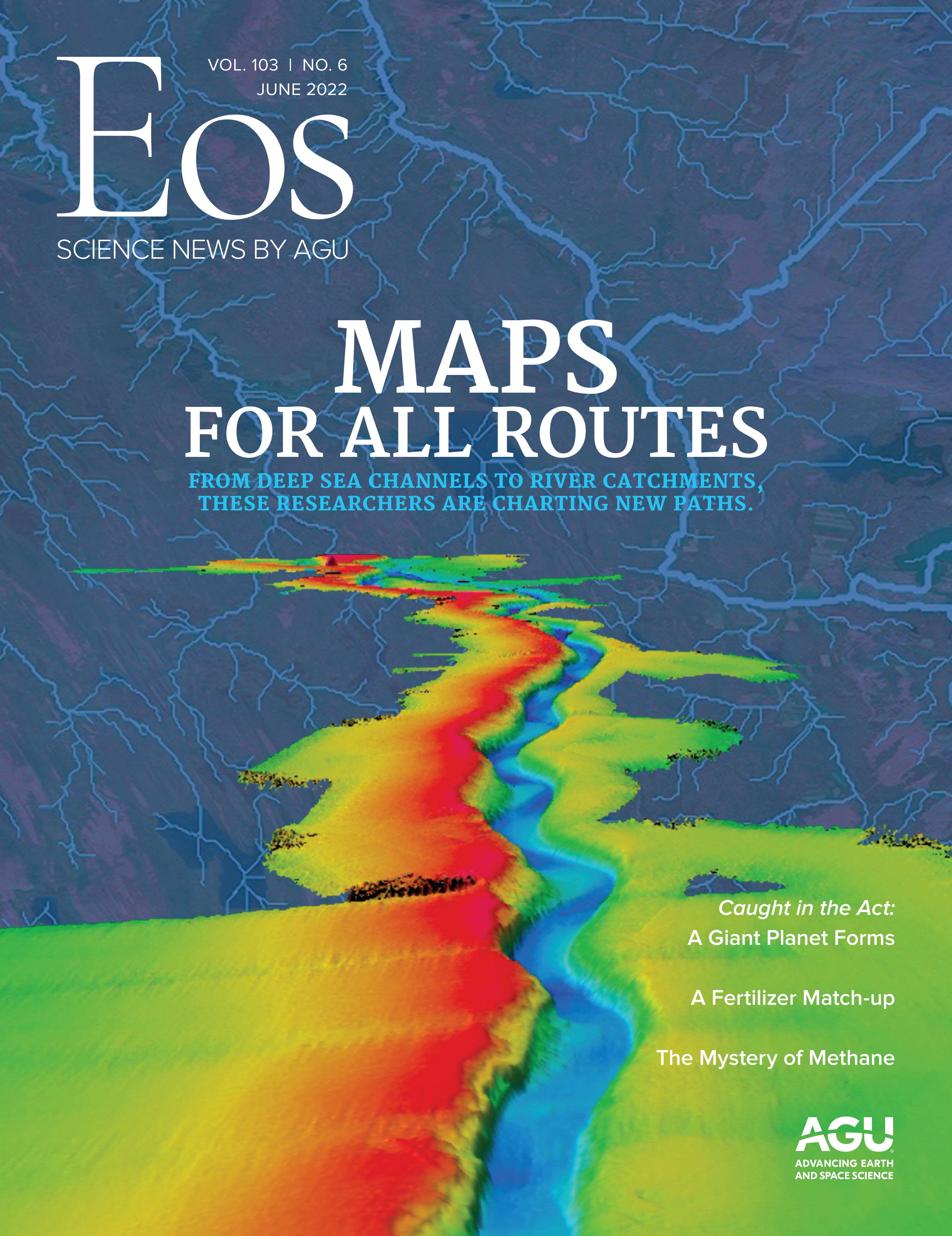

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Eos

SCIENCE NEWS BY AGU

MAPS FOR ALL ROUTES

FROM DEEP SEA CHANNELS TO RIVER CATCHMENTS, THESE RESEARCHERS ARE CHARTING NEW PATHS.

Caught in the Act: A Giant Planet Forms

A Fertilizer Match-up

The Mystery of Methane

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Charting Paths to New Knowledge

We may not always need roads to get where we're going, but everyone can use a good map. In our June issue of *Eos,* we look at the scientists who are recording planetary features so that we can deepen our understanding of the world's seemingly mysterious processes.

In "Mapping a River Beneath the Sea," Sebastian Krastel and colleagues do what they say on the tin. Their team has been exploring submarine channels, and on page 22, they take us with them to traverse what is perhaps the longest submarine channel in the world. The channel was dredged from sediment outwash of melting glaciers and stretches from the Hudson Strait, through the Labrador Sea, and around Newfoundland before reaching its end in the Sohm Abyssal Plain. Scientists have known about the channel for decades and conducted some cartographic research in the past, but Krastel and his team spent summer 2021 on an expedition that would result in the most detailed mapping yet. Be sure to head to the online version to be swept along in a video they created—a still from that video is featured on our cover.

The places where tectonic plates meet can be some of the most exciting on Earth, but any kind of excitement always carries danger along with it. On page 28, Mong-Han Huang and colleagues map out the road to better understanding these dangers in "Exploring Subduction Zone Geohazards on Land and at Sea." Rather than looking at a specific project, Huang's team gives us insight into the suite of state-of-the-art observational tools available these days and how they can be used with better models to map out the risks to communities that live near subduction zones.

Let's meander over to rivers for our last feature in the issue. Bernhard Lehner and colleagues give us insight into the latest digital hydrographic maps in "A Sharper Look at the World's Rivers and Catchments" on page 34. HydroSHEDS, Lehner's team writes, is emerging as perhaps the most useful of these global mapping tools. Researchers are hard at work on the second version, HydroSHEDS-X, which will have extended coverage and other enhancements to provide researchers with the information they need to better understand water availability, flood risk, and other environmental and resource concerns.

Finally, be sure to read a fascinating Opinion by Nathan J. Robinson before you put down the issue (p. 20). He posits that among the wonders of the deep sea could be the extremophile that will give us the knowledge to fight the next pandemic. Given the vast unknowns of the ocean, we should surely keep looking, no matter what we may find.

Heather Goss, Editor in Chief

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Randy Fiser, Executive Director/CEO

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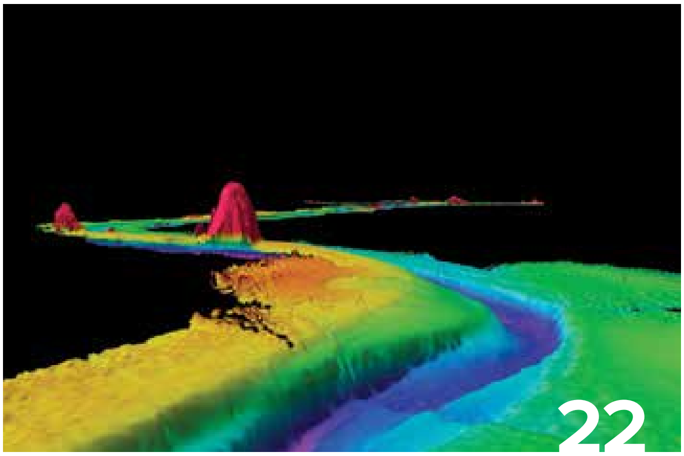

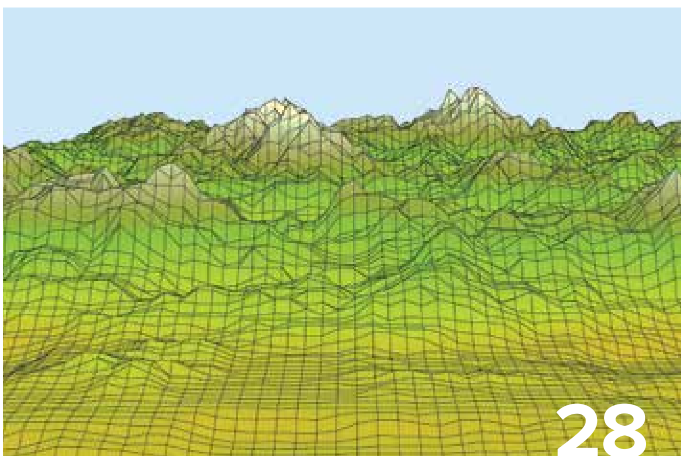

Features

On the Cover

River flow paths in Iceland derived from HydroSHEDS. Credit: Lehner et al., 2022 (background); A stretch of the Northwest Atlantic Mid-Ocean Channel, mapped using high-resolution multibeam bathymetry. Credit: David C. Mosher, Atlantic Division, Geological Survey of Canada, Dartmouth, N.S. (foreground)

Columns

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Impact Structure Hidden Under Arctic Ice Dates to the Paleocene

A Paleocene-aged impact structure lurks beneath Hiawatha Glacier in northwestern Greenland. Credit: Pierre Beck

In northwestern Greenland, there's a secret hidden deep beneath glacial ice: a circular depression hundreds of meters deep and tens of kilometers wide. It's believed to have been formed by an asteroid impact, and researchers now have analyzed bits of rock sloughed off from the structure to determine its age: about 58 million years. That's a surprise—earlier work suggested that the impact might have occurred as recently as a few tens of thousands of years ago, during the Pleistocene, and therefore might have been responsible for the cold period known as the Younger Dryas.

What Lies Beneath

From the surface, Hiawatha Glacier looks like any other expanse of glacial ice. But in 2016, researchers flying in a converted DC-3 plane used ice-penetrating radar to peek beneath the icy mass. They discovered a bowl-shaped depression in the underlying bedrock more than 30 kilometers in diameter with an uplifted central region, geometry characteristic of an asteroid impact. On the basis of estimates of how quickly the structure was eroding, in 2018 a team suggested that the impact had occurred relatively recently, during the Pleistocene.

But now researchers, including some members of the 2018 team, have pinned down a more precise age of the Hiawatha impact structure. It is much, much older than previously believed—58 million or so years, which places its formation solidly in the Paleocene. To arrive at that age estimate, the scientists analyzed grains of sand and pebble-sized rocks collected just a few kilometers from the impact structure's northern rim. This material, transported out from under the ice by flowing water, was shed from the impact structure, the team presumed.

