efficiency strategies decreased projected sand demand by half. Zhong and the other researchers tested how the overall need for sand would change, for instance, by tweaking floor area per person or increasing the longevity of existing buildings. They found that using alternatives to concrete, such as timber, would help somewhat, and limiting floor space—specifically, not following current projections for future floor space per capita—could also decrease projected sand use. Most important, new buildings should have longer lifetimes than existing ones.

Studies like Zhong’s and businesses like Doudou’s highlight how individuals can help limit environmental impacts. “Value your local and traditional construction materials and encourage your local authorities to refurbish and restore buildings [instead of] demolishing and replacing them,” said Vander Velpen.

Sand as a Strategic Resource

“Sand is a strategic resource, not only economically but also for our environment,” said Vander Velpen. “There are sometimes reasons to excavate sand from a beach, but we call for sand from the beach system not to be used as a source of construction or industrial material.” Sands of the beach and nearshore environment provide long-

Recommendation 1	**Recognise sand as a strategic resource** that delivers critical ecosystem services and underpins the construction of vital infrastructure in expanding towns and cities globally.
Recommendation 2	**Include place-based perspectives for just sand transitions**, ensuring the voices of all impacted people are part of decision-making, agenda-setting and action.
Recommendation 3	**Enable a paradigm shift to a regenerative and circular future.**
Recommendation 4	**Adopt strategic and integrated policy and legal frameworks** horizontally, vertically and intersectionally, in tune with local, national, and regional realities.
Recommendation 5	**Establish ownership and access to sand resources** through mineral rights and consenting.
Recommendation 6	**Map, monitor and report sand resources** for transparent, science-based and data-driven decision-making.
Recommendation 7	**Establish best practices and national standards, and a coherent international framework**
Recommendation 8	**Promote resource efficiency & circularity** by reducing the use of sand, substituting with viable alternatives and recycling products made of sand when possible.
Recommendation 9	**Source responsibly** by actively and consciously procuring sand in an ethical, sustainable, and socially conscious way.
Recommendation 10	**Restore ecosystems and compensate for remaining losses** by advancing knowledge, mainstreaming the mitigation hierarchy, and promoting nature-based solutions.

This table from the United Nations Environment Programme (UNEP) report offers 10 recommendations to avert a sand crisis.

Stakeholder group	Relevance	Who
Governments/ Public Authorities	Responsible for the natural resources, and mining and extractive industries at the national, municipal and/or sub-national scale. They also influence local livelihoods and (equitable) development pathways, implement environmental and social protection laws, and national monitoring and reporting efforts.	National governments Municipal/sub-national governments and line ministries (local land and spatial planning, economic development, water management, fisheries management, buildings) Law enforcement (e.g., local police force) Village chiefs
Civil Society	Organisations and groups along the value chain of sand engaging in environmental and social advocacy, peer support, research, education and capacity development, and global awareness raising to support decision-making. They also lead some of the thinking behind best practices and innovation in the sand sustainability challenge.	Local communities, youth, dissenters, activists, CSOs (involved and/or impacted by extraction activities) Education & research institutions Nongovernmental organisations (NGOs) Media
International Entities	Organisations involved in norm-setting, knowledge transfer, convening, consensus-building, research, global data monitoring programs.	Inter-governmental organisations Transboundary cooperation platforms Standard-setting and certification bodies
Extractive Industry & Sand Producers	Enterprises of different sizes directly engaged in extractive activities in rivers, coastal zones, marine zones, terrestrial sand deposits, quarries, as well as in trading and transporting sand resources for further use.	Primary sand extraction, dredging and production companies Aggregates associations Artisanal and small-scale miners Firms involved in the initial processing and transport of sand resources Recycling industry and producers of substitutes to naturally occurring sand or crushed rock including secondary aggregates, by-products, co-products
End-users	Users of sand resources and/or products that use sand.	Commercial material suppliers (e.g., concrete and concrete products) Civil engineering firms engaged in sourcing crushed rock, sand, gravels and using these materials in construction activities. R&D and materials scientists, construction project managers, operations managers, sales support, supply chain managers (at firm level) Architects
Infrastructure Procurement & Finance	Entities that fund construction and infrastructure projects, both in the private and public sector, and thus have a say in the procurement of sand resources	Development banks Municipal & national governments Private & industry investors

This table from the UNEP report lists relevant stakeholders in sand and sustainability.

term defense against storms and sea level rise while housing fish stocks, plants, and many endangered species.

Regionally tailored solutions to sand need to involve small-scale sand miners so they don't bear the brunt of the transition, said Stephanie Chuah of UNEP/GRID and a coauthor of both the UNEP and ore-sands reports.

Because most sand is a local resource, "price setting needs also to be done locally and not globally," said Vander Velpen.

Sand mining also has a gender dimension that needs to be addressed, said Chuah. Women may not own or even have access to land, which can be a problem in parts of the developing world where women are responsible for providing food and water for their families, said Chuah. Sand mining can cause water quality to diminish such that women have to go much farther to obtain potable water. However, families may depend directly on sand mining for their livelihood, she explained. In some instances, men are miners, but in others, women are becoming directly involved in sand mining because traditional ways to support their families, for instance, by fishing, have become threatened.

The UNEP report describes a project in the southeastern coastal state of Andhra Pradesh, India, involving a decades-old government scheme called the Development of Women and Children in Rural Areas (DWCRA), which focuses on creating opportunities for women in rural communities to improve their lives. The state government gave DWCRA women's groups mining rights in the mid-2010s. These groups were responsible for managing the purchase and delivery of sand, earning 25% of profits from sales and monthly salaries for employed women.

The project was plagued with problems, however. For instance, women reported delays in receiving payment, as well as concerns over their own health and personal safety, and it is unclear whether DWCRA groups continue to participate in sand mining–related activities.

"A lot of people working within the artisanal small-scale mining industry often exist and work in poverty and [engage in] very informal governance when it comes to sand," said Chuah. In addition to more sustainable business models, the authors of the sand mining reports are "also calling for better governance when it comes to managing sand resources," she said. Moreover, she explained, "we will also need a just transition, where we take into consideration the voices of all people and avoid any deterioration in workers' rights, increased hardship, or poverty."

"There's this need to extract this material for development—for livelihoods—and at the same time, the need to preserve the ecosystem and the natural services that the sand provides," said Chuah.

"The gravel and the sand, that's the architecture of the river channel," said Kondolf. It's also the architecture of the coastal seafloor and the architecture of thousands of local economies.

"You build a house literally out of sand to protect yourself," said Vander Velpen. "In the same way, we need sand—nature—as a protection. We need such an enormous amount of sand in our environments…for resilience."

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

International Ocean Discovery Program

IODP INTERNATIONAL OCEAN DISCOVERY PROGRAM

CALL FOR APPLICATIONS

Apply to participate in a *JOIDES Resolution* expedition

Expedition 403: Eastern Fram Strait Paleo-Archive

4 June to 2 August 2024

The North Atlantic and Arctic Oceans are major players in the climatic evolution of the Northern Hemisphere and in the history of meridional overturning circulation of the Atlantic Ocean. The establishment of modern North Atlantic water has been identified as one of the main forcing mechanisms for the onset of the Northern Hemisphere glaciation. Many uncertainties remain about the establishment, evolution, and role of the northern North Atlantic-Arctic Ocean circulation in relation to the opening of the Fram Strait, and its impact on the Earth's global climate during major climatic transitions that have occurred since the Late Miocene. Understanding system interactions between ocean currents and the cryosphere under changing insulation and CO_2 conditions of the past is particularly important for ground truthing climate models. The reconstruction of the paleo Svalbard-Barents Sea Ice Sheet (SBSIS) is critical as it is considered the best available analogue to the West Antarctic Ice Sheet, whose loss of stability is presently the major uncertainty in projecting global sea level in response to present-day global climate warming induced by rapidly increasing atmospheric CO_2 content. Reconstructing the dynamic history of the western margin of Svalbard and eastern side of the Fram Strait at the gateway to the Arctic is key to understanding the linkage between atmospheric CO_2 concentration, ocean dynamics, and cryosphere as main drivers of climate changes.

The key scientific objectives of Expedition 403 are:

(1) the development of a high-resolution chronostratigraphic record of the Late Miocene-Quaternary; (2) the generation of multi-proxy data sets to better constrain the forcing mechanisms responsible for Late Miocene to Quaternary climatic transitions; (3) the identification of orbital, sub-orbital, millennial scale climate variations such as Heinrich events and possible associated meltwater; (4) the evaluation of impacts and feedbacks involving past sediment-laden prominent meltwater events on water masses properties, ocean circulation, ice sheet instability, slope stability, and biota; (5) the reconstruction of paleo SBSIS dynamic history in relation to changes in the ocean current pathways and characteristics as mechanisms inducing ice sheet instability and fast retreat; (6) the study of glacial and tectonic stresses and their effect on near-surface deformation and Earth systems dynamics; and (7) the linkages between large-scale environmental changes and microbial population variability. These objectives will be accomplished through coring and borehole logging multiple holes at five sediment drift sites to create a composite stratigraphy.

For more information on the expedition science objectives and the *JOIDES Resolution* schedule see http://iodp.tamu.edu/scienceops/. This page includes links to the individual expedition web pages with the original IODP proposals and expedition planning information.

APPLICATION DEADLINE: 1 March 2023

WHO SHOULD APPLY: We encourage applications from all qualified scientists. The *JOIDES Resolution* Science Operator (JRSO) is committed to a policy of broad participation and inclusion, and to providing a safe, productive, and welcoming environment for all program participants. Opportunities exist for researchers (including graduate students) in many shipboard specialties, including sedimentologists, biostratigraphers (siliceous, calcareous, and organic-walled microfossils and palynomorphs), organic and inorganic geochemists, microbiologists, physical properties specialists/borehole geophysicists (including downhole measurements and stratigraphic correlation), and paleomagnetists. Good working knowledge of the English language is required.

WHERE TO APPLY: Applications for participation must be submitted to the appropriate IODP Program Member Office (PMO). For PMO links, see http://iodp.tamu.edu/participants/applytosail.html.