> **"This crater is 4,500 times older than the Younger Dryas."**

Dating Sand and Rocks

Michael Storey, a geochronologist at the Natural History Museum of Denmark in Copenhagen and a member of the research team, led the analysis of the sand grains. Storey and his colleagues selected 50 grains, each a few millimeters in diameter, that all showed evidence of having been melted. The researchers then used argon-argon age dating, a technique that involves measuring the relative concentrations of two isotopes of argon, ^{39}Ar and radiogenic ^{40}Ar, to estimate the grains' ages. Storey and his team found that the grains ranged in age, but none was younger than about 50 million years. "The $^{40}Ar/^{39}Ar$ ages hit a brick wall in the late Paleocene," said Storey.

Gavin Kenny, a geochemist at the Swedish Museum of Natural History in Stockholm and also a team member, next led an independent analysis of two rocks from the impact structure to estimate their ages. The centimeter-scale specimens, which showed signs of having experienced conditions representative of an impact, were a critical find, said Kenny. That's because given their size, it's more likely they were derived from whatever cataclysm created the impact structure. Sand grains, said Kenny, "could have been scattered from somewhere else."

Kenny and his collaborators homed in on zircon crystals, which form deep underground and incorporate tiny bits of uranium into their crystalline structure as they grow. Because uranium radioactively decays to lead over time at a known rate, the age of a zircon crystal can be inferred by measuring its relative abundances of uranium and lead. However, an asteroid impact results in extremely high temperatures and pressures, conditions that can cause zircon to recrystallize and kick out the lead within it. By measuring the ages of recrystallized zircon, it's therefore possible to infer when an impact occurred.

The researchers analyzed 28 zircon crystals that were likely to have recrystallized. They recovered ages as old as roughly 1.9 billion years—probably tracing the rocks that existed at the time of the impact, the team surmised—but also a cluster of ages in the Paleocene, around 58 million years ago. Given that clustering, and the fact that none of the $^{40}Ar/^{39}Ar$-derived ages of the sand grains was younger than the Paleocene, the team concluded that the event that formed the Hiawatha impact structure occurred 58 million years ago. There's accordingly no link whatsoever between this event and the Younger Dryas, a period of cooler-than-normal temperatures roughly 13,000 years ago that's been tied to the rise of agriculture, said Storey. "This crater is 4,500 times older than the Younger Dryas."

"It's not Chicxulub. It probably didn't have a significant effect on the global climate, but it may have had interesting effects on a continental scale."

A Greenland of Rain Forest, Not Ice

Fifty-eight million years ago, northwestern Greenland would have looked nothing like it does today. For starters, there wouldn't have been any ice, said Storey. "What the asteroid hit was a temperate rain forest." The landscape would have been home to hippopotamus-like creatures, alligators, and crocodiles rather than polar bears, he said. "It was a really different world."

And the destruction wrought by the impact might have been significant, but the effects probably weren't felt globally, said Storey. "It's not Chicxulub. It probably didn't have a significant effect on the global climate, but it may have had interesting effects on a continental scale." These results were published in *Science Advances* (bit.ly/Hiawatha-impact).

In the future, it would be valuable to extract material directly from this impact site, said Aaron Cavosie, a planetary scientist at the Space Science and Technology Centre at Curtin University in Perth, Australia, who was not involved in the research. That means drilling through hundreds of meters of ice into bedrock, which is no small feat, he acknowledged. But doing so would provide rock samples that unambiguously trace the impact event. "That'll provide ground-truth evidence," said Cavosie.

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

U.S. Fires Quadrupled in Size, Tripled in Frequency in 20 Years

Throughout the 2000s, fires increased in number, size, and frequency across the contiguous United States compared with the previous 2 decades, new research shows. Extreme fires increased primarily in the western and Great Plains regions, whereas moderate and small fires worsened across the entire country. These fire pattern changes, which threaten human and ecosystem health, are attributed to a combination of climate change impacts and human expansion into new and burnable land.

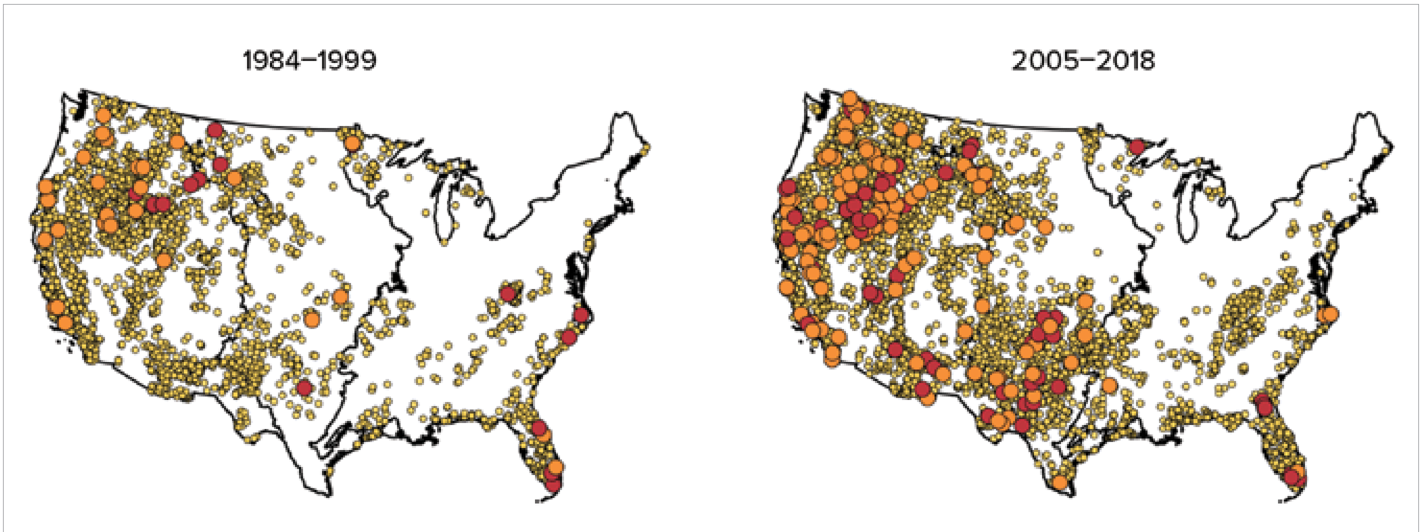
"Every year we spend billions of dollars fighting fires, and we lose homes, infrastructures, and lives," said Virginia Iglesias, a climate scientist at the University of Colorado Boulder's Earth Lab and lead author of the new study (bit.ly/large-US-fires). "And then there's smoke, which affects the well-being of millions of people. Because the impacts of fires are increasing, there's this idea that fires are also getting worse." Recent work has shown that development along the wildland-urban interface is exposing more people to natural hazards and contributing to the increases in loss, "and now we wanted to tell the other side of the story. We wanted to test whether, in addition to an increase in exposure due to development, fires were also getting worse."

Bigger Fires and More of Them

The researchers analyzed more than 28,000 fires that took place from 1984 to 2018 across the contiguous United States. They gathered data from the Monitoring Trends in Burn Severity data set, which combines Landsat data with federal and state fire reports. They split the data into two time periods, 1984–1999 and 2005–2018, and into West, Great Plains, and East regions to examine how fire size and frequency have shifted over time in different parts of the country.

"We found that all regions see more fires since 2005 than in the past," Iglesias said. "In the West and East, there are twice as many fires as before, and in the Great Plains there are 4 times as many fires as before. We saw that fires doubled in size in the West and increased by 150% in the Great Plains."

Wildfire burns trees and shrubs in the 2013 Rim Fire in Yosemite National Park. Credit: Jon Keeley/USGS, Public Domain



These maps show the spatial distribution of fires in the United States in 1984–1999 and 2005–2018. Small yellow dots represent small fires, large orange dots represent fires considered large by 1984–1999 standards, and red dots represent fires considered large by 2005–2018 standards. Credit: Iglesias et al., 2022, https://doi.org/10.1126/sciadv.abc0020, CC BY-NC 4.0 (bit.ly/ccbync4-0)

The team found that in recent years, the total land area burned increased fourfold in the West and more than sevenfold in the Great Plains. In the East, fires didn't change significantly in size or in total area burned. These results were published in *Science Advances.*

"We know that the social side is getting worse because of development. We're exposing more [land]," Iglesias said. "Now we're showing that the physical side, the hazard itself, is also changing."

Peter Teensma, a senior policy and science adviser with the U.S. Department of the Interior's Office of Wildland Fire, said in a statement that "the study was a more detailed statistical and geospatial analysis of wildfires... than our office has conducted, but the results are generally consistent with our observations." Teensma added that research like this helps provide a sound scientific basis for the Interior Department's wildland fire management strategy and that ongoing climate and fire research will provide further scientific footing and direction for wildfire management.

Cascading Consequences

Although some ecosystems benefit from periodic wildfires, much of the new land that has burned or is likely to burn in the future includes ecosystems that have not adapted to frequent fires and are not as quick to recover. Some research already has shown that "reestablishment is compromised in some areas after a fire because climate has already changed, so seedlings can't survive," Iglesias said. A slow-to-recover burnt landscape might lead to polluted water sources, erosion or landslides, and health impacts from airborne ash. "The effects of fires cascade down the ecosystem, make it all the way to our societies, and can have very unexpected consequences," Iglesias added.

Despite repeated calls for climate mitigation and better fire prevention, none of these trends is likely to abate in the future without significant action.

The researchers suggested that the new fire patterns in the early 2000s are likely due to changes in three underlying factors: drought, ignitions, and fuel. Changes in all three can be traced back to humans. Anthropogenic climate change has increased the severity, extent, and duration of droughts in the United States over recent years, turning more and more land arid and at risk of catching fire. In addition, recent studies have revealed that humans ignite 84% of fires in the United States through accident, neglect, or arson. And cities increasingly are developing outward into undeveloped, high-fire-risk land, bringing the primary ignition source (people) into contact with new burnable fuel. Despite repeated calls for climate mitigation and better fire prevention, none of these trends is likely to abate in the future without significant action, Iglesias speculated.

Teensma said the federal government "is working to adapt to the trends this study identified, including large wildfires occurring across geographic areas, wildfires recurring more frequently than the natural fire regime would support, and the impact of nonnative species on changing wildfire patterns." Those changes include transitioning to a year-round wildland fire workforce to address the increasing demand posed by the new fire patterns.

Teensma added that the Infrastructure Investment and Jobs Act, which was signed into law in November 2021, will provide a historic increase in wildland fire management funding that will expand the Interior Department's efforts to reduce wildfire risk, restore ecosystems, prepare for and respond to harmful wildfires, and support postfire recovery, including in communities that historically have been overlooked.