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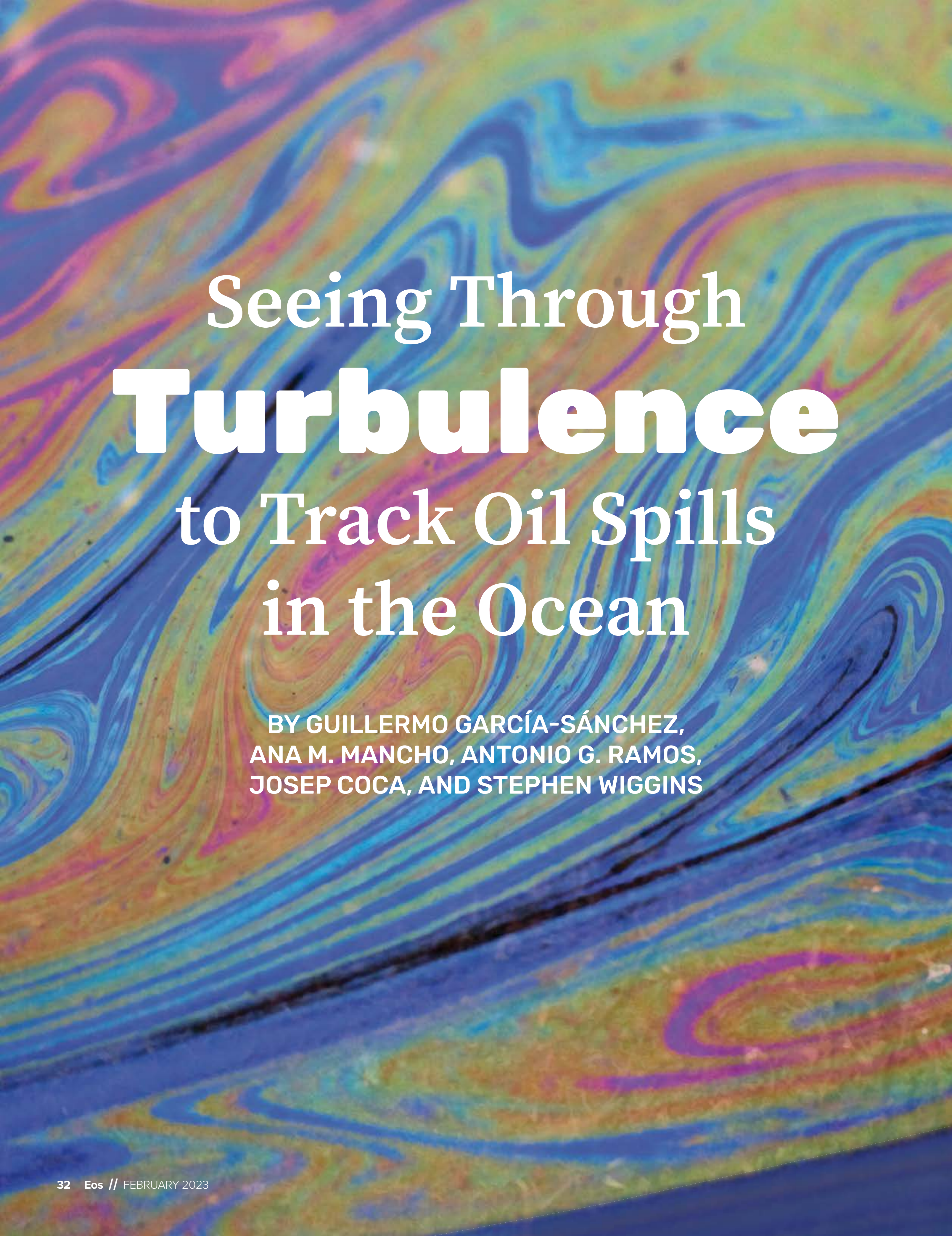


Seeing Through Turbulence to Track Oil Spills in the Ocean

BY GUILLERMO GARCÍA-SÁNCHEZ,
ANA M. MANCHO, ANTONIO G. RAMOS,
JOSEP COCA, AND STEPHEN WIGGINS

ia__64/Depositphotos.com

After oil and tar washed up on eastern Mediterranean beaches in 2021, scientists devised a way to trace the pollution back to its sources using satellite imagery and mathematics.

In mid-February 2021, heavy storms brought intense downpours to the eastern Mediterranean coast, keeping residents indoors. After the storms passed, people returned to local beaches and noticed signs that something was amiss. In Israel, clumps of tarred sand appeared on coastlines, along with oil-covered wildlife like turtles and fish. A 17-meter-long fin whale also washed ashore—an autopsy revealed oily liquid in its lungs, although the source of the oil was not identified definitively.

Experts estimated that more than a thousand metric tons of tar had landed along 180 kilometers of Israeli and Lebanese shorelines in mid-February (Figure 1). Gaza reported similar arrivals of tar on its beaches. The findings forced Israeli authorities to announce the temporary closure of the country's beaches on Sunday, 21 February, and prompted calls to identify the source (or sources) of the oil, which was not immediately clear.

Israeli soldiers clean tar from a beach in February 2021 after oil from a spill in the eastern Mediterranean washed ashore. Credit: Israeli Defense Forces Spokesperson's Unit, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

It may have come from deliberate dumping from one or more ships, possibly the result of malicious acts or operational discharges (e.g., releases of oily water after flushing cargo tanks or emptying ballasts). *Pavlakis et al.* [1996] reported that such spills occur with considerably higher frequency than those caused by ship accidents. In a 1998 report, the European Space Agency (ESA) estimated that 45% of marine oil pollution comes from operational discharges from ships. The same ESA report estimated that more than 4.5 million metric tons of oil are poured into the sea worldwide annually. It is thus clear that oil spills in the ocean are not isolated events. Rather, they are a constant hazard that silently poisons water, air, and flora and fauna at sea and on coasts and, as a direct result, poses risks to humanity.

As authorities began addressing the 2021 spill, they found immediate differences between their investigation and other oil spill investigations. Normally, the origin of a spill is known, and the investigation is focused on monitoring the evolution of the slick, with associated attempts to prevent the oil from contaminating the natural landscape. In this case, the affected areas and wildlife were evident, but the locations and number of spills involved were unknown.

Oceanic turbulence, which leads to constantly changing conditions as it produces swirling eddies and redirects currents, created further difficulties for investigators trying to identify the oil spill's origins. To address these challenges, we have developed a model that makes use of remote sensing data and our understanding of the dynamics of nonlinear systems to identify the source or sources of oil spills—and to keep turbulence from serving as a cover for environmental pollution.

Remote Sensing Detects Oil Slicks

The first step in identifying the source of a marine oil spill is to locate the associated oil slick. One way to do this is to examine synthetic aperture radar (SAR) images gathered by satellites (e.g., Sentinel-1) or aircraft. SAR works by transmitting successive microwave pulses to "illuminate" a target scene and then receiving and recording the scattered echoes of the pulses. The method can thus be used to detect atmospheric or oceanic phenomena that imprint their signal on the ocean surface.

We have developed a model to identify the source or sources of oil spills—and to keep turbulence from serving as a cover for environmental pollution.

For example, wind can generate roughness in the form of small "wrinkles," or capillary waves, on the water's surface, whereas effects of gravity can create undulations called gravity waves with wavelengths stretching from a few to several tens of centimeters (similar to the radar wavelength). The radar sensor records the SAR pulses scattered by a rough ocean surface, producing an image of the surface roughness.

By contrast, floating oil spills smooth the sea surface, damping capillary waves and preventing radar backscattering. As a result, oil spills can be identified from the dark patterns they produce in SAR imagery (Figure 2). Other phenomena, however, such as fishing activities or biogenic slicks produced by phytoplankton, can produce patterns similar to oil slicks in SAR images. Thus, knowledge of the study area and supplementary information—from wind field data, remotely sensed ocean color data, and radiometric imagery (e.g., from Sentinel-2)—are helpful for discriminating among different phenomena.

To track the source (or sources) of the 2021 tar deposits, we used SAR data from Sentinel-1A and -1B first to identify oil slicks in the Mediterranean at the time. We used sea surface wind field data from the European Union's Copernicus Marine Service, wind advanced scatterometer (ASCAT) data from the Metop A and B satellites, and operational model variables from the European Centre for Medium-Range Weather Forecasts, as well as ocean color data from the Ocean and Land Colour Instrument (OLCI) sensors aboard Sentinel-3A and -3B to support our interpretation of the SAR imagery.

Applying these techniques, we detected several dark features thought to be related to oil slicks near the coasts of Gaza, Israel, and Lebanon (Figure 3). In principle, oil and tar from any of them could have reached the shoreline. To prove it, though, we needed to simulate the evolution of these slicks over time.

Chaos at Sea

The biggest challenge in studying oceanic transport of oil slicks or other pollutants like marine litter is that the ocean is turbulent. Turbulence in the ocean comes from various sources: Winds create ripples that travel laterally over the surface as well as vertically through the water column. Daytime heating and nighttime cooling cause seawater to migrate along temperature gradients. Currents moving in different directions spin off eddies, and in shallow waters, currents become turbulent as they drag along the bottom.

In addition to turbulence, researchers must also consider complications introduced by chaos in the ocean. Chaos refers to the observation that in dynamical systems, small differences in the initial conditions of the system can yield widely diverging outcomes, rendering long-term prediction of such systems' behavior extremely difficult. Chaos does not represent randomness; rather, it appears in deterministic systems, that is, systems whose behavior follows a unique evolutionary path that is fully determined by initial conditions, with no random elements involved. In deterministic systems, this evolution can be traced backward in time, potentially revealing that portions of material (e.g., different clumps of oil or tar) that are physically close together at a given time might have come from different starting points. Thus, oil from multiple different spills could end up on the same beach.

State-of-the-art simulations of oil spill evolution involve modeling slicks as a collection of particles with different properties, such as mass, density, and composition, among others—the more particles, the better the representation. In a case like the 2021 eastern Mediterranean oil spills, the typical approach would be to place the particles initially along the affected coastal areas and then run the simulation backward. However, because the ocean is turbulent and chaotic—and we don't know the exact sequence of events—the result would be a cloud of particles spread over a broad area. But we know that the oil that polluted

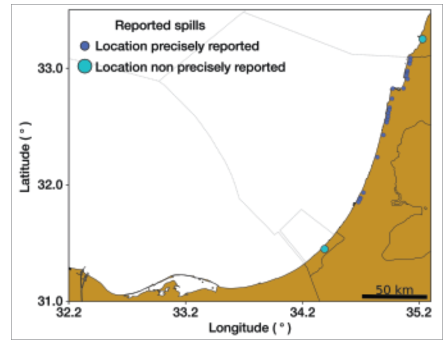


Fig. 1. Oil and tar were observed in many locations along the coasts of Gaza, Israel, and Lebanon in February 2021. Credit: Adapted from García-Sánchez et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

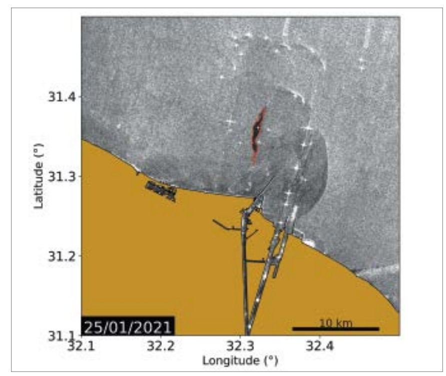


Fig. 2. Satellite radar imagery taken over Port Said, Egypt, (at the entrance to the Suez Canal) on 25 January 2021 shows evidence of an oil spill (outlined in red). The area shown in brown is land. Credit: Adapted from García-Sánchez et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

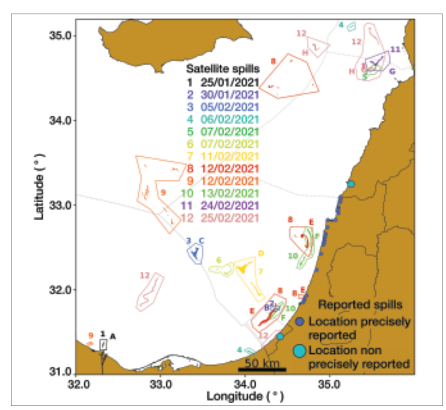
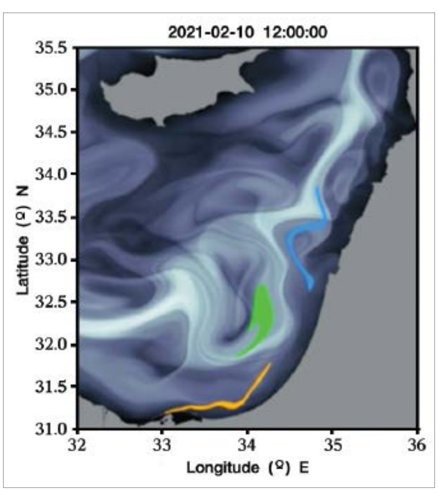


Fig. 3. Analysis of synthetic aperture radar data from Sentinel-1A and -1B between 25 January and 25 February 2021 revealed various oil slicks in the eastern Mediterranean. Letters refer to regions with slicks detected and traced using the methodology described in this article. Credit: Adapted from García-Sánchez et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

Fig. 4. Structures and shapes formed by turbulent flows in Jupiter's atmosphere, as captured by the JunoCam imager on NASA's Juno spacecraft in December 2018 (left), resemble those formed in a phytoplankton bloom in the Baltic Sea in July 2018, observed by the Operational Land Imager on Landsat-8 (right). Credit: (left) NASA/SwRI/MSSS/GeraldEichstädt/Seán Doran, CC BY-NC-SA 3.0 (bit.ly/ccby3-0); (right) NASA Earth Observatory



Three oil slicks can be seen in this snapshot from 10 February from a simulation of oil spills in the eastern Mediterranean in early 2021, one that began on 25 January (orange), 31 January (blue), and 5 February (green). The initiation of the slicks and the timing when two of the slicks reached the coastline in the simulation do not appear in this snapshot. Credit: García-Sánchez et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

the coast in 2021 must have had more localized origins, so how can we determine which of the slicks seen in the SAR images were responsible? We need a new tool that allows us to navigate through turbulence and seeming disorder.

Revealing Order in a Disordered Ocean

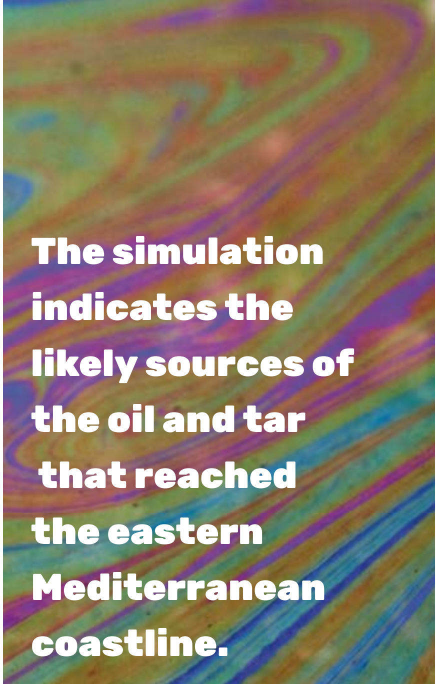
Observational technologies based on satellite imagery and remote sensing techniques have uncovered deep connections between the structure of transport in fluids such as oceans and atmospheres and the mathematical theory of nonlinear dynamical systems. Indeed, imagery often reveals geometric structures and shapes—for example, in Jupiter's atmosphere or Earth's oceans (Figure 4)—displaying subtle and sophisticated order over many scales.

Transported material in these flows—whether ammonia in Jupiter's atmosphere or green phytoplankton in the Baltic Sea—aligns along boundaries called invariant manifolds or Lagrangian coherent structures (LCSs). In nonlinear dynamical systems like the ocean, LCSs can be treated mathematically to help identify how and why fluid flows are organized into ordered patterns. LCSs can be considered to represent the "skeleton" of turbulence, and although they are typically hidden from plain sight, they can be visualized using visible tracers (e.g., Figure 5). LCSs thus allow us to classify the fluid in regions with similar dynamics. This ability is vital for modeling the evolution of oil slicks because it gives us guidelines to recognize, at a glance, domains in the ocean surface with intricate shapes in which fluid parcels have similar origins or fates, thus providing an intuitive vision of oil spill evolution and how oil mixes on the ocean surface.

The representation of LCSs in simulations can be achieved using ocean current data sets and Lagrangian descriptors (LDs), a mathematical tool that highlights time-dependent invariant manifolds in flows. In our work, this approach revealed patterns and paths along which oil spills in the eastern Mediterranean became aligned in February 2021. These patterns, in turn, enabled identification of the source locations of the spills that severely affected coastal areas [*García-Sánchez et al.*, 2022].

A video available on the online version of this article (bit.ly/Eos-oil-spills) shows the evolution of the LDs—and of flow paths and spills—in the eastern Mediterranean from 25 January to 25 February 2021. The simulation model flows in a layer that extends from the sea surface to a depth of 0.5 meter. The darker the region of the sea, the quieter the ocean is; that is, the particles in those regions travel less than particles in the brighter regions. The brighter coloration highlights the swirling LCSs, which act as dynamic barriers that the oil particles cannot cross. Oil slicks identified

Geometric structures and shapes—for example, in Jupiter's atmosphere or Earth's oceans—display subtle and sophisticated order over many scales.



from SAR imagery during this time are denoted initially in red, and the evolution in shape and location of several over time are represented by blobs of color: orange for a slick that originated near the coast of Egypt on 25 January; blue for one originating off southern Israel on 31 January; and green for one that began farther offshore on 5 February. As the video progresses, we see the slicks align with the LCSs, and portions of two slicks eventually reach the coastline (pink) beginning on 16 February. Thus, the simulation indicates the likely sources of the oil and tar that reached the eastern Mediterranean coastline as the spills first seen on 25 and 31 January.

The approach described here—combining capabilities for remote sensing and modeling turbulent, nonlinear systems—is thus capable of finding order in the apparent chaos of the ocean. With continuing improvements, we foresee our method's potential operational application not only for pinpointing the sources and dates of specific oil spills but also for monitoring whether specific areas of the ocean are being used as dumping grounds. It can also help identify areas where oil spills present the greatest hazard to coastal communities and ecosystems.

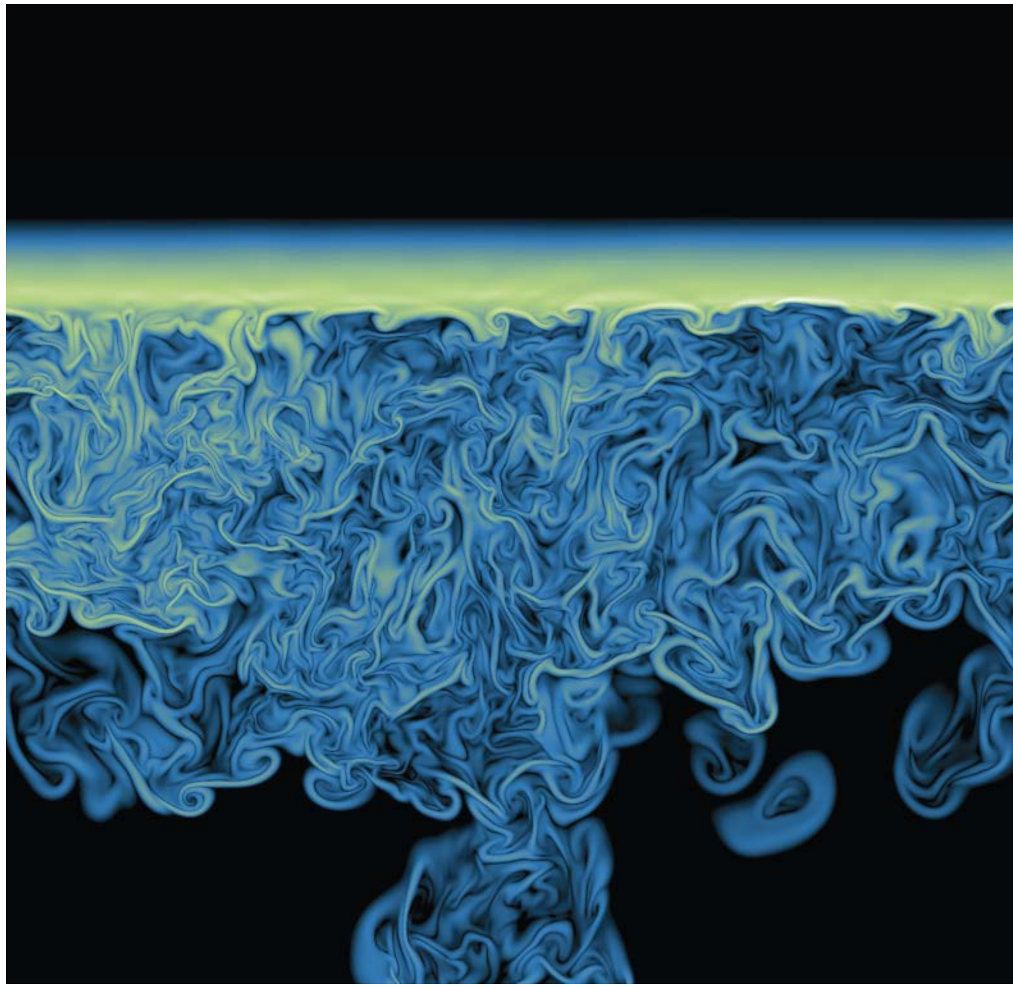


Fig. 5. Eddies of different shapes and sizes are seen in this simulation of the turbulent structure of a stratocumulus cloud top. Credit: J. P. Mellado

Acknowledgments

We accessed SAR data from Sentinel-1A and -1B from the Copernicus Open Access Hub and processed these data using ESA's Sentinel Applications Platform (SNAP). Wind data were gathered from the Copernicus Marine Service (product code 012_004V6); the wind data product corresponds to global near-real-time wind data every 6 hours with a spatial resolution of 0.25°. Ocean color data were gathered from the Copernicus Open Access Hub and were processed using SeaDAS.

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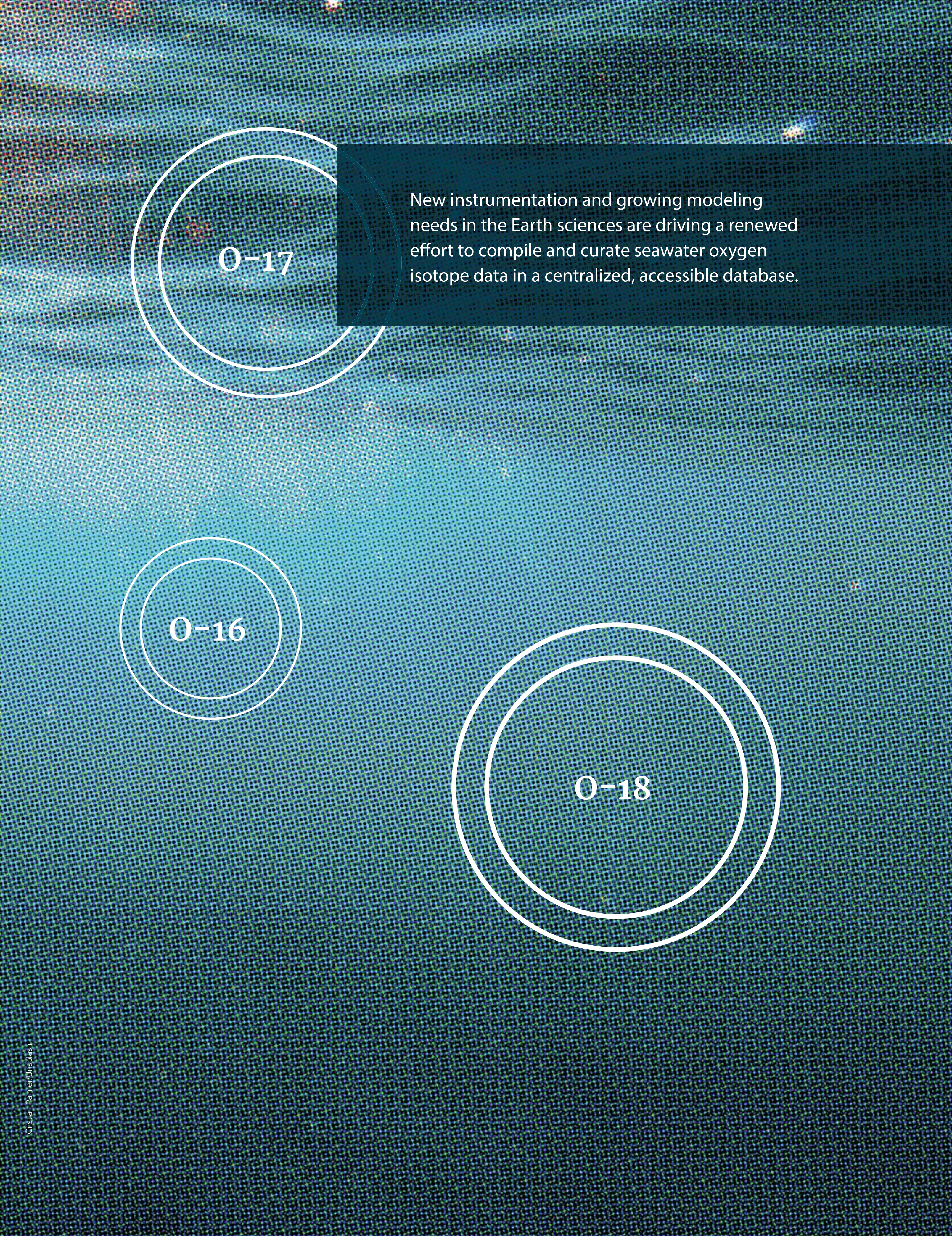
▶ Read the article at bit.ly/Eos-oil-spills

CLUES from the SEA PAINT A PICTURE of Earth's Water Cycle

By Kristine L. DeLong, Alyssa Atwood, Andrea Moore, and Sara Sanchez



New instrumentation and growing modeling needs in the Earth sciences are driving a renewed effort to compile and curate seawater oxygen isotope data in a centralized, accessible database.