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

Giant Planet's Formation Caught in Action

Planetary scientists strive to understand the ins and outs of planet formation. Discoveries of unusual planetary systems don't make this formidable task any easier. In particular, Jupiter-class gas giants on far-flung orbits have challenged what is known as the standard formation scenario.

Scientists converged on the scenario that our solar system's giant planets formed via accretion within the gaseous protoplanetary disk. Rocky planetary cores fed on pebbles or planetesimals, and once the cores reached a certain mass, they began gobbling up the surrounding gas, rapidly becoming giant planets. But that process works only when planets form relatively close to their host stars—the gas giants found on wide orbits would not have had time to grow a sufficiently massive core before the gaseous disk dissipated.

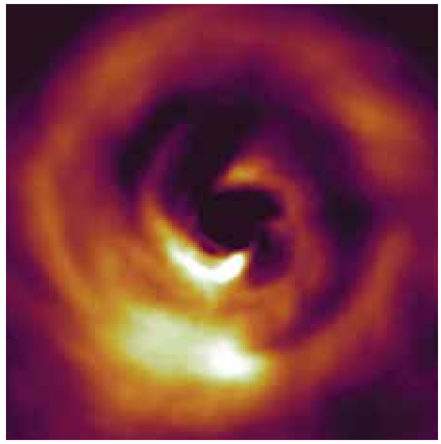
The unstable disk model is one of several alternative models suggesting that a massive and gravitationally unstable protoplanetary disk could fragment into dense clumps, directly giving birth to wide-orbiting planets. However, the model still lacks convincing evidence.

"This is probably the youngest directly imaged planet in a disk."

Now, a team of scientists has made a discovery that might be just the evidence the community has been waiting for. The team imaged a massive protoplanet orbiting the star AB Aurigae at about 93 times the distance between Earth and the Sun. Scientists caught the planet in an early stage of formation, still embedded in a protoplanetary disk. The properties of both the planet and the disk match well the predictions of the unstable disk model. The study was published in *Nature Astronomy* (bit.ly/AB-Aurigae).

AB Aurigae System Takes Shape

The young system AB Aurigae has been on astronomers' radar for a long time. The central star is more than twice as massive as the Sun and lies about 520 light-years away. Its massive protoplanetary disk, mapped over a wide wavelength range from optical to radio, is incredibly complex. Two gaseous spiral arms wind and twist away from the star within a region encircled by a pebble-sized dust ring. Something had to clear the dust inside the ring, and the spirals indicate an unstable disk; both features are smoking gun evidence of baby planets hidden in the disk.



This image of the AB Aurigae system shows protoplanet AB Aur b (the lower bright "blob") orbiting a long distance from its host star. Credit: Thayne Currie/Subaru Telescope

These considerations were in the back of Thayne Currie's mind when he pointed the Subaru Telescope in Hawai'i toward the system for the first time. "For some reason, we couldn't observe our primary target, so I had to make a flash decision, and I said, 'AB Aurigae!'" recounted Currie, an astrophysicist at NASA Ames Research Center and lead author of the study.

Currie and his colleagues observed planet-forming disks in near-infrared light with a stellar coronagraph. This specialized instrument is designed to block a host star's light and thus enable the observation of the much fainter disk.

The first images of the AB Aurigae system contained a bright blob south of the star. Subsequent observations with other instruments and a reanalysis of archival Hubble Space Telescope data confirmed that the blob was genuine. After performing several checks—such as observing the object's position changing in time, consistent with counterclockwise orbital motion—the team realized they were looking at a protoplanet (named AB Aur b) of about 9 Jupiter masses embedded in the disk.

"The conclusion of the source being a planet seems robust," said Ilse Cleeves, an assistant professor at the University of Virginia who was not involved with this study. "This is probably the youngest directly imaged planet in a disk." Infant planets like this one are hard to find, although not for lack of trying. So far, the search has come up with two other protoplanets, both orbiting the same star. But in contrast to AB Aur b, they have already cleared most of their disk's material.

"In the field of planet formation, we're not starved for ideas, but we're starved for actual constraints on the ideas."

The Fate of the Protoplanet Unknown

"In the field of planet formation, we're not starved for ideas, but we're starved for actual constraints on the ideas," said Sean Raymond, an astronomer at the Laboratoire d'Astrophysique de Bordeaux in France who was not involved with the research. "Having real, concrete observations of what's happening is key." In that sense, AB Aur b is quite a catch. It provides direct evidence that Jupiter-like planets can form at large distances from a star. Moreover, together with the spiral features, the discovery supports the unstable disk model.

Other plausible models for the formation of wide-orbiting gas giants invoke planet migration. According to Raymond, a planet can indeed form closer in and then have its orbit expand, but the models have yet to convince astronomers that such a scenario is robust.

The fate of AB Aur b is not clear-cut. "We don't know necessarily if it will survive in the long term," said Cleeves. Depending on the properties of the disk, the protoplanet might migrate inward, which could tear it apart. But given that the protoplanet has already begun tidying up the inner region, "its fate might actually be OK," said Cleeves.

By **Jure Japelj** (@JureJapelj), Science Writer

Traditional Fertilizers Beat Out Industrial Chemicals in Soil Health Test

As the population of India grows, ramping up food production is crucial—but so is preserving the sustainability of the ecosystem so that food production can persist into the future. Since the 1960s, the Indian government has subsidized chemical-intensive fertilizers to enhance crop growth.

iStock.com/prasannapix

Now, new research from western India has shown that in a head-to-head test of soil properties, organic fertilizer based on Traditional Ecological Knowledge encouraged better soil structure and fertility, even during drought periods. Only about 10%–15% of farms in the region studied use the traditional fertilizer, but studies like this one could incentivize more sustainable agricultural practices.

Time-Tested Fertilizer

For years, Seema Sharma, an assistant professor of environmental sciences at Krantiguru Shyamji Krishna Verma Kachchh University, had heard stories from farmers about a traditional organic fertilizer that cultivated more healthy and sustainable soils than chemical approaches. The traditional fertilizer recipes and application timing were even written in Vedic scriptures more than a thousand years ago, she said.

A few years ago, Sharma was at a global conference discussing traditional agricultural strategies from western India, a semiarid region of the country. She said other researchers asked whether science supported the stories that the traditional approach was better for soil health. "The research was already there because the ancient people did their research long ago," she said. "But when it comes to the scientific community, you need research that is in a peer-reviewed journal and then finally verified."

Sharma decided to put the traditional fertilizer to the test.

Traditional and Chemical Fertilizers Go Head-to-Head

Soil health broadly comes down to key physical, chemical, and biological characteristics. In a 2020 study, Sharma compared the biological characteristics of soils fertilized with chemicals and soils fertilized with a combination of farmyard compost and jeevamrutha, a fermented liquid of cow dung, cow urine, a form of cane sugar called jaggery, gram flour, and soil (bit.ly/fertilizer-comparison). Traditionally fertilized soils showed greater microbial diversity—a sign of nutrient availability, soil health, and resilience—than chemically fertilized soils did.

In a new study published in *PLOS Sustainability and Transformation,* Sharma empirically tested and compared physical and chemical characteristics of traditionally and chemically fertilized soils (bit.ly/soil-fertilizers). Characteristics included maximum water holding capacity, density, electrical conductivity, and pH.

For the experiment, Sharma tested soils from 20 farms in the Kachchh district of Gujarat in western India. Half of the farms used commercial chemical fertilizers; the rest used traditional fertilizer. She tested the soils before, during, and after the crop harvest over six cropping seasons and 3 years.

Back in the lab, Sharma found that the water-holding capacity of the traditionally fertilized soil was higher than in soils using chemical fertilizers, even throughout two seasons of drought. The more water soil can retain, the less it leaches nutrients, making it more sustainable in the long term. Soils using traditional fertilizer also had lower soil density, which is crucial for plant rooting, and more stable pH levels throughout the drought periods, even though dry conditions tend to increase salinity. Soils treated with chemical fertilizers tended to have higher pH over time, which can decrease the solubility of nutrients. Overall, jeevamrutha worked better than chemical fertilizers for improving the soil structure and fertility.

Sudeshna Bhattacharyja, a soil scientist at the Indian Council of Agricultural Research–Indian Institute of Soil Science, said that she wasn't surprised by the results because similar studies have been carried out around the country, but having data from western India, where the soil is drier and more salinated, gave a broader understanding of what traditional organic fertilizers can do. "The important thing is the area where the study has been done," she said, because the data can help inform models for better predictions of soil health under different management systems. "If we have ground data from a different corner of the country with a different agroclimatic situation, that will be really good for the future."

Promoting Sustainable Agriculture

Sharma said that her next steps are to test whether crop yields using the traditional fertilizer can be as high as those with chemical fertilizers. Changing from chemical to organic fertilizers can result in yield losses for several years, so farmers must know that the transition will be worth it. "The farmers that I work with are now telling me that we have yields that are on par with the common system of chemical farming," she said. "But that study has to be done."

By **Andrew Chapman** (@Andrew7Chapman), Science Writer

New Hazard Exposure Model for Africa

Earthquakes, landslides, volcanoes, droughts, floods, and storms have all struck Africa in the past half century, affecting half a billion people through death, displacement, and economic loss. Now, researchers have proposed a new disaster exposure model for the continent that could be used to conduct risk assessment for a variety of natural hazards.

The Global Earthquake Model (GEM) Foundation in Pavia, Italy, previously featured in *Eos* (March 2021), led an effort to develop an open seismic hazard and exposure model for the continent in collaboration with AfricaArray, a public-private partnership supporting training and research in Earth, atmospheric, and space sciences.

The group went on to develop a more comprehensive exposure model for all natural hazards and recently published a paper about it in the *International Journal of Disaster Risk Reduction* (bit.ly/uniform-exposure-model).

The 4 million residents of Addis Ababa, Ethiopia, are exposed to moderately high seismicity given their proximity to the East African Rift System, a new risk model reveals. Credit: iStock.com/FrankvandenBergh

Risks of Rapid Urbanization

Disaster risk is an increasingly relevant issue for cities around the world, said Nicole Paul, a seismic risk modeler at GEM and lead author of the new study. Logistics and diverse demographics can make disaster response complex, and risk modeling must incorporate those factors.

"We are fortunate in Africa to have this model.... To put together all of the data sets for such a large continent can be a mammoth task."