Cristian Palmer/Unsplash

In the global water cycle, water that evaporates from the ocean into the atmosphere is transported as water vapor. Some of this water returns directly to the ocean, while the rest eventually precipitates as rain, snow, or ice on land before much of it is ultimately recycled to the ocean via rivers and other sources. As water changes phase from liquid to vapor, the lighter, more abundant isotope of oxygen (^{16}O) preferentially enters the vapor phase compared with the heavier, less abundant isotope (^{18}O), and the reverse occurs when water vapor condenses to liquid water and ice. This variable partitioning of these stable oxygen isotopes by mass provides a means of tracing water as it moves through the hydrologic cycle—a vital tool in studies of climate, meteorology, oceanography, and more.

A wide variety of research networks (e.g., the Global Network of Isotopes in Precipitation, Global Network of Isotopes in Rivers, and National Ecological Observatory Network) have measured—and maintain databases of—the oxygen isotope ratios ($\delta^{18}O$) of water on and above land (namely, in precipitation, rivers, and the atmosphere) to examine the cycling of water between the land and atmosphere. However, no such active observing network exists to document the oxygen isotope ratios of seawater ($\delta^{18}O_{sw}$) needed to understand the cycling of water between the ocean and the atmosphere.

Measurements of $\delta^{18}O_{sw}$ provide important information about the modern ocean and its part in the water cycle. For example, $\delta^{18}O_{sw}$ can inform us about processes related to ocean circulation (upwelling and advection), riverine input into the oceans, ocean-atmosphere water exchange through precipitation and evaporation, and continental ice sheet volume on timescales spanning glacial-interglacial periods and longer.

In 2017, the PAGES (Past Global Changes) CoralHydro2k project was formed to investigate the variability of temperature and $\delta^{18}O_{sw}$ in the surface ocean during the past 2,000 years. Corals incorporate oxygen from seawater into their calcareous skeletons, thus preserving a record of the environment in which they live, and with the very limited coverage of modern $\delta^{18}O_{sw}$ measurements, corals offer vital information for oxygen isotopic variability in the ocean.

The CoralHydro2k investigation combines measurements of $\delta^{18}O$ in corals and of coral strontium-to-calcium ratios (Sr/Ca). Coral Sr/Ca is a seawater temperature proxy, whereas the $\delta^{18}O$ preserved in coral skeletons varies depending on both the water temperature and the $\delta^{18}O_{sw}$ at the time the coral skeleton is formed. Therefore, $\delta^{18}O_{sw}$ can be calculated using the combined measurements of $\delta^{18}O$ and Sr/Ca in corals, given that the calibrations for the coral proxies (Sr/Ca and $\delta^{18}O$) to ocean conditions are known, yet verification of these $\delta^{18}O_{sw}$ reconstructions requires $\delta^{18}O_{sw}$ measurements.

To aid in this effort, we are creating an updated open-access database of modern $\delta^{18}O_{sw}$ measurements. Here we summarize our crowdsourcing efforts and describe the $\delta^{18}O_{sw}$ database to date.

A Host of Questions Await Isotopic Clues

Measurements of $\delta^{18}O_{sw}$ provide important information about the modern ocean, but they are sparse in space and time. Unlike meteorological observations on land, oceanic observations remained relatively limited and regionally focused until the past few decades. This is because most ocean observations are made by satellite remote sensing or by in situ measurements at coastal and island locations that have the infrastructure to support sustained observations of ocean surface properties.

These ocean observations generally include measurements of salinity; however, they rarely include $\delta^{18}O_{sw}$ because there is no cost-effective, easily deployable instrumentation to measure seawater isotopes in situ. Seawater samples must be taken back to a laboratory for isotopic analysis, and these data are rarely provided publicly in real time as other ocean observations are.

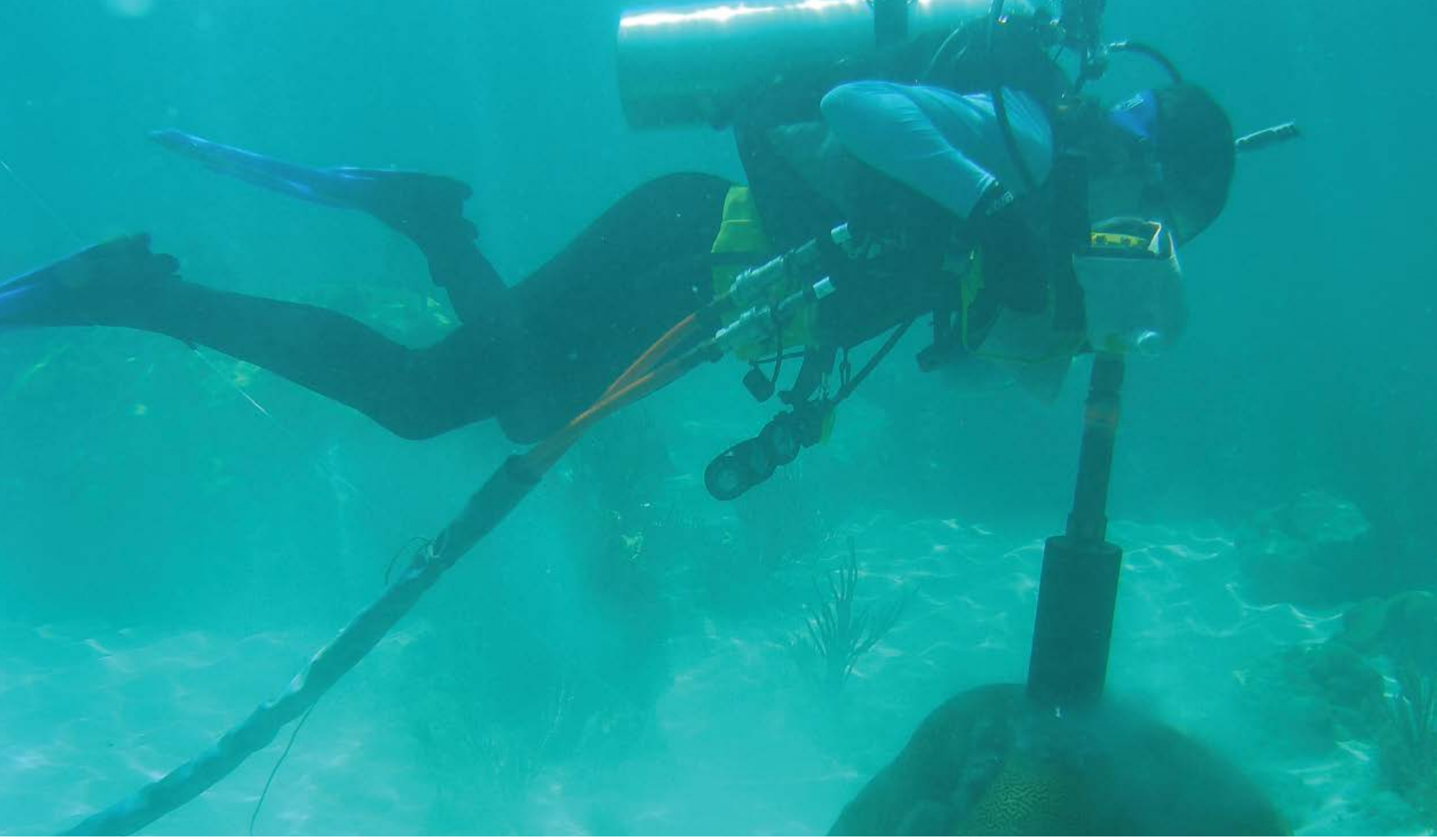
Surface seawater $\delta^{18}O$ covaries with salinity because precipitation and evaporation exert a similar influence on both variables. Lighter isotopes are preferentially evaporated—and heavier isotopes are preferentially precipitated—leaving the ocean isotopically heavier and saltier in regions dominated by evaporation (relative to precipitation) and isotopically lighter and fresher in regions dominated by precipitation. However, the strength of this relationship can vary across time and space, even within individual ocean basins, making salinity an imperfect proxy for $\delta^{18}O_{sw}$ [*Conroy et al.*, 2017]. One reason for this is that $\delta^{18}O_{sw}$ is sensitive to changes in the source and transport pathway of atmospheric water vapor, whereas seawater salinity is not. Thus, measurements of $\delta^{18}O_{sw}$ taken independently of salinity measurements provide additional useful information for models of the ocean-climate system, yielding, for example, more accurate constraints on local moisture budgets and ocean mixing.

Measurements of the oxygen isotope ratios of seawater ($\delta^{18}O_{sw}$) provide important information about the modern ocean and its relationship to the water cycle.

Modern $\delta^{18}O_{sw}$ data are also essential for calibrating proxies of past ocean variability in marine carbonates, such as corals, foraminifera, mollusks, ostracods, and coralline algae, that are used in paleoclimate reconstructions. Recent paleoclimate data assimilation efforts such as the Last Millennium Reanalysis project [e.g., *Tardif et al.*, 2019] would greatly benefit from a spatial network of $\delta^{18}O_{sw}$ data for training the proxy system models that underlie those efforts. Such reconstruction and assimilation efforts enable scientists to extend climate records back into the preindustrial era, thereby contextualizing anthropogenic climate change and improving the skill of future climate projections.

Modern $\delta^{18}O_{sw}$ data are also essential for calibrating proxies of past ocean variability in marine carbonates that are used in paleoclimate reconstructions.

In addition, observational $\delta^{18}O_{sw}$ data are needed by climate model researchers running isotope-enabled Earth system models (e.g., NCAR iCESM, iHadCM3, ECHAM5-wiso); these data allow researchers to assess model performance and skill and provide model boundary conditions (in model configurations that include only



A researcher collects a core from a coral head in Dry Tortugas National Park, more than 100 kilometers west of Key West, Florida, in the Gulf of Mexico in 2008. Credit: Kristine DeLong

active atmosphere and land surface). Given these wide-ranging applications, $\delta^{18}O_{sw}$ data are useful to research communities in oceanography, atmospheric science, geology, and geography alike. For these reasons, a comprehensive database of $\delta^{18}O_{sw}$ data that are publicly available and actively maintained is critically needed.

Seawater Isotope Data Enter the FAIR Era

A major effort to gather $\delta^{18}O_{sw}$ data was completed in the 1990s [*Schmidt*, 1999; *Bigg and Rohling*, 2000], resulting in the NASA Goddard Institute for Space Studies (GISS) Global Seawater Oxygen-18 Database, which includes more than 25,500 individual data points. That database was used to construct a global gridded data set of $\delta^{18}O_{sw}$ and to characterize regional relationships between $\delta^{18}O_{sw}$ and salinity [*LeGrande and Schmidt*, 2006]. It has subsequently been used in many studies. However, the support needed to maintain that database has been limited in recent years, and it is no longer being updated—the last $\delta^{18}O_{sw}$ measurements were added more than a decade ago, in 2011.

New isotope analyzers using cavity ring-down spectroscopy (an ultrasensitive laser-enabled form of spectroscopy) have reduced analytical costs and rejuvenated the collection and measurement of water $\delta^{18}O$. During the past decade, a growing number of new $\delta^{18}O_{sw}$ data sets, many collected using cavity ring-down spectroscopy, have been published, yet there is no active repository dedicated to archiving these $\delta^{18}O_{sw}$ data. As a result, authors often resort to providing their data in supplemental tables in journal articles or to merging their $\delta^{18}O_{sw}$ measurements with other geochemical data and submitting them to repositories dedicated to those other types of data. Researchers cannot easily find or access these "hidden" data sets, thus limiting their inclusion and usability for further research [*Chamberlain et al.*, 2021]. Other $\delta^{18}O_{sw}$ data sets are publicly available and findable, but they are scattered across a myriad of repositories (e.g., GISS, PANGAEA, GEOTRACES, Waterisotopes.org, and EarthChem) and thus are not easily collated together for analysis.

During the past decade, a growing number of new $\delta^{18}O_{sw}$ data sets have been published, yet there is no active repository dedicated to archiving these data.

CoralHydro2k is building upon previous PAGES 2k efforts, namely, Ocean2k [*Tierney et al.*, 2015] and Iso2k [*Konecky et al.*, 2020], which compiled published coral $\delta^{18}O$ and other data into new machine-readable databases. To aid in the calibration and interpretation of these coral records and in recognition of the value of $\delta^{18}O_{sw}$ data to the broader Earth science community, the CoralHydro2k project is also collecting $\delta^{18}O_{sw}$ data.

We are collating these records in a new, machine-readable, and metadata-rich database consistent with findability, accessibility, interoperability, and reusability (FAIR) standards for digital assets. Funding agencies and many publishers are now requiring researchers to archive their data in FAIR-compliant public repositories, providing yet another reason for the new database, as no such repository exists for seawater oxygen isotopes. Once the first version of the data-

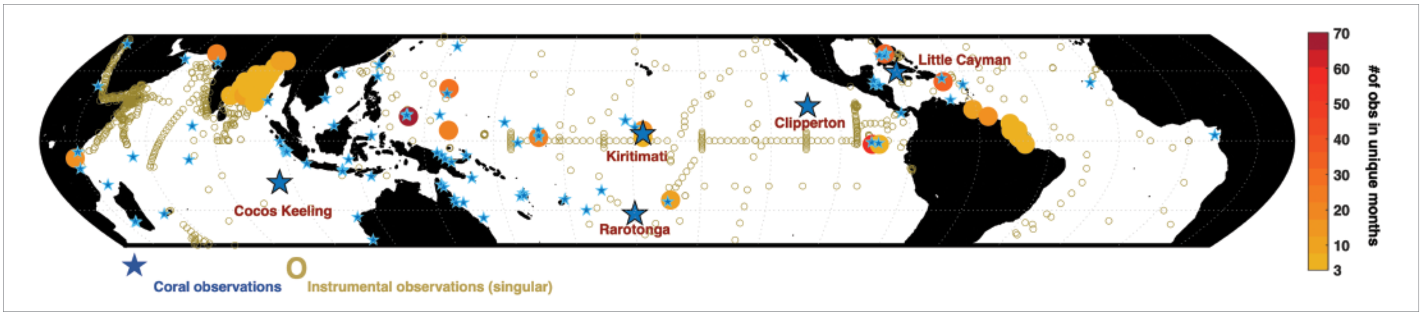


Fig. 1. The locations of all instrumental $\delta^{18}O_{sw}$ in the NASA Global Seawater Oxygen-18 Database and select coral-derived $\delta^{18}O_{sw}$ observations from the CoralHydro2k $\delta^{18}O_{sw}$ Database, binned into 2° × 2° grid boxes, are shown here. Small gold circles indicate grid boxes for which two or fewer distinct months of $\delta^{18}O_{sw}$ observations are available. Larger solid circles denote locations for which more than two distinct months of observations are available; the color bar corresponds to the number of unique months observed. Blue stars denote the locations where the coral $\delta^{18}O$ records selected for Figure 2 were collected.

base is made public—slated for late summer 2023—it will be accessible via the NOAA World Data Service for Paleoclimatology (bit .ly/seawater-oxygen-isotopes). We are also working with EarthChem to set up a Seawater Oxygen Isotopes Community, whereby new $\delta^{18}O_{sw}$ data sets can be submitted and each data submission will be assigned a digital object identifier (DOI) so that the researchers who produced the $\delta^{18}O_{sw}$ data can be cited directly when their data are used by other researchers.

Gathering All the Data

As of 9 Dec 2022, we have collected a total of 19,322 $\delta^{18}O_{sw}$ measurements. Approximately 51% of these measurements are from hidden sources (e.g., direct data submission by authors, journal articles, and student theses and dissertations) and 49% are from public databases and repositories (e.g., GEOTRACES, NASA GISS Seawater Oxygen-18 Database, PANGAEA). A majority of the measurements (60%) are from the surface ocean (upper 5 meters), and 75% of observations are from the tropics and subtropics (35°N to 35°S). We will continue accepting new data submissions and adding to the database as part of the ongoing CoralHydro2k project, with the goal of including as many $\delta^{18}O_{sw}$ data points as possible from the global ocean.

Our compilation thus far reveals the sparse distribution of surface $\delta^{18}O_{sw}$ observations in both space and time (Figure 1). There are vast ocean regions for which no $\delta^{18}O_{sw}$ measurements are available, including large swaths of the tropical oceans. In places where data exist, there are typically fewer than two measurements. Notable exceptions are Palau and the Galápagos Islands (marked with red circles in Figure 1), where researchers have collected some of the longest $\delta^{18}O_{sw}$ records with weekly sampling maintained for several years [*Conroy et al.*, 2017].

Comparing $\delta^{18}O_{sw}$ outputs from several isotope-enabled models as well as coral-derived $\delta^{18}O_{sw}$ reconstructions from five coral study sites demonstrates the wide variability of $\delta^{18}O_{sw}$ among the different models and between models and reconstructions (Figure 2). The discrepancies among the models may be due to their structural differences (e.g., in their resolution, subgrid-scale parameterizations, or treatment of atmospheric exchange or ocean mixing processes). To reconcile these discrepancies, more direct measurements of $\delta^{18}O_{sw}$ data are needed to train the models and assess their skill.

We will continue adding to the new database as part of the ongoing CoralHydro2k project, with the goal of including as many $\delta^{18}O_{sw}$ data points as possible from the global ocean.

Furthermore, at several locations (Little Cayman, Kiritimati, and Rarotonga), the coral-derived $\delta^{18}O_{sw}$ variability exceeds that of nearly all the model estimates (Figure 2). Large variability in coral-based $\delta^{18}O_{sw}$ has also been found relative to an isotope-enabled regional ocean model (isoROMS) [*Stevenson et al.*, 2018]. More $\delta^{18}O_{sw}$ observations are needed to determine whether such model-reconstruction offsets are due to deficiencies in the models, uncertainties in the coral $\delta^{18}O_{sw}$ reconstructions associated with the calculation of $\delta^{18}O_{sw}$ from coral $\delta^{18}O$ and Sr/Ca, or both.

The CoralHydro2k Seawater $\delta^{18}O_{sw}$ Database project is accepting data submissions as we continue populating the new database. All $\delta^{18}O_{sw}$ observations are welcomed (published and unpublished), regardless of the depth or location where the water samples were collected. We strongly encourage submissions with detailed metadata (analytical precision, standards and instrument used, etc.) as part of our commitment to generating a FAIR-aligned database. Researchers can submit their data to the CoralHydro2k $\delta^{18}O_{sw}$ database via our Qualtrics survey, where we also provide a YouTube video with instructions on how to submit the data (bit. ly/seawater-d18O-data). If you know of $\delta^{18}O_{sw}$ data that should be included in the database, please submit this information along with a DOI or citation via our Google Form (bit.ly/seawater-isotopes-survey). Following release of the first version of the database, it will be updated periodically with additional data.

We are confident that this new and growing seawater isotope database will become a vital tool for scientists as they work to paint a clearer picture of Earth's dynamic water cycle and its relationship