Cities provide economic opportunities, but rapid growth can pose challenges to ensuring adequate infrastructure and housing. In locations where urban planning fails to keep pace, slums and overcrowded communities are likely to proliferate. Overcrowded communities are often accompanied by a higher vulnerability to damage, losses, and displacement following natural hazards, Paul explained.

Africa is home to some of the world's fastest growing urban areas, including the megacities of Kinshasa, Democratic Republic of the Congo, and Lagos, Nigeria, both of which have populations of more than 15 million. The continent also has almost 2 dozen cities with populations of 1–2 million.

Many of these growing cities, like Addis Ababa, Ethiopia; Bujumbura, Burundi; and Lilongwe, Malawi, are exposed to moderately high seismicity given their proximity to the East African Rift System.

These cities are made vulnerable by "development in hazard-prone areas such as in floodplains, [as well as by] poor drainage management systems, or a lack of building code enforcement that would otherwise mitigate damage due to hazards such as earthquakes and fires," Paul said.

Developing the Model

Modeling disaster risk in Africa and investing in disaster response planning is crucial, said Paul and her colleagues at GEM. "Investments and planning decisions made in the near term will shape disaster risk experienced by current and future residents of African cities, a population estimated to reach 1.3 billion by 2050," she said.

More sophisticated risk modeling is especially relevant, with countries such as Angola, Niger, Somalia, and Tanzania anticipated to double their number of buildings by 2050, according to the new research.

"That's a lot of buildings still to be built in the next few years and a massive opportunity to reduce future disaster risk through risk-informed design and planning," said Paul. Risk-informed plans or mitigations include creating building codes where they don't exist, removing debris from drainage systems, and upgrading informal settlement infrastructure.

The exposure model covers residential, commercial, and industrial buildings in Africa through 2050. The inclusion of all buildings is a key asset of the new model, said Brian Mubiwa, assistant program manager at the United Nations Environment Programme–South Africa who was not involved in the study. "This new model highlights the potential impact on such important assets as the commercial and industrial building stock, which are often overlooked, as existing models tend to shine the spotlight on residential building stock," he said.

"We are fortunate in Africa to have this model.... To put together all of the data sets for such a large continent can be a mammoth task," said Mayshree Singh, director at Maya Geophysics, a South African seismic hazard consulting service. Singh was not involved in the study.

Another "bonus" in the new model "is that the data sets and hazards are presented quantitatively using a unified, well-established modern approach that is also used internationally, so researchers in Africa can now build on this study and particularly improve on areas where there are gaps in the data sets," Singh said.

Incorporating data on construction typology (e.g., low-rise adobe masonry or high-rise steel towers) is particularly important in Africa's developing cities. With 68% of the continent's population expected to be living in cities in 2050 resilient construction needs to "turn toward pragmatic approaches with direct implications on human livability," said Zaheer Allam, an urban sustainable futures researcher based in the Republic of Mauritius.

Singh agreed. "We see, for example, in South Africa, low-cost houses are quite vulnerable to a small amount of earthquake shaking as compared with well-constructed houses. Funny enough, some traditionally built houses perform better during...earthquake shaking," she said.

Translating the Model into Action

Paul cautioned that the new model cannot be used to make decisions that are specific to individual buildings or neighborhoods, as it does not represent building-by-building statistics.

Instead, said Mubiwa, African policymakers and practitioners can use the model as a tool for informed decisionmaking in terms of development and building design standards.

"Funny enough, some traditionally built houses perform better during... earthquake shaking."

"This science should find expression in the policies and climate action, mitigation, adaptation, and means of implementation strategies."

"Our hope is that future researchers and practitioners can use [these] data to model disaster risk and mitigation strategies for a variety of hazards and purposes throughout the continent," Paul said. "We've made the model open and key assumptions within the model transparent so that others can provide feedback and improve the model as additional information becomes apparent or available."

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

Drones Discover Hidden Weaknesses of Collapsing Volcanoes

When viscous lava erupts, lava domes can form at the top of many volcanoes. If these domes become unstable, their collapse can be extremely hazardous, as was seen when Mount St. Helens in Washington collapsed in 1980, leading to the largest landslide in recorded history. Although potentially catastrophic, the cause of these events has not been fully understood, in part because of the difficulty and danger of reaching summits by foot. But finding the cause can help experts better predict and prepare for volcano dome collapses, potentially saving lives and infrastructure.

So how can scientists reach great and treacherous heights to study volcanoes' lava domes and their destabilization? One answer: drones.

In a new study published in *Scientific Reports,* a team of international researchers set their sights on the summit dome atop Indonesia's most active volcano—Mount Merapi—where hazardous pyroclastic flows have occurred (bit.ly/lava-dome). By using drones, the researchers not only accessed Merapi's summit but also monitored its new lava dome, which had been forming since 2018 and was collapsing along a hidden zone of fractures.

Mixed Methods Pinpoint Weak Areas

The team flew a drone about 500 meters above the lava dome, capturing more than 1,000 high-resolution images over a span of 10 years. According to Valentin Troll, a petrologist from Uppsala University in Sweden and a coauthor of the study, getting usable images was challenging. "Gas emissions or clouds can obscure the view into the crater and onto the dome at times," he said.

Once enough images were collected, 3D information was extracted from them using software. The collection of aerial drone surveys was also combined with mineralogical, geochemical, and mechanical rock strength measurements that reflected areas of weakness resulting from hydrothermal alteration. The tests were conducted on samples of hydrothermally altered dome rocks that the team collected from the flanks of the dome area. These samples were assumed to represent the typical alteration sequence of Merapi's lava dome.

The decadelong process led the researchers to unearth the processes that contributed to the weakening and collapse of Merapi's lava dome. A horseshoe-shaped fracture system—a mechanically weakened part of the dome rock—that formed in 2012 was buried under younger lava in 2018. The rock's fractures and pores made space for migrating fluids (brines and gases) to initiate hydrothermal alteration, in which primary minerals were replaced with mechanically weaker secondary minerals, reducing rock strength further. By 2019, the new lava dome that had formed in 2018 collapsed along this older fracture system, covering the earlier dome structures. New, weaker minerals replaced older minerals in the rock gaps, causing more weakening and collapse.

This oblique view of Mount Merapi in 2019, captured by drone from an altitude of 3,087 meters, shows the new dome growing. Credit: Thomas Walter

Understanding lava domes' yearlong changes "is hugely significant in more accurately understanding locations of lava dome collapses, as well as for application in numerical models of collapse processes."

The new research showed the importance of understanding yearlong changes to more accurately monitor volcanic hazards. According to Claire Harnett, a volcanologist at University College Dublin in Ireland, doing so "is hugely significant in more accurately understanding locations of lava dome collapses, as well as for application in numerical models of collapse processes."

Beyond Merapi and farther afield, drones could be a useful way to achieve long-term monitoring of hidden structural changes at other volcanic domes. "Continued drone recordings will likely allow [us] to identify areas of weakness that later become integrated into the volcano edifice by burial with new lava, for instance," said Troll. These data from drones and other monitoring methods could provide an indication of where internal structural weaknesses may be expected in the future.

By **Clarissa Wright** (@ClarissaWrights), Science Writer

The Alps Are Dusted with Nanoplastics

To test for the presence of nanoplastics in the Alps, researchers gathered samples of melted snow at Sonnblick Observatory, 3,106 meters above sea level. Credit: Elke Ludewig

Plastics are ubiquitous, with more than 350 million tons produced worldwide every year. The far-reaching effects of synthetic materials are also in the news, from the pile of garbage circulating in the Pacific Ocean to elephants dying from consuming nonbiodegradable plastic waste. Now, a new study from an international team of researchers has found tiny plastic particles high in the Alps (bit.ly/nanoplastic-Alps).

Pervasive Plastics

Because plastics do not have a permanent environmental sink, they continue to degrade, becoming increasingly smaller until they are considered nanoplastics, which are 100 times thinner than a human hair. These fragments of plastic are tiny enough to be carried aloft and distributed by the wind. However, data on the distribution and concentration of nanoplastics are rarely reported.

Dušan Materić, a researcher at Utrecht University in the Netherlands, and colleagues were interested to see whether nanoplastics were present in high-altitude, remote places, like the Alps, so they gathered 38 samples at Sonnblick Observatory from February to March 2017. The observatory sits on an isolated peak in the Austrian Central Alps, more than 3,100 meters above sea level. They focused on four commonly used plastics: polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), and polystyrene (PS). The team used thermal-desorption proton-transfer-reaction mass spectrometry to measure and identify the tiny particles in the samples they collected. After analyses, the results were compared to 40 unique ions identified from new plastic exemplars.

"We only recently developed a method that is sensitive and selective enough to track and measure plastics within the aerosol," said Materić.

Although all four types of plastics were detected in the samples, the researchers discovered that two were dominant: PET and PP, which are most commonly used in everyday products, including single-use packaging, clothing, and rope. PET concentrations reached 15.1 nanograms per millimeter of melted snow and spiked on days without precipitation. Materić believes this type of plastic was delivered by wind (dry deposition). PP was also high, averaging 29.5 nanograms per millimeter of melted snow. The concentration of PP peaked during precipitation events, suggesting distribution by wet deposition. Materić was surprised by how much nanoplastic the team measured but noted that the transport and deposition processes of these plastics require further study.

"These are totally new particles, now pollutants, and no proxy from traditional environmental studies can adequately describe their behavior," said Materić. "This is like a fresh daily 'dusting' on the snow surface."

According to outside expert Alice Horton, an anthropogenic contaminants scientist at the National Oceanography Centre in the United Kingdom, this study "is one of very few that have yet managed to detect nanoplastics within environmental samples." She added that this work "enhances and develops our understanding of plastic distribution and degradation within the environment."

Tracking Nanoplastic Movement

To trace the movement of the plastic pollutants to the observatory, the team "rewound" atmospheric models for the region more than 90 hours before the samples were collected. They identified major European cities as the hot spots for the plastics, from London to Munich. But it is possible that the source was even farther west, possibly in the Atlantic Ocean. (Previous studies have suggested that ocean plastic could be a source for microplastics in the atmosphere.)

Using the data from the study, Materić and his colleagues calculated an annual deposition rate of 43.7 kilograms of nanoplastics per square kilometer for the region. This finding raises concerns because nanoplastics can be harmful to human health. Particles smaller than 1 micrometer can penetrate the lungs, enter the bloodstream, and be toxic to the body.

"We need to prioritize this field of research, considering that nanosize particles are toxicologically much more active than bigger particles," said Materić.