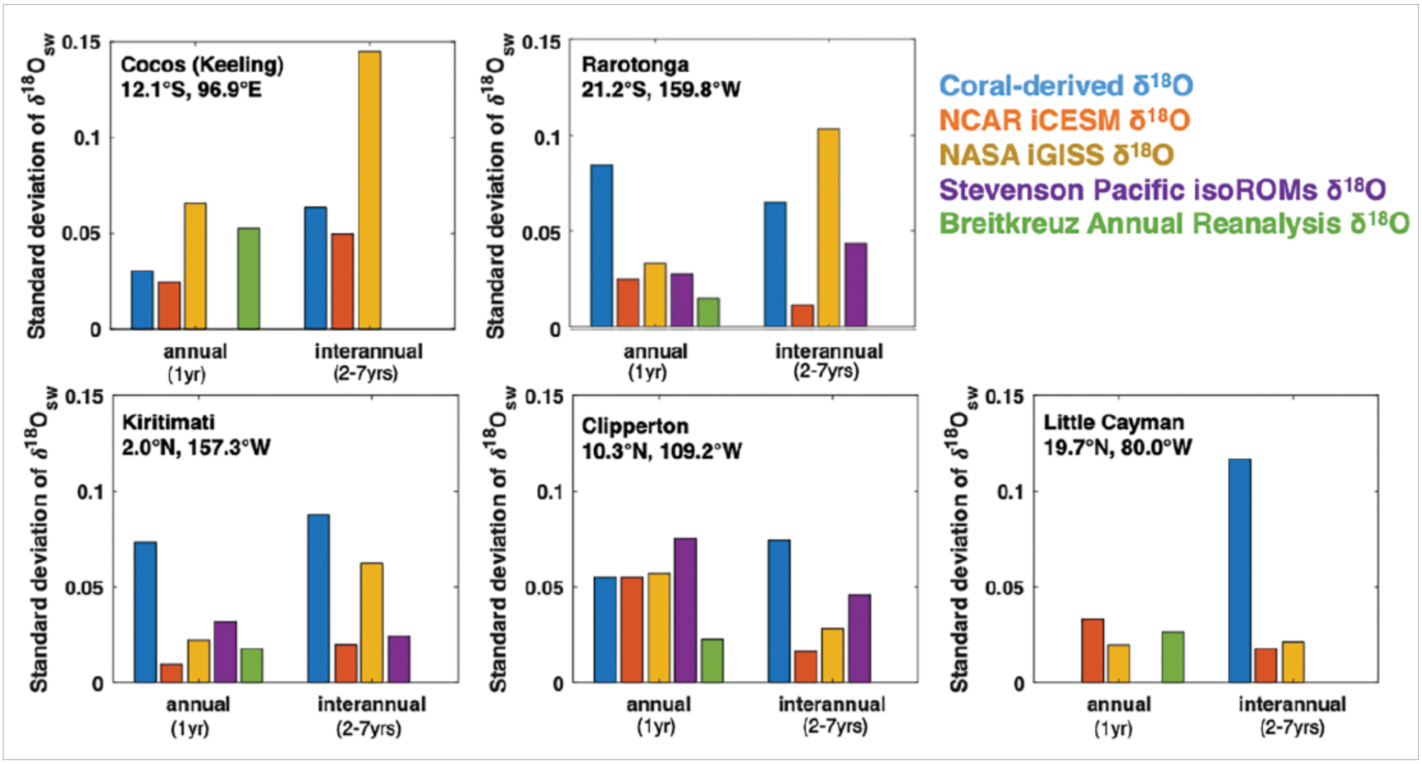


Fig. 2. These plots compare coral-derived $\delta^{18}O_{sw}$ with simulated $\delta^{18}O_{sw}$ from isotope-enabled Earth system models and from a reanalysis product for the five island locations denoted by large blue stars in the map in Figure 1: Cocos (Keeling) in the eastern Indian Ocean, Rarotonga and Kiritimati in the central Pacific Ocean, Clipperton in the eastern Pacific Ocean, and Little Cayman in the Atlantic Ocean. Blue bars show the annual standard deviation of $\delta^{18}O_{sw}$ calculated from the monthly climatology of $\delta^{18}O_{sw}$ at each location in the coral archives. Orange bars show the National Center for Atmospheric Research Community Earth System Model Last Millennium Ensemble (1,000 years) [Brady et al., *2019]. Yellow bars show the NASA Goddard Institute for Space Studies E2-R last millennium simulation (ensemble member E4rhLMgTck; 255 years)* [Colose et al., *2016]. Purple bars show the isoROMs Pacific Ocean simulation (44 years)* [Stevenson et al., *2018]. Green bars show the 2018 Breitkreuz reanalysis (monthly climatology constrained by global monthly $\delta^{18}O_{sw}$ data collected from 1950 to 2011 and climatological salinity and temperature data collected from 1951 to 1980* [Breitkreuz et al., *2018a, 2018b]). The interannual standard deviation of $\delta^{18}O_{sw}$ was calculated from the 2- to 7-year bandpass-filtered time series of each data set, except for the Breitkreuz reanalysis data set (for which an interannual standard deviation cannot be calculated from the monthly climatology).*

to the oceans and climate in the past, present, and future.

Acknowledgments

We thank the paleoclimate, paleoceanography, and oceanography communities for contributing their $\delta^{18}O_{sw}$ data. We thank the other members of the PAGES CoralHydro2k team for their efforts in building this $\delta^{18}O_{sw}$ database, especially the helpful comments and suggestions from Amy Wagner, Thomas Felis, Hali Kilbourne, and Emilie Dassié. Many thanks are owed to Erika Ornouski for her work in finding hidden $\delta^{18}O_{sw}$ data files. We are grateful to Kerstin Lehnert and the EarthChem team at Lamont-Doherty Earth Observatory and Carrie Morrill and Bruce Bauer at NOAA Paleoclimatology for providing opportunities to host the new database. Questions about the database can be directed to Alyssa Atwood (aatwood@fsu.edu). We also recognize the efforts of Gavin Schmidt, Eelco Rohling, Grant Bigg, and Allegra LeGrande in building and maintaining the first $\delta^{18}O_{sw}$ database.

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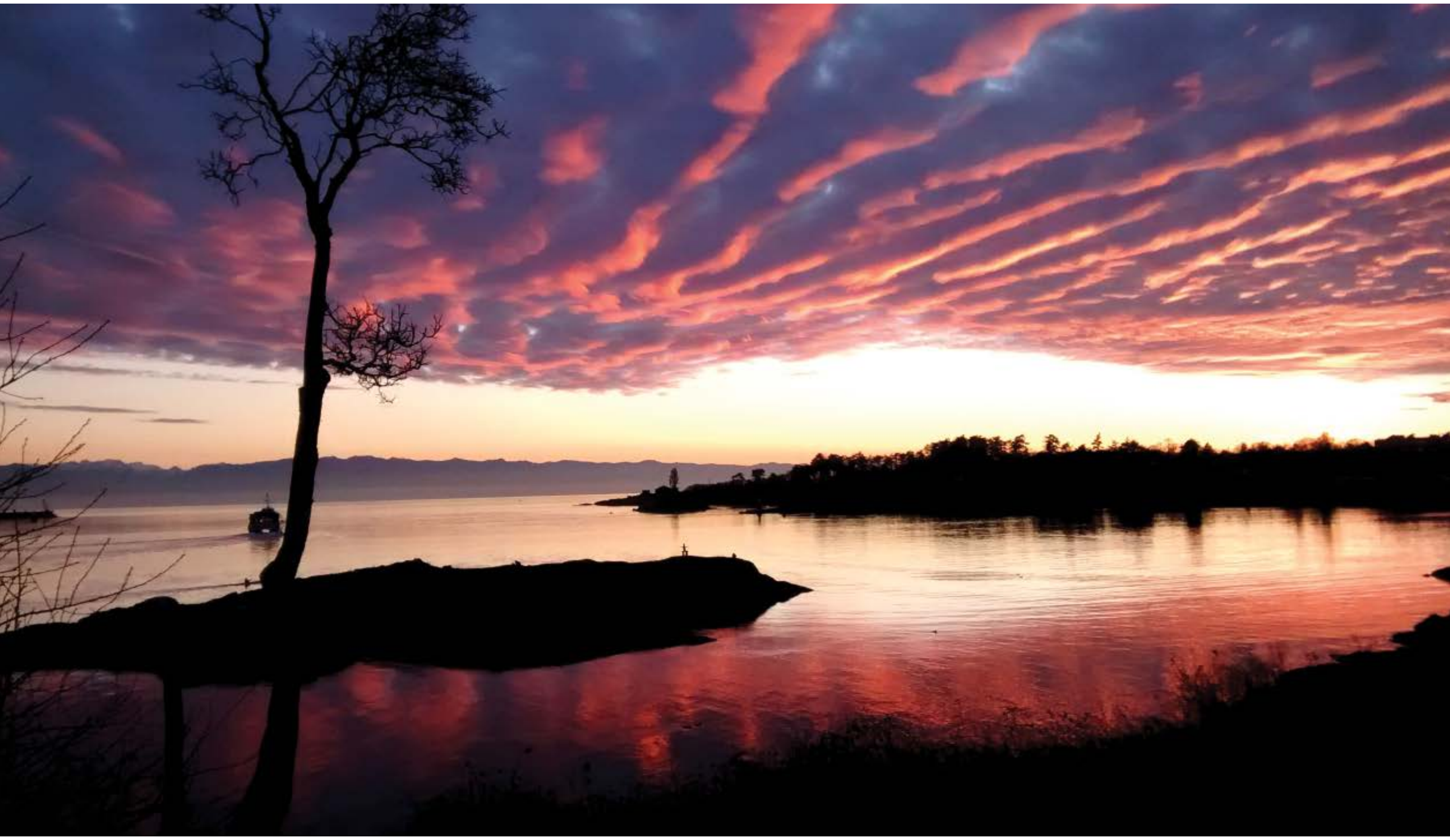
Measuring the Ins and Outflows of Estuaries



A sunset casts pink hues onto clouds over the Strait of Juan de Fuca, one of three estuaries scientists modeled to determine how best to monitor total exchange flow. Credit: Suzette Delmage/NOAA, Public Domain

In coastal inlets such as bays and fjords, mixing of saltwater and freshwater regulates many aspects of the local environment, from nutrient concentrations to oxygen levels and the composition of phytoplankton communities. Studying these areas is critical to our understanding of specialized ecosystems and ocean-land exchanges, but knowing how best to distribute monitoring instruments to capture a full picture of these dynamic environments is challenging.

In 2011, scientists began refining a framework called total exchange flow (TEF) for analyzing how water mixes in estuaries. Until recently, TEF had predominantly been used to model highly defined situations. But in a new study, *Lemagie et al.* investigated realistic hydrodynamic models to predict the best way of using moored instruments to measure TEF in three large natural estuaries: San Diego Bay off Southern California, the Salish Sea and Strait of Juan de Fuca between British Columbia and Washington State, and the outlet of the Columbia River off Oregon and Washington.

The three locations represent very different types and shapes of estuaries. San Diego Bay is a shallow estuary that receives little rainfall; the Strait of Juan de Fuca is a relatively deep fjord; and the outlet of the Columbia River is a salt wedge, where fresh water flows outward atop inflowing salt water.

In each model, the researchers varied the lateral and vertical distribution of the instruments to identify the best configurations. Their results suggested that in all three cases, distributing three to four monitoring devices evenly across the estuary channel, with each taking measurements at one to five depths, could capture more than 90% of water exchange. The findings are encouraging, the authors say, because they suggest that monitoring with a limited number of instruments is a feasible way to measure TEF in estuaries and better understand the water exchanges that regulate these complex ecosystems. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2022JC018960, 2022) **—Saima May Sidik,** *Science Writer*

Powerful Impact Provides Insight into Deep Structure of Mars

NASA's InSight lander (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) launched in 2018 with the goal of peering deep into Mars's interior for the first time to gain important information about the planet's structure and formation. To help with this task, the lander is equipped with a sensitive seismometer that allows it to detect subtle marsquake vibrations. By recording the way these vibrations are reflected and bent as they travel through the planet, InSight has helped scientists map the layout of Mars's crust, mantle, and core. Recently, an unusual series of vibrations provided an opportunity for even deeper understanding.

In a new paper, *Durán et al.* describe a seismic event that is both one of the largest—and farthest from InSight's location—recorded on Mars. It is the first such event with pressure waves (*P* waves) that reached into the lower mantle more than 800 kilometers beneath the planet's surface and all the way to the core, where they were diffracted. After analyzing the vibrations, the authors concluded that the event, which turned out to be an impact, occurred near Mars's Tharsis volcanic plateau, on the opposite side of the planet from InSight, in agreement with satellite images showing the impact site.

The depth of the detected vibrations allowed the researchers to constrain the structure of Mars's lower mantle in more detail than has previously been available. They found that the lower mantle appears to be more variable, in terms of both its temperature and composition, than suggested by previous seismic models. However, they say, it will require more data to determine precisely how the thermal and chemical makeup of the lower mantle varies, and why. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL100887, 2022) **—Rachel Fritts,** *Science Writer*

A Better Operational Lava Flow Model

When a volcanic eruption occurs in an inhabited area, rapid and accurate lava flow forecasts can save lives and reduce infrastructure and property losses. To ensure that current lava forecasting models can provide outputs fast enough to be useful in practice, they unfortunately must incorporate physical simplifications that limit their accuracy.

To aid evacuation plans, forecast models must predict a lava flow's speed, direction, and extent. These attributes are intimately connected to how the lava solidifies as it cools. Yet to achieve real-time speed, most current models assume that a flow has a uniform temperature. This is a major simplification that directly influences modeled rates of cooling; generally, lava flows are much cooler at their boundaries, where they are in contact with air or the ground, than they are internally.

Aiming to strike a better compromise between speed and realism, *Hyman et al.* developed a 2D, physics-based lava flow model called Lava2d. They extended the traditional, vertically averaged treatment of a lava packet by considering it as three distinct regions: the portion near the lava-air boundary, the portion near the lava-ground boundary, and the fluidlike central core. The top and bottom regions of a modeled flow cool based on the physics of heat transfer to the air and ground, while the temperature in the center remains uniform, as in prior approaches. This setup enables the model to account for a temperature gradient without requiring a computationally expensive 3D approach.