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

Just 15.5% of Global Coastline Remains Intact

Human activities heavily influence ecosystems, but scientists are not always able to quantify those influences at a global scale. A new study measured cumulative human impact on the world's coastlines and found that just 15.5% had low anthropogenic pressure. The findings were published in *Conservation Biology* (bit.ly/coastline-pressures).

"We knew it would be high, but it was surprising how much human influence there was across the coastal regions," said coastal ecologist Brooke Williams, a postdoctoral researcher at the University of Queensland, who led the study.

Canada, along with Greenland and Russia, had the largest amount of intact coastline, which researchers defined as regions with low levels of human influence. The intactness was likely due to their relatively small numbers of inhabitants.

"It stands to reason that areas that are more remote are going to...have less human pressure on them. But it is sort of amazing to see, essentially, the whole world [has] these pressures," said Merryl Alber, a University of Georgia coastal ecologist who was not involved in the new study.

Remote beaches in Canada had the lowest instances of human impact, according to a new study. Credit: Ruth Troughton, Unsplash

A Study of Land and Sea

Researchers made use of two separate data sets from 2013 measuring human impact on terrestrial and marine environments. Land-based human footprint data included built environments, population density, electric grids, and navigation structures like roads and railways. Human influences on marine environments, meanwhile, took into account fishing, climate change factors such as sea level and ocean acidification, watershed pollution (including agricultural runoff), and oceanic shipping activities. Researchers designated intact coastal areas within a 50-kilometer radius of a given coastal point.

Science about terrestrial and aquatic environments tends to be conducted (and funded) separately, a frustration for coastal ecologists. Bringing these data together, said Alber, was the paper's biggest contribution.

"It used to be that if you were working in the coastal areas, sometimes you couldn't even figure out where to look for funding because each agency thought the other side was funding it," Alber said. "Making sure that we recognize that both sides [land and water] influence and impinge on these areas is a really important point."

Cumulative Human Pressure

The study showed that more than 60.1% of coastal regions around the world were under high human pressure in 2013, with the greatest impacts being on coastlines with seagrasses, savannas, or coral reefs. In contrast, deserts, forests, and salt marshes composed the coastal areas less pressured by human activity.

Even among specially designated, protected coastal zones, 43.3% showed high levels of human impact. Countries including Denmark, Finland, and Singapore, for instance, ranked high in governmental effectiveness in protecting coastlines but had low intactness scores. (Some other countries with high governmental effectiveness, like Australia and the United States, fared better.) Williams said these results don't necessarily mean leaders in these countries are doing a poor job: "A lot of those coastal regions are already quite badly damaged; they're already degraded."

Williams stressed that the research provided a good general outline of the impact of human activity on coastlines but was not specific or prescriptive. "We are estimating cumulative human pressures, not actual realized state at the biological levels," she said. "Quantifying ecological conditions in the actual state of ecosystems across Earth is extremely complicated. There [are] so many things that make up these ecosystems and biological assemblages...from really tiny scales to big scales."

Overall, though, Williams said she's not pessimistic about these findings. She hopes they encourage individuals to educate themselves and become more involved in helping to protect coastal ecosystems through voting and mindful consumerism.

"If people were more aware of how companies were earning their money...then maybe they would be more inclined to support companies that are more sustainable, and to support politicians who are in favor of regulating these big companies," she said.

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

Mapping Teotihuacan's Past, Present, and Future

For Primo Espinoza, living in the Valley of Teotihuacan 50 years ago was a completely different experience than it is today. What he remembers as a neighborhood with few houses is now a complex urban system that surrounds the mighty archaeological ruins of the ancient civilization only 40 kilometers from the modern metropolis of Mexico City.

Being a third-generation inhabitant of San Juan Teotihuacan made Espinoza an expert on the area he calls home. He started his career selling mud and obsidian handicrafts to tourists but ended up working as a digger in the archaeological zone, which is a quick 15-minute walk from his house.

But what Espinoza didn't know until just months ago is that the constructions built 2,000 years ago determined the exact orientation of the street on which he lives: 15° east of north, the same orientation as the massive monuments of Teotihuacan itself.

That orientation is why every time Espinoza goes out, Cerro Gordo, the mountain that looms over Teotihuacan's Pyramid of the Moon, dominates the skyline at the end of his street. The alignment is intentional, corresponding to strict urban planning organized during Mesoamerica's Classic period.

A recent lidar mapping study found that Espinoza's neighborhood is not unique—around 65% of all modern construction around Teotihuacan (including land divisions, paved and unpaved roads, boundaries, and permanent structures) are aligned with the ancient structures (bit.ly/lidar-mapping).

The lead author of the study, anthropologist Nawa Sugiyama of the University of California, Riverside, explained how thousand-year-old underground sediments made people unconsciously follow the same construction patterns through time. "Soil is not the same when there's a city under it," she said. "Vegetation changes and makes it easier or not to build over.... This is how actions from the past affect our decisions of the present."

"Soil is not the same when there's a city under it; vegetation changes and makes it easier or not to build over.... This is how actions from the past affect our decisions of the present."

A Developing Threat to Cultural Heritage

Lidar technology has been used for years to find hidden ruins of ancient civilizations in Mexico and around the world, but the new research, published in *PLOS ONE*, focused on understanding the impact of human activities on the Valley of Teotihuacan's landscape across time.

People began modifying the landscape more than a millennium ago: Teotihuacan's engineers quarried hundreds of thousands of kilograms of soil and rock from the valley to construct the city, which grew to a population of about 125,000 at its height around 300 CE. At the same time, they modified the courses of the San Lorenzo and San Juan rivers to align them for symbolic and calendrical reasons.

In addition to examining the urban planning of ancient Teotihuacanos, researchers were also able to analyze the impact of mining and urbanization in the valley over the past century. For instance, they identified more than 200 early features that have been destroyed since the 1960s.

Tezontle and basalt mines, many of them illegal, dot around 150 hectares in the Valley of Teotihuacan, largely driven by demand for construction material in Mexico City.

Ariel Texis, one of the Mexican archaeologists in charge of verifying the team's lidar findings, got a surprise when he compared the first map to what the hills look like now. "We had [the hills] in the map, but they no longer exist," he said, having been replaced by open-air mines.

Much of the mining documented by the lidar study was happening at the same time that a new airport serving Mexico City was being built nearby. Although that project was ultimately canceled, another, only about 10 kilometers from Teotihuacan, is currently under construction.

The Pyramid of the Sun at Teotihuacan is outlined in the likeness of Cerro de Patlachique. Ancient engineers constructed the monument echoing the character of the sacred mountain, just outside the modern metropolis of Mexico City. Credit: Milthon Carlos

For Citlali Rosas, archaeologist in chief of the Department of Legal and Technical Protection of the Archaeological Zone of Teotihuacan administered by Mexico's National Institute of Anthropology and History (INAH), such construction around Teotihuacan is "worrying." An airport at that distance, she said, will encourage construction of restaurants, hotels, and other businesses catering to tourists that may put delicate artifacts at risk.

A 1988 presidential decree cracked down on illegal extractive activities in the area, but more could be done, said Rosas. On average, the Department of Legal and Technical Protection suspends around 100 construction projects being carried out without INAH's permission every year.

"It's chaotic [on the periphery of the monument area]; there are constructions everywhere. It's sad."

"It's chaotic [on the periphery of the monument area]; there are constructions everywhere. It's sad," said Veronica Ortega, an archaeologist with Mexico City's National School of Anthropology and History who has spent the past 20 years studying ancient structures around the zone. Ortega was not involved in the new study.

Ortega explained that 60% of the territory of the Valley of Teotihuacan has archaeological remains underneath, but much of the area remains unmapped. Lidar efforts like Sugiyama's would help archaeologists generate a new protection polygon for sediments, artifacts, and remains that lie beyond the archaeological zone.

However, having scientific evidence is not enough, Ortega warned. Stopping the "destruction of one of the most important cultural heritages on the planet" will need broad participation and articulation from Mexico's federal government, municipal authorities, and local communities, she said.

By **Humberto Basilio** (@HumbertoBasilio), Science Writer

Mars's Dust Cycle Controls Its Polar Vortex and Snowfall

Stronger southern dust cycles on Mars stifle its northern polar vortex and increase its snowfall rate, up to a point at least. These results, which are based on an analysis of observations taken over 10 Earth years (5 Mars years), shed light on the global connection between Mars's dominant dust cycle and its global climate.

Mars's atmosphere is less complex than Earth's, explained Noora Alsaeed, and has circulation patterns that directly connect the equatorial regions with the poles. Alsaeed is a doctoral candidate in atmospheric and planetary science at the University of Colorado Boulder. "What this means is that any process that occurs elsewhere on the planet is going to have a more direct impact on the polar region than it would on Earth."

If Mars's polar vortex worked like Earth's, Alsaeed said, it would grow larger, colder, and more stable in winter. "My work is showing that that doesn't happen on Mars, and the reason it doesn't happen is that the dust cycle inhibits the growth and messes with the stability of the northern polar vortex."

Shrinking in the Face of Dust

On lush Earth, the water cycle has significant influence over nearly every atmospheric and surface process. On desiccated Mars, however, it's the dust cycle that dominates, creating beautiful features on the surface and, at times, completely enveloping the entire planet. The dusty season in the southern hemisphere coincides with northern winter, and even a dust season of average strength has been observed to coincide with changes in Mars's weather and climate, including its polar vortices and how much carbon dioxide (CO_2) snow falls in winter. However, not much is known about how or why changes in dust conditions lead to changes in polar vortex strength and size or changes in CO_2 snow emplacement.

Carbon dioxide snow and ice linger on dunes during Mars's northern spring, as seen by the High Resolution Imaging Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter (MRO). Credit: NASA/JPL/University of Arizona, Public Domain

Alsaeed and her team sought to quantify how dust, the polar vortex, and snowfall are connected to better understand the mechanisms that drive it. They gathered infrared radiometry data on Mars's southern hemisphere dust seasons, northern polar vortex, and northern atmospheric CO_2 density for 2008–2018 from the Mars Climate Sounder on NASA's Mars Reconnaissance Orbiter (MRO). MRO has been studying Mars from orbit since 2006. Using these data, the team examined how yearly changes in Mars's southern dust season correlated with the size and intensity of the northern polar vortex and how much snow fell that year.

The researchers found that when dust activity increased in the south, the northern polar vortex shrank in size and grew colder regardless of whether it was winter or summer in the north. And although CO_2 snow fell all throughout northern winter, the combination of colder polar temperatures and the increased availability of dust as condensation nuclei enhanced snowfall when dust activity rose. They also saw that snow didn't fall evenly at all longitudes around the planet; one hemisphere saw significantly more snow than the other each year, a lopsidedness that the researchers attributed to topography altering the shape of the vortex. Alsaeed presented these results at the 53rd Lunar and Planetary Science Conference (bit.ly/Mars-polar-vortex).

"The results broadly agree with previous modeling work in the sense that they see a drop in vortex area with increased dust loading," commented Emily Ball, a doctoral student in geographical sciences at the University of Bristol in the United Kingdom who was not involved with this research. Ball's past research has modeled the connection between heat, snow, and the polar vortex on Mars. The longitudinally uneven snowfall also matched the past modeling efforts of Ball

Images from the MRO showcase the variety of snowy landscapes that grace Mars's surface. Clockwise from top left: frost in late fall, summer ice at the south pole, crescent dunes at the north pole, frost in the dunes of Aonia Terra in the southern hemisphere, and cracked ice over dunes in springtime. Credit: MRO/NASA, Public Domain

and her colleagues, she said, "although I'm not sure if [that] pattern has been seen in CO_2 cloud density before, so that's cool."

There's Such a Thing as Too Much Dust

Alsaeed and her team speculated that as dust is carried from south to north, it brings with it enough heat to press against the boundaries of the polar vortex and restrict its growth; thus, more dust leads to a smaller vortex. That theory is supported not just by average dust cycles but also by the global dust storm that encircled Mars in 2018. The team's MRO data from that year showed that the northern polar vortex never grew during winter.

"The dust event starts off much earlier that year," Alsaeed said. "[Dust] doesn't even give a chance for the polar vortex to begin growing. It's immediately shut down." Moreover, despite the all-encompassing dust, snowfall was enhanced only along the lower-latitude boundaries of the vortex rather than throughout.

William Seviour, an atmosphere dynamics researcher at the University of Exeter in the United Kingdom and one of Ball's research supervisors, agreed that Alsaeed's observations agree with past modeling results and said that he hopes that future work "will focus on better understanding transport and mixing across the polar vortices, and any potential connections this may have to understanding the formation of Mars's polar layered deposits, [the] stratified layers of ice and dust at the poles."

Alsaeed said that she and the team plan to explore in more detail the year-to-year variations in the strength and shape of the polar vortex due to dust storms. They also plan to expand their data set to include what happened after 2018's global dust storm to see whether it matches what happened after the previous planetwide storm. That might give them more insight into the mechanics of dust and heat transport and how Mars's climate reacts during extreme events.

"The Mars dust cycle is very important, and the poles are very important in terms of regulating heat and atmospheric circulation," Alsaeed emphasized. "The fact that they're so tightly coupled makes sense in a way, but it's really important to understand just how that coupling works. This work highlights just how tightly coupled they are, and I hope that more work in the future looks at what the direct line of influence is."

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

It's Getting Hot Under Greenland

Water draining more than a kilometer from the top of Greenland's Sermeq Kujalleq (Store Glacier) generates significant energy at the ice sheet's base, new research finds. Credit: Tom Chudley

Greenland's 3-million-year-old ice is disappearing, with extreme melt events that even include rain at the highest peak on the island. The 1 millimeter the meltwater adds to sea level every year makes it "by far the most rapidly increasing contribution" to sea level rise, said Poul Christoffersen, a professor of glaciology at the University of Cambridge.

Christoffersen is part of a research team that investigated what happens when meltwater drains through fractures in the ice and falls a kilometer or more to the bottom of the ice sheet. "We haven't really understood the overall implication of this transfer of what ultimately are huge volumes of meltwater," said Christoffersen.

To better investigate those implications, Christoffersen and his colleagues installed an autonomous phase-sensitive radio echo sounding (ApRES) instrument 30 kilometers inland on Sermeq Kujalleq (Store Glacier) and drilled a borehole alongside it. Using data collected from both the radar and the borehole, they tracked the water underneath the ice sheet and how it interacted with the ice above. The research was published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/GIS-meltwater).

During a rainfall event, "82 million cubic meters of water were delivered to the base of this glacier in a single day."

They found average melt rates of 14 millimeters per day, on par with those measured at the surface. The most extreme measurement was 57 millimeters, recorded during a rainfall event when temperatures in the borehole hit 0.88°C. During that event, said Christoffersen, "82 million cubic meters of water were delivered to the base of this glacier in a single day."

Potential Energy

The researchers claimed that the energy generated by the meltwater's dramatic drop is on par with the amount of energy produced by the world's largest hydropower stations. This energy contributes significantly to the melt rate experienced by the glacier or ice sheet. In fact, Christoffersen said, the melt rates are 100 times higher than when the process isn't included in models of sea level rise.

The idea of that amount of energy being generated at the bottom of an ice sheet was initially met with skepticism, said Christoffersen. "It's just that we forgot to calculate the potential energy of that elevation drop," he explained.

It's generally been accepted that water forms channels as it flows through glaciers (the Röthlisberger theory), but Christoffersen and his colleagues observed a hydrological system spread over a wide area of the glacier's bed. Even though the water heats as it travels, instead of forming channels it spreads out and heats the ice over a larger area. This mechanism could cause the ice sheet to leave a thawed bed with a small frozen core at its center, said Christoffersen. That pattern would result in faster ice flow, more ice displacement, and cracks and fractures at the surface. "It's a super powerful mechanism that's going to alter the thermal state of the interior of the ice sheet as we get meltwater at higher and higher elevations," he said.

Christoffersen pointed out that the mechanism is applicable only to Greenland's subglacial drainage areas and not to the entire ice sheet. It's also less important for smaller glaciers and ice sheets with thicknesses of less than a kilometer, he said.

The study marked the first time ApRES radar, which was developed for use on floating ice shelves, was deployed inland. This use of the instrument, which has millimeter-range precision, was interesting, said Christian Schoof, a professor at the University of British Columbia who wasn't involved in the study.

"It would be really interesting to see a study like this done where you take not one of these instruments, but you put up an array of them, and you actually get an idea of how spatially variable this melt rate is as well," he said.

By **Danielle Beurteaux** (@daniellebeurt), Science Writer

A Climate Mystery Warns Us to Heed the Unknown

A basic fact about climate change is curiously absent from public consciousness.

One reason: It holds a riddle that scientists don't yet understand.

Methane, a potent greenhouse gas, has been rising in the atmosphere at an accelerating rate since 2007. But the cause of the acceleration remains unknown.

In April, NOAA announced more sobering news (bit.ly/CH4-trends). In 2021, methane rose more than in any other year on record, according to a preliminary analysis of weekly measurements taken at 40 sites globally. 2020 also broke records.

Academic journals whirl with theories of methane's rise. Conference sessions unravel into brainstorming. One group of academics has taken the extraordinary step of sending surveys to ask other researchers their opinion on the matter.

It's rare to feel like climate change is a mystery anymore. When the Intergovernmental Panel on Climate Change (IPCC) formed, controversy besieged even basic facts: Is the planet warming? Are sea levels rising?

Those squabbles have long since ebbed, and political logjams have risen in their place. While lawmakers debate, people suffer and lose their lives from heat and storms worsened by climate change. With so much at stake, there's a heightening sense that the science is settled. In a *Scientific American* article published in November 2021, science historian Naomi Oreskes called for the end of the IPCC's deliberations on the physical science of climate change, arguing that all efforts must instead go toward finding solutions.

But when it comes to methane, the science is not settled. And that matters.

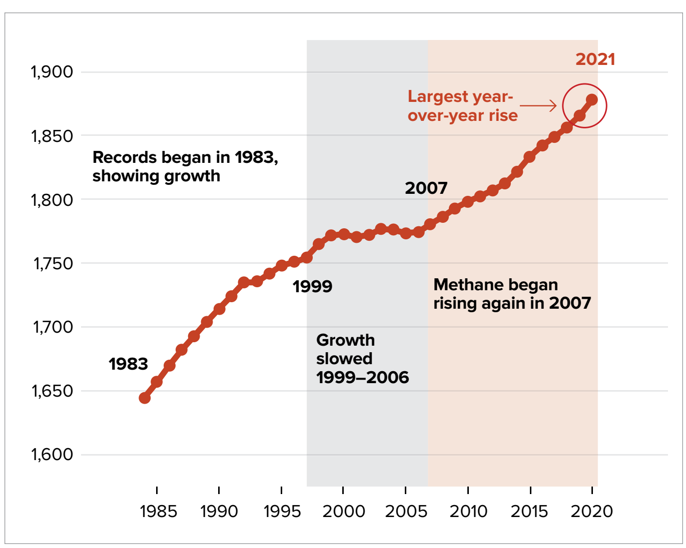
Methane is one of the most powerful levers to quickly stop warming. According to the IPCC's latest report, meeting the goals of the Paris Agreement is impossible without cutting methane emissions by one third this decade.

The good news is that we know where to start. A large portion of methane emissions from oil and gas could be slashed with existing low-cost technology, according to the IPCC and others. Many industry heavy hitters have said they're on board with the plan.

But there's a fear from scientists that even if we cut emissions from fossil fuels, methane in the atmosphere will continue to increase. Higher emissions may be coming from natural swamps, bogs, and marshes, and anthropogenic emissions from livestock and landfills are likely growing as well. Thawing permafrost from the North looms large, too.

The good news is that we know where to start. A large portion of methane emissions from oil and gas could be slashed with existing low-cost technology, according to the IPCC and others.

"It's a very scary and serious situation," said Ben Poulter, a climate scientist at NASA who has studied methane in the atmosphere for more than a decade.



Global methane concentration in parts per billion. Credit: Jenessa Duncombe; Data: NOAA Global Monitoring Laboratory

The Curve

This series, *The Curve*, will chart the mysterious rise of methane in our atmosphere and document researchers' quest to find its source.

I first learned about the puzzle of rising methane last year. Since then, I've traveled with scientists who are searching for answers, from the doorstep of the Arctic to the tropical mangroves of the Gulf Coast. Along the way, researcher after researcher described the methane curve—one even drawing it in the air with her fingers, a shape she knew from memory.

We now have one more data point to add: Methane rose by 16.99 parts per billion last year. The year before, it grew by 15.27 parts per billion, which was the previous record increase since measurements began in 1983. The 2021 value is still being vetted by scientists and may drop slightly when the official number is released later this year.