To evaluate the technique, the authors applied Lava2d to three increasingly realistic scenarios: a hypothetical synthetic flow, a laboratory-created flow described in the literature, and a flow from a real-world eruption. They found good agreement between modeled and measured flow extent and speed for the laboratory flow, although the modeled surface temperatures of the flow were cooler than those that were measured, a discrepancy the authors attribute to the difficulty of modeling the experimental setup.

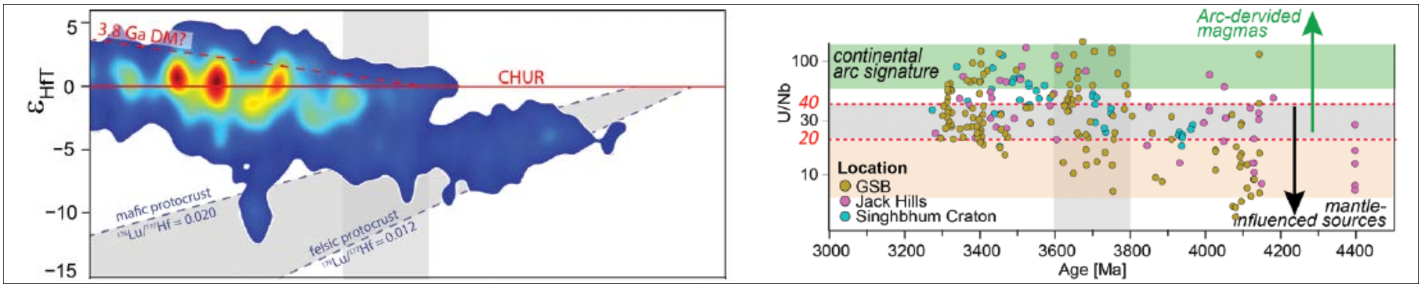
For the real-world test, the researchers configured the model with inputs based on the first few hours of the 1984 Mauna Loa eruption, in

ʻAʻā lava erupted from Ahuʻailāʻau (formerly known as fissure 8) on Kīlauea's lower East Rift Zone flows over a road on the island of Hawaiʻi on 1 June 2018. Credit: A. Lerner/U.S. Geological Survey, Public Domain

Hawaiʻi. They then simulated 12 hours of flow, comparing the modeled extent to the measured positions of the real flow at the end of the eruption. The model correctly identified the general morphology of the real-world flow, although the extents of various subflows were underpredicted or overpredicted.

The model's computational efficiency, however, was clear. The 12 hours of simulated flow were achieved in just 4.5 minutes of computation time. In a real-world forecasting scenario, that speed would enable an ensemble of model runs to be performed and averaged, the researchers note, which would help compensate for inaccuracies within individual runs. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2022JB024998, 2022) **—Morgan Rehnberg,** *Science Writer*

Zircons and Plate Tectonics

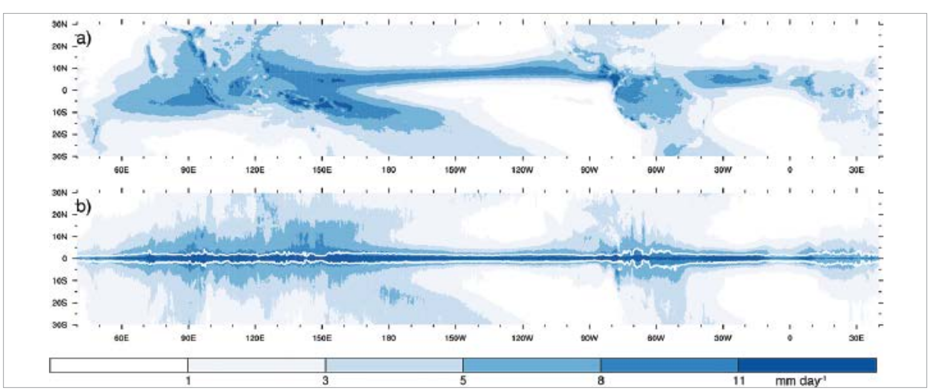


The left panel shows a density plot (warmer colors = higher density) of the results of all zircon hafnium isotope analyses that was created using bivariate kernel density estimates. The outer contour represents the 95% confidence interval in which all other analyses are located. (ε relates the hafnium isotope ratio of a sample to that of the chondritic uniform reservoir standard.) In the right panel, uranium-niobium (U/Nb) ratios are shown for zircons from the Green Sandstone Bed (GSB) in South Africa, the Jack Hills in Australia, and the Singhbhum Craton in India. The gray vertical bar indicates the proposed transitional period between long-lived protocrust and mobile lid plate tectonics. Credit: Drabon et al.

The existence of zircons with ages of up to 4.4 billion years (Ga) indicate that crust was formed early in Earth's history. However, the significance of this early crust with respect to Earth's differentiation is debated. The early Earth record has been dominated by zircons from the Jack Hills in the Yilgarn Craton of Australia, and *Drabon et al.* make a welcome addition by reporting on zircons from the 3.31-billion-year-old Green Sandstone Bed (GSB) formation of the Barberton Greenstone Belt in South Africa, which contains zircons as old as 4.15 Ga.

The authors report high uranium-niobium ratios in zircons younger than 3.6 Ga, similar to zircons from a subduction-type tectonic setting. Zircons older than 3.6 Ga show little uranium-niobium fractionation. In addition, the variation in hafnium isotopic compositions through time indicates a change of origin for GSB zircons around 3.6 Ga from a protolith extracted from a primordial mantle to one that included more juvenile material. The concomitant change in isotope and trace element chemistry is strong evidence for the transition from stagnant lid tectonics to plate tectonics "as we know it" at 3.6 Ga. (https://doi.org/10.1029/2021AV000520, 2022) **—Vincent Salters**

Why Does It Rain So Much Over Tropical Land?



Mean precipitation (a) measured by the Tropical Rainfall Measuring Mission (TRMM) and (b) obtained by shifting each longitude of precipitation meridionally so that its maximum (hydrological equator) lies at the equator is shown here. The shifted precipitation distributions, which are computed for every month and then averaged, emphasize the zonality of the tropical rain belt and its broadening over land. The white lines indicate where precipitation amounts to 50% of the time-averaged maxima. Credit: Hohenegger and Stevens

Rain forests and other ecosystems in the moist tropics depend on large amounts of rain to compensate for their substantial loss of water by evapotranspiration. What maintains these high rainfall rates has been a scientific conundrum, especially given that it rains as much over tropical land as it does over the tropical ocean.

On the basis of observations and conceptual models, *Hohenegger and Stevens* propose that land causes the tropical rain belts to broaden and move more than they do over the ocean, giving rise to the unexpectedly high rainfall rates. The researchers show that these factors support a negative feedback between surface water storage and precipitation, causing land to receive more than its fair share of rain compared with the ocean. This observation contrasts with results from current climate models, which tend to disfavor rain over land and may make predictions of tropical rainfall that are oversensitive to climate change. (https://doi.org/10.1029/2021AV000636, 2022) **—Nicolas Gruber**

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CIGLR

ASSISTANT RESEARCH SCIENTIST IN HYDRODYNAMICS

SUMMARY: The Cooperative Institute for Great Lakes Research (CIGLR) is seeking a **full-time Assistant Research Scientist in Hydrodynamics** in collaboration with the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) and the School for Environment and Sustainability (SEAS). You will lead CIGLR's portfolio of research in hydrodynamics of the Great Lakes. This position is essential to our core areas of research including forecasts of harmful algal blooms, hypoxia, and floods; models of transport of oil and other pollutants; models of key ecological processes such as eutrophication and transport of commercially important and invasive species; short-term predictions of water level fluctuations; ice forecasts that inform the shipping industry and thus support the "blue economy"; and predicting how climate change will affect the thermal structure and circulation of the lakes. We are particularly interested in candidates who can lead the development of coastal coupling between hydrodynamic and hydrologic models, to eliminate coastal "blind spots" and improve our ability to predict coastal flooding.

QUALIFICATIONS: Candidates must have a PhD in physical oceanography, limnology, or related fields. The successful candidate is expected to have a strong record of publication, including first-author publications. Candidates should also have the following:

- Experience with 3D hydrodynamic modeling using state-of-the-art ocean ocean models (FVCOM, ROMS, SCHISM or similar), analyzing oceanographic datasets, and model skill assessment.
- Experience with high performance computing systems (e.g., shell scripting, programming) and proficiency in FORTRAN, Python, R, or similar programming language.
- Experience linking multiple model components, such as linking a hydrodynamic model with a hydrological or wave model.
- Ability to effectively collaborate with diverse experts at CIGLR, SEAS, GLERL, and other partner agencies/institutions/organizations.
- Ability to effectively communicate, supervise and mentor employees and students, and provide scientific leadership of an interdisciplinary team.
- US citizenship or permanent residency.

APPLY

- For more information and to apply, visit the full job ad: **https://careers.umich.edu/job_detail/227591/assistant-research-scientist-hydrodynamics**
- The application deadline is **February 6, 2023.** Review of applications will begin **January 17, 2023** and will continue throughout the posting period or until the position is filled.
- For assistance or for further information, you may contact Greg Dick, Director of CIGLR at **gdick@umich.edu**.

NEW YORK UNIVERSITY

POSTDOCTORAL ASSOCIATE - OCEAN-ICE INTERACTION AT NYU COURANT

Seeking Expression of Interest from **postdoctoral researchers interested in Ocean-Ice Interaction** to join the group of Prof. David Holland (**https://efdlhome.org/**) in the Mathematics department at NYU Courant. The research will primarily involve ocean modeling of grounding zone areas of outlet glaciers in the polar regions. Opportunities for field research to grounding zones exist. This position does not include teaching responsibilities. The position will begin in **September 2023**. This is a full-time appointment, initially for one year, and renewable, conditional on satisfactory performance and funding.

NYU Courant is a highly-rated institute for cutting-edge research and advanced applied mathematics and environmental science training. It is located in the very heart of the world's leading artistic and financial center in downtown Manhattan. The review of applications will start on **January 1, 2023**, and will continue until the position is filled.

In compliance with NYC's Pay Transparency Act, the annual base salary range for this position is $58,500 - $90,000. New York University considers factors such as (but not limited to) the specific grant funding and the terms of the research grant when extending an offer.

QUALIFICATIONS:
The applicant should have a Ph.D. in the mathematical, computational, or physical sciences.

APPLICATION INSTRUCTIONS AND REQUIREMENTS:
- CV including publications list
- Cover letter
- Two confidential reference letters

Submit your application through Interfolio via this direct link: **http://apply.interfolio.com/118867**

EQUAL EMPLOYMENT OPPORTUNITY STATEMENT
For people in the EU, click here for information on your privacy rights under GDPR: **www.nyu.edu/it/gdpr**

NYU is an Equal Opportunity Employer and is committed to a policy of equal treatment and opportunity in every aspect of its recruitment and hiring process without regard to age, alienage, caregiver status, childbirth, citizenship status, color, creed, disability, domestic violence victim status, ethnicity, familial status, gender and/or gender identity or expression, marital status, military status, national origin, parental status, partnership status, predisposing genetic characteristics, pregnancy, race, religion, reproductive health decision making, sex, sexual orientation, unemployment status, veteran status, or any other legally protected basis. Women, racial and ethnic minorities, persons of minority sexual orientation or gender identity, individuals with disabilities, and veterans are encouraged to apply for vacant positions at all levels.