But this story is bigger than methane. As policymakers implement carbon-cutting technology on a scale and pace never seen before, I think there is a lesson we can learn from this riddle: Climate action can include more research, debate, and room to be wrong.

An early chapter of our climate story was illustrated by the dramatic upward curve of carbon dioxide over time. The Keeling curve became one of the most famous (or infamous) pieces of climate imagery on Earth.

In our next chapter, I expect that methane, and its curve, will step into the spotlight.

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

The Curve *is a series charting the mysterious rise of methane in our atmosphere and the quest to find its source.*

Deep-Sea Exploration Could Help Us Fight the Next Pandemic

A crewed submersible dives amid a school of fish near Cocos Island, Costa Rica, in 2015. Credit: Didier Noirot/OceanX; ©2021, OceanX

Having a cotton swab probe the deep recesses of your nose is hardly a pleasant experience, but it has saved countless lives. A nasal swab, and the polymerase chain reaction (PCR) test used to analyze it, is one of the most effective methods for determining whether a person is carrying a virus, such as influenza-causing strains or the COVID-19-causing SARS-CoV-2 virus. Many public health experts agree that developing infrastructure to conduct diagnostic testing on an unprecedented global scale will be key to preventing future pandemics.

As scientists search for faster, cheaper, and more accurate means to conduct PCR tests and for other medical innovations to fight the spread of disease, the next breakthroughs might emerge from discoveries made in some of the most remote habitats on the planet—at the bottom of the ocean.

The Advent of Modern PCR

For something that can be so deadly, viruses are amazingly tiny, typically just tens of nanometers to a few hundred in diameter. They're so tiny and contain so little genetic material that detecting them in a nasal swab would be an almost insurmountable challenge without assistance from PCR. PCR is a technique for duplicating genetic material, such as the single strand of DNA found inside most viruses. With consecutive duplications, the quantity of genetic material increases exponentially until there is enough viral DNA to be readily detected via routine laboratory techniques.

Scientists figured out the fundamentals of duplicating DNA in the mid-1970s, but the process they were using was painfully slow. Duplicating DNA required temperatures of up to 90°C (194°F), but at that temperature, the enzymes used to jump-start the process quickly broke down. Thus after each round of duplication, the process had to be paused to add a new batch of enzymes. This stopping and starting took considerable time, so the hunt began for DNA-duplicating enzymes that remained stable at higher temperatures.

Viruses are so tiny and contain so little genetic material that detecting them in a nasal swab would be an almost insurmountable challenge without assistance from the polymerase chain reaction (PCR).

Custom enzymes can be created in the laboratory, but this process generally requires extensive testing, and there is no guarantee of success. As all living organisms contain their own DNA-duplicating enzymes, researchers suspected that nature might have already done the hard work of developing heat-tolerant enzymes. The key would be finding an organism that could survive at near-boiling temperatures. It turned out that two scientists, Thomas D. Brock and Hudson Freeze, had already found just such a critter in the hot springs of Yellowstone National Park.

Numerous species of extremophilic microbes—organisms that tolerate temperatures, salinities, acidity, or other conditions outside the habitable range of most species—thrive in the geothermally heated waters of Yellowstone. One of these species, discovered by Brock and Freeze in 1967 and named *Thermus aquaticus*, is particularly at home in near-boiling waters and was later found to possess a thermally stable DNA-duplicating enzyme called *Taq* polymerase. By incorporating this enzyme into the PCR process, DNA duplication could be run continually and without pausing to add new enzymes. It was a watershed development for gene duplication and medical testing.

Yet the demands of modern PCR testing require that we improve this method further, for example, by using natural enzymes capable of withstanding even higher temperatures or replicating DNA with less potential for error (i.e., incorrectly replicated nucleotides).

The Promise of Deep-Sea Microbes

T. aquaticus and its enzymes are still central to modern PCR techniques, but this microbe is not the only species that can survive extreme temperatures. At the bottom of the ocean, there are fissures from which hydrothermal vents spew jets of mineral-rich, superheated water at temperatures that can exceed 400°C (752°F)—that's 4 times the boiling point of water at sea level. The only reason this deep water does not immediately boil into a gas and evaporate is because of the crushing pressures at the bottom of the ocean.

The demands of modern PCR testing require that we improve this method further, for example, by using natural enzymes capable of withstanding even higher temperatures or replicating DNA with less potential for error.

Despite the combination of extreme temperatures and pressures, hydrothermal vents are surrounded by a bustling diversity of life that includes all-important, temperature-defying microbes. Inside one or more of these microbes could be the key to advances in PCR technology. In fact, useful molecules from species other than *T. aquaticus* have already been found: In 1991, scientists isolated another DNA-replicating enzyme, called *Pfu* polymerase, from the hydrothermal vent microbe *Pyrococcus furiosus*. Although *Pfu* polymerase is not as fast as *Taq* polymerase for replicating DNA, the resulting DNA contains far fewer errors, making it well suited for techniques that require high-fidelity DNA synthesis.

Deep-sea microbes from other environments may also hold secrets that could benefit medical or industrial applications, perhaps in unforeseeable ways. For example, in a recent study considering more than 50 species of microbes that live inside deep-sea sponges, researchers discovered that more than half the species contained chemicals that can serve as effective antibacterial or antifungal treatments (bit.ly/deep-sea-microbes). As the prevalence of antibiotic-resistant infectious pathogens, such as methicillin-resistant *Staphylococcus aureus* (MRSA), continues to grow worldwide, such new sources of antibiotics could be especially valuable if they can help circumvent these resistances.

These discoveries alone speak to the extraordinary value of deep-sea exploration, yet they represent only the tip of the iceberg. More than 90% of marine eukaryotes—and a far greater proportion of prokaryotes, including bacteria and archaea—have yet to be scientifically described. The vast array of naturally produced antibiotics that still may be found in organisms living at the bottom of the ocean is therefore almost beyond imagining. Realizing medical benefits from these natural products, however, requires that we take the plunge and commit to exploring the dark, deep depths of the ocean. What we discover in these habitats could have wide-ranging implications that echo around the globe.

Exploring for Undiscovered Bounties

Despite the potential discoveries that await us at the bottom of the ocean, four fifths of this vast underwater realm remains unexplored and not mapped at high resolution. It is almost cliché, yet entirely true, to say that we have more accurate maps of the Moon's surface than of the bottom of the ocean. As many people have pointed out, this disparity stems in part from chronic underfunding of deep-sea exploration, especially in comparison with space exploration. It is time to address this imbalance and promote deep-sea exploration at national and international levels.

A necessary first step in this exploration is to generate accurate and thorough maps of the entire seafloor. Such efforts have already begun, including the international Nippon Foundation-GEBCO (General Bathymetric Chart of the Oceans) Seabed 2030 Project, which aims to map 100% of the seafloor using modern sonar methods by 2030. With detailed maps of the structure of the entire seafloor, we will be able to better identify those unique or particularly interesting habitats that could harbor bounties of undescribed species.

This Bolosoma sponge was observed at a depth of about 2,500 meters near Sibelius seamount, north of Hawaii, during a 2017 expedition of NOAA's Okeanos Explorer. *Credit: NOAA Office of Ocean Exploration and Research, CC BY-SA 2.0 (bit.ly/ccbysa2-0)*

Once we know where to focus our efforts, the next step will be to explore these habitats firsthand, concentrating not only on the most charismatic of deep-sea species that often command our attention but also on tiny microbes that might otherwise go unnoticed. Indeed, as we have learned time and again—from the revelations of penicillin, *Taq* polymerase, and more—it is in the smallest organisms that sometimes the biggest discoveries are found.

This exploration will require submersibles, submarines, remotely operated vehicles, and other tools at the technological forefront of deep-sea exploration. The use of such high-tech equipment might sound expensive, but it is worth remembering that the cost of a single space shuttle launch in 2011, upward of $1 billion by some estimates, could have funded two deep-sea submersible dives per day for 110 years! So as we work to combat the ongoing COVID-19 pandemic and we think about what hazards the future could hold for our health, perhaps we need to spend a little less time looking at the stars and more time with our eyes under the water.

By **Nathan J. Robinson** (nathanjackrobinson@gmail.com), Instituto de Ciencias del Mar, Consejo Superior de Investigaciones Científicas, Barcelona, Spain

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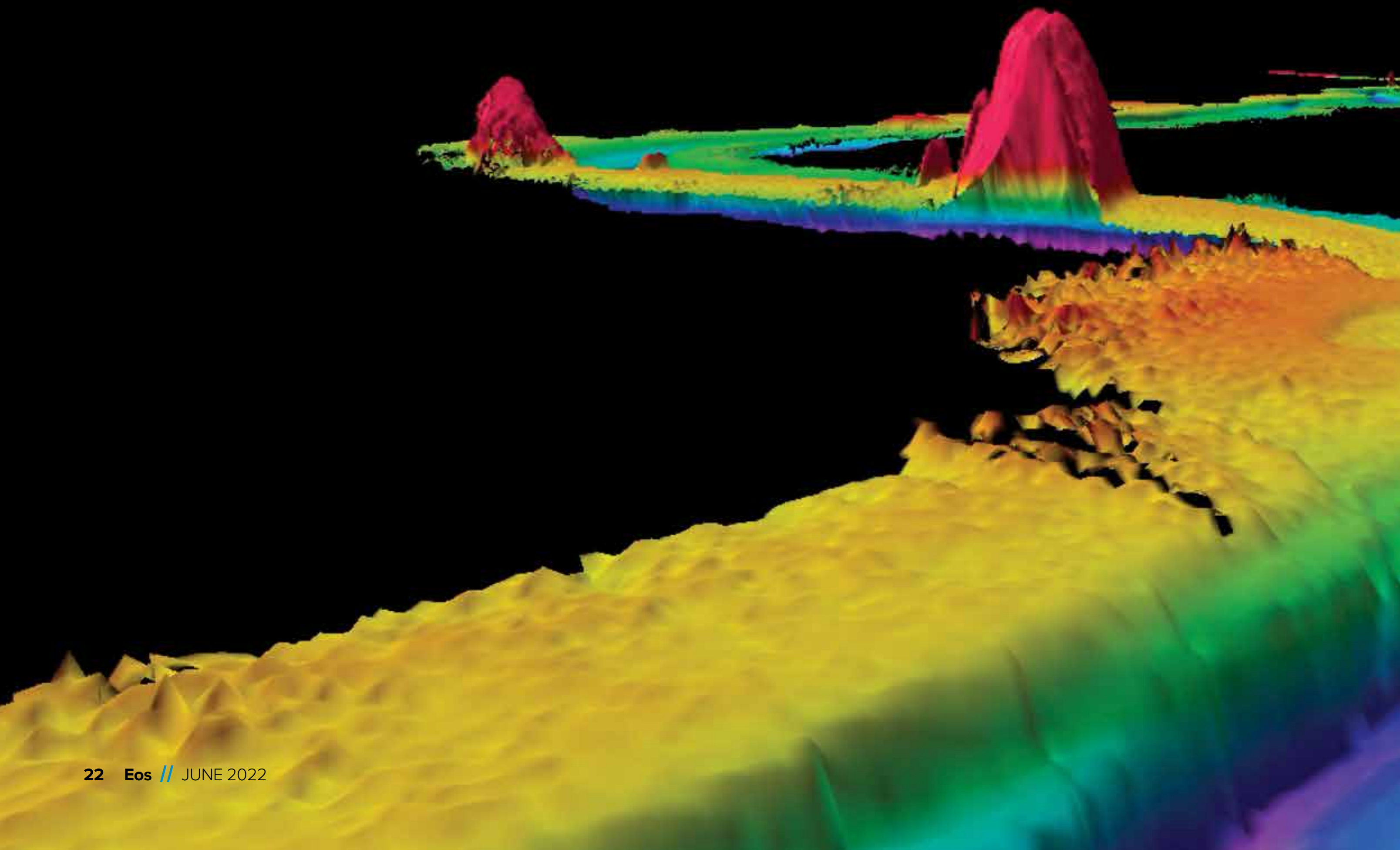
MAPPING A RIVER BENEATH THE SEA