SUSTAINABILITY STATEMENT
NYU aims to be among the greenest urban campuses in the country and carbon neutral by 2040. Learn more at **nyu.edu/sustainability**

HARVARD
Faculty of Arts and Sciences
ORGANISMIC AND EVOLUTIONARY BIOLOGY

TENURED PROFESSOR IN TERRESTRIAL ECOLOGY

POSITION DESCRIPTION: The Department of Organismic and Evolutionary Biology (OEB) seeks to appoint a **tenured professor in terrestrial ecology to serve as the next director of Harvard Forest.** Terrestrial ecology is defined broadly, including studies at the physiological, population, community, or ecosystem level, and encompasses both above- and below-ground terrestrial ecosystems, and all biological kingdoms. We are especially interested in individuals who conduct rigorous observational and/or experimental work on how the structure, composition and functioning of eastern temperate forests are changing as a result of human activities. In addition, we are also interested in individuals who are advancing our understanding of how to conserve biodiversity in natural and human-dominated landscapes, the role of biodiversity in the maintenance of ecosystem services, and the dynamics of coupled human-natural systems.

Both OEB and Harvard Forest value diversity and are committed to building and sustaining culturally diverse intellectual communities on campus and at Harvard Forest. We especially welcome applications from members of groups historically under-represented in STEM and candidates with experience teaching and working with diverse communities and students. The professor will teach and advise at the undergraduate and graduate levels. Harvard Forest and the OEB Department have strong linkages to other allied departments and institutions, including: the Dept. of Earth and Planetary Science, the Arnold Arboretum, the Harvard University Herbaria, the Harvard Museum of Comparative Zoology, the Harvard Center for the Environment, the School of Engineering and Applied Sciences, Harvard's professional schools, and Harvard's new Salata Institute for Climate and Sustainability.

Harvard Forest (**https://harvardforest.fas.harvard.edu**), located in central Massachusetts, hosts integrated research, and educational and outreach programs investigating responses of forest dynamics to natural and human disturbances and environmental changes over broad spatial and temporal scales. It has more than 30 full-time staff, including six senior researchers. Its mission is to advance understanding of biological, physical, and social dimensions of terrestrial ecosystems in the forest landscapes of the eastern United States. Harvard Forest practices an open, inclusive, and collaborative approach to addressing local to global environmental challenges. The Forest's 4,000-acre land base hosts 100+ active research projects annually by PIs at more than two dozen institutions. Research includes deep engagement with regional stakeholders including conservation and forestry organizations, tribal nations, and state and federal agencies. Harvard Forest is one of the founding Long-Term Ecological Research (LTER) sites and plays a major role in LTER leadership, strategic planning, network-wide studies, and public engagement programs. It is also a National Ecological Observatory Network (NEON) site and member of the Ameriflux and ForestGEO research networks. Successful candidates will be expected to provide innovative leadership for Harvard Forest's mission in research and experiential education, particularly in the areas of ecology, ecosystem science, conservation biology, or global climate change. In addition, candidates will be expected to develop creative and impactful programs that leverage Harvard Forest's unique resources toward the benefit of research and education at the broader University.

The appointment is expected to begin on or after **July 1, 2023**.

Keywords:*
• faculty, instructor, tenure, professor, senior
• Boston, Cambridge, Massachusetts, MA, Northeast, New England
• terrestrial ecosystem science, ecology, climate change

BASIC QUALIFICATIONS: Candidates are required to have a doctorate in terrestrial ecology, ecosystem science, or related discipline.

ADDITIONAL QUALIFICATIONS: Demonstrated strong commitment to teaching, advising, and research is desired. Candidates should also evince intellectual leadership and impact on the field and potential for significant contributions to the department, University, and wider scholarly community. Also desired is a history of collaborative research and synthesis, student mentorship, and community engagement.

SPECIAL INSTRUCTIONS: Please submit the following materials through the ARIeS portal (**https://academicpositions.harvard.edu/postings/11821**). Review of applications will begin on **January 9th 2023**.
1. Cover letter
2. Curriculum Vitae
3. Teaching/advising statement (describing teaching philosophy and practices)
4. Research statement
5. Statement describing the candidate's vision for the future of inclusive leadership of a high-impact field station and center for experiential learning, including a history of collaborative research and synthesis, student mentorship, and engagement with broad stakeholders.
6. Statement describing efforts to encourage diversity, inclusion, and belonging. This can include a description of past and ongoing efforts, and anticipated future contributions.
7. Authorization form

Harvard University is committed to fostering a campus culture where everyone can thrive and experience a sense of inclusion and belonging. Community members are encouraged to model our values of integrity, responsible mentorship, equity, and excellence no matter where they are.

To support this commitment to our values of inclusion and excellence, **the external finalist for this position will be required to complete a conduct questionnaire** – specifically regarding findings of violation, on-going formal complaint investigations, or formal complaint investigations that did not conclude due to the external finalist's departure concerning: harassment or discrimination, retaliation, sexual misconduct, bullying or intimidating/abusive behavior, unprofessional relationship, or misconduct related to scholarship, research, teaching, service, or clinical/patient care.

Harvard will also make **conduct inquiries to current and former employers of the external finalist** regarding such misconduct. To facilitate these inquiries, Harvard requires all external applicants for this position to complete, sign, and upload the form entitled "Authorization to release information for external applicants" as part of their application. If an external applicant does not include the signed authorization with the application materials, the application will be considered incomplete, and, as with any incomplete application, will not receive further consideration.

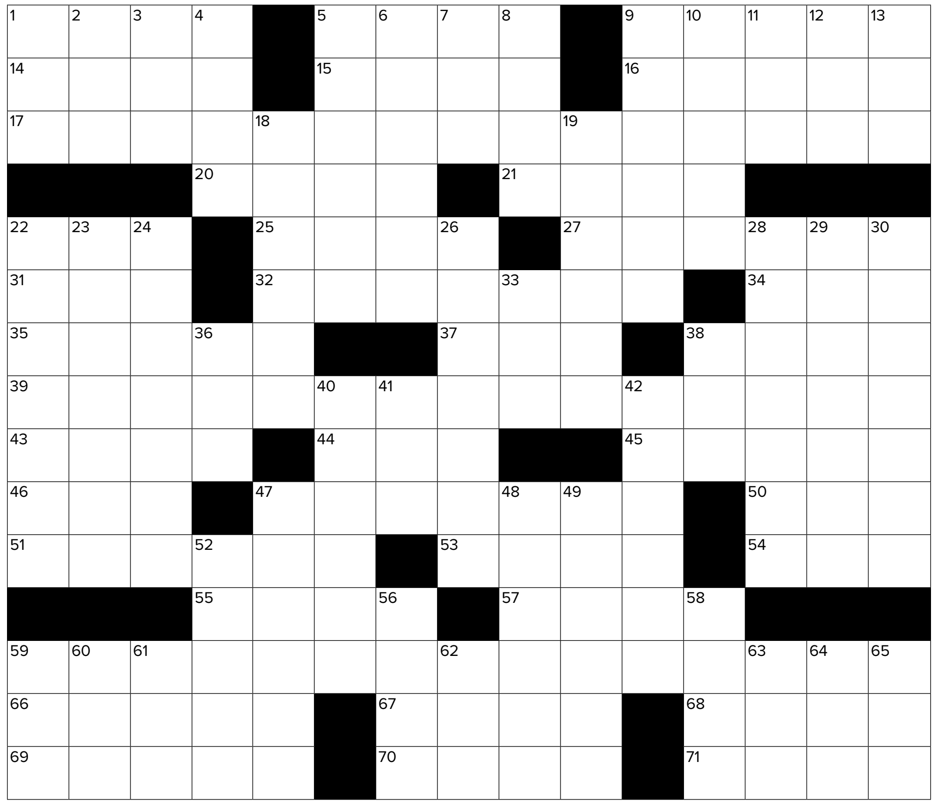
Harvard University is committed to fostering a campus culture where everyone can thrive and experience a sense of inclusion and belonging. Community members are encouraged to model our values of integrity, responsible mentorship, equity, and excellence no matter where they are. To support this commitment, the external finalist for this position will be required to complete a questionnaire regarding misconduct and Harvard will make parallel inquiries to his/her/their current and former employers. View the definitions of misconduct and processes Harvard will use.

Harvard is an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to race, color, sex, gender identity, sexual orientation, religion, creed, national origin, ancestry, age, protected veteran status, disability, genetic information, military service, pregnancy and pregnancy-related conditions, or other protected status.

CONTACT INFORMATION: Paul Moorcroft or Missy Holbrook, Search Committee, Department of Department of Organismic and Evolutionary Biology (**paul_moorcroft@harvard.edu, holbrook@oeb.harvard.edu**)

It's Happenin' on the Ocean Floor

By Russ Colson, Minnesota State University Moorhead



ACROSS

1 Coral reef risk factor
5 Transportation in snow
9 Like an opened bottle of champagne or a foamy beach, rhyming with "roomie"
14 Ending for "car" that spells a type of gun
15 Partner to kin
16 Ebenezer, early on
17 What's up on the ocean floor? Think Darwin's disappointment
20 Battering, jet, and certain sheep
21 Stir-fry containers
22 Government org. for businesses
25 Aunt's sister?
27 Home to part of shrinking Mead
31 A square _____ in a round hole
32 Farmers market setting, often
34 Overalls type
35 One that's always negative
37 The end for many hydrocarbons
38 Jones with a deep locker
39 What's cool on the ocean floor? Think crystal structures
43 Bleats
44 What some mining companies might call 40-down
45 Abu Dhabi princes
46 Acronym for streaming services
47 Makes dependent on
50 Government org. for information security
51 COVID-19 is not just ______ ______
53 Mixture of clay and carbonate
54 Hair, tooth, or nail treatment
55 Unglazed ceramic jar for cooking or gardening
57 Tide near third-quarter moon
59 What's goin' down on the ocean floor? Think feature named for a 16th century Greek mariner
66 Japanese dog
67 Oregon or Kansas, in Paris
68 Companion to "Roger" or "10-4"
69 Untidy
70 Grows pale
71 What's the buzz under the waves? Cetacean vocalization

DOWN

1 1, 2, 3; do, re, mi; ______ ______ ______
2 Government org. for espionage
3 Comfort or Quality
4 Beloved
5 Star chart
6 I'll take a peck
7 The end for many minerals
8 Candida and Pygmalion writer
9 What's cookin' on the ocean floor? A black ______
10 16th-century pope
11 Branch of the mil. that works in the ocean
12 New York player
13 13 BCE, 1999, and 2019, e.g. (abbr.)
18 Beezus Quimby's little sister
19 Wealthy
22 Automated junk source
23 Nonprofit organization promoting ocean health, ______ the Waves
24 Churn
26 A pepper or a city
28 Decreasing in intensity
29 Description of an ecosystem with a high number of species
30 Vast plain on the deep ocean floor
33 This one, that one, whatever
36 Surprised sounds
38 Type of river obstruction or equine mother
40 Manganese or phosphorus, on the ocean floor
41 Old word for Earth, or the heart of eiderdown
42 What we'd get if the 2022 Oscar ceremony were repeated?
47 From dawn to dusk
48 Cabaret dance
49 Chips, candy bars, and ice cream
52 Type types
56 The number of individuals living on an acre of lightless, low-food, ocean floor is usually just ______ ______
58 Nonprofit open-access publisher that supports science and medicine
59 Type of preserve or an informal musical performance
60 Hawaiian inst.
61 Learning machines (abbr.)
62 Lizard genus
63 Guacamole ingr.
64 X
65 About one fourth of one tenth of a millionth of a calorie

▶ See p. 31 for the answer key