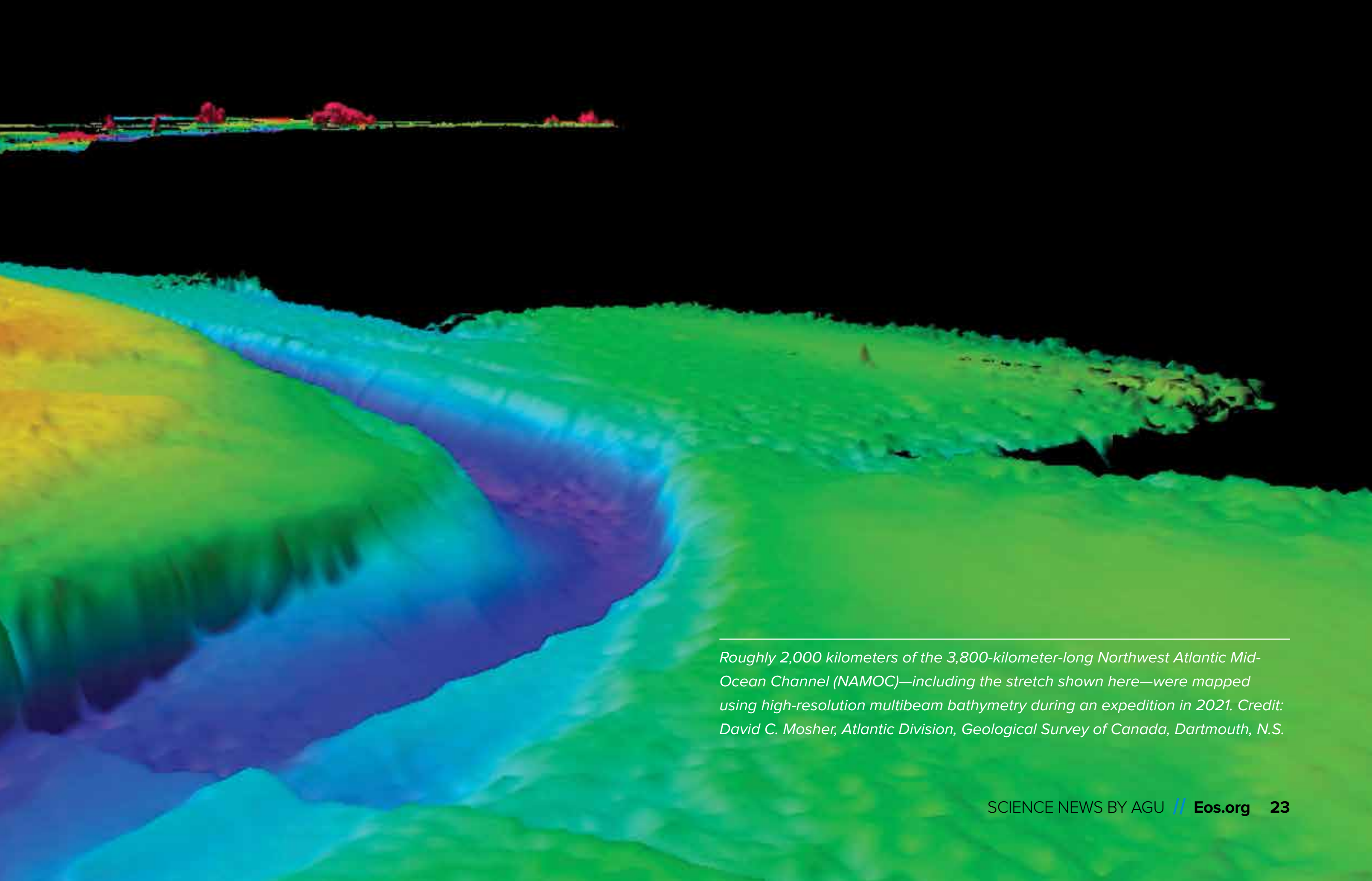
BY SEBASTIAN KRASTEL AND DAVID C. MOSHER



Along the sloping margins of most of the world's continents, underwater canyons and channel systems extend from sources on land to sinks in the deep sea. These submarine channels, which share many similarities of form and function with rivers on land, are critical in Earth's sedimentary and biogeochemical cycles. They not only distribute eroded continental material to the deep sea but also redistribute carbon and vital nutrients such as iron, calcium, phosphorus, and sulfur across Earth's surface.

The Bengal Channel, for example, carries massive quantities of eroded sediment from the Himalayas to the Indian Ocean and accounts for 10%–20% of the global burial of organic carbon [*Galy et al.*, 2008].

Because they deliver and bury carbon, submarine channels play important roles in long-term sequestration—and therefore in climate over geologic timescales—as well as in the manufacture of hydrocarbons and reservoir rock in deepwater systems along continental mar-



Roughly 2,000 kilometers of the 3,800-kilometer-long Northwest Atlantic Mid-Ocean Channel (NAMOC)—including the stretch shown here—were mapped using high-resolution multibeam bathymetry during an expedition in 2021. Credit: David C. Mosher, Atlantic Division, Geological Survey of Canada, Dartmouth, N.S.

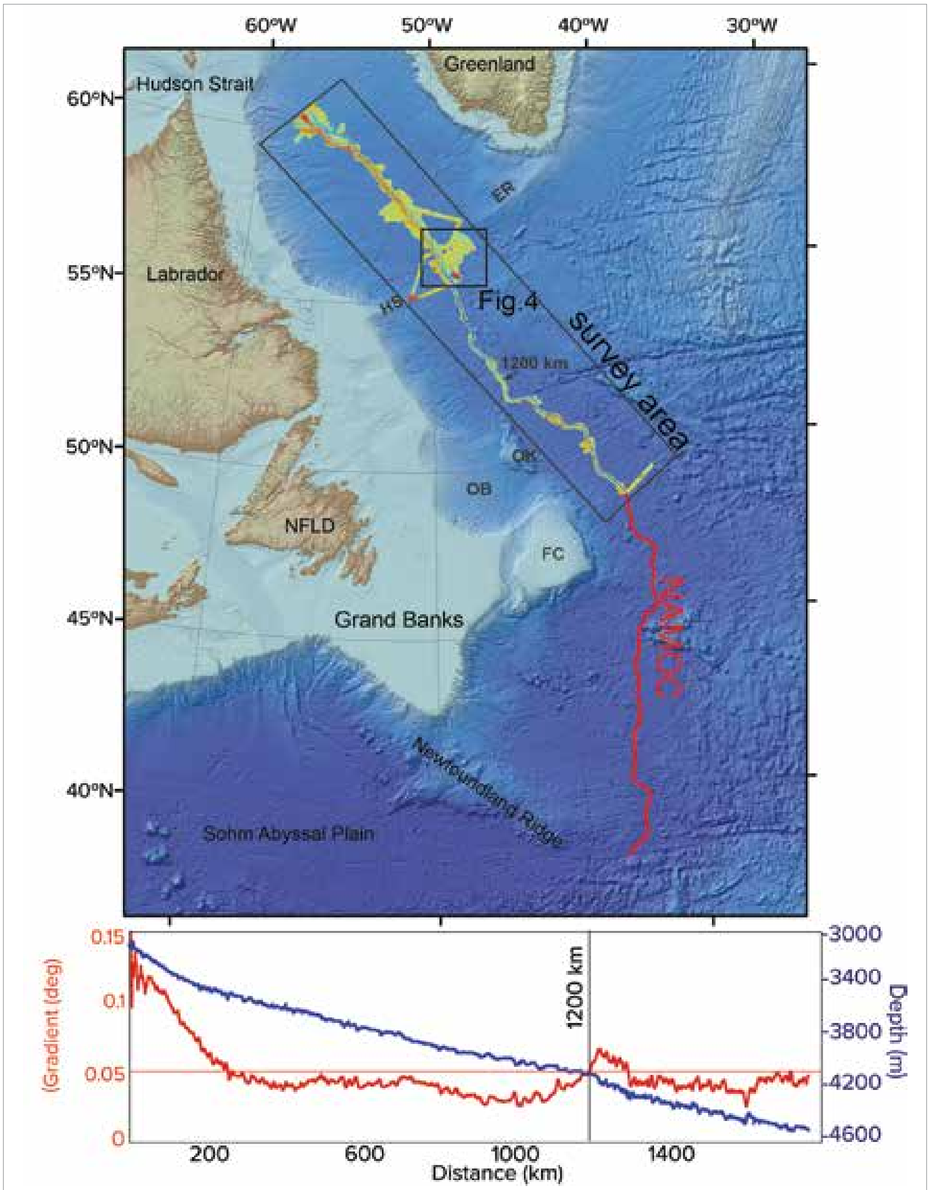


Fig. 1. Top: The area mapped during expedition 102 on R/V Maria S. Merian *(MSM102) in the Labrador Sea is shown here (black rectangle) and is overlain with the multibeam bathymetry data acquired (blue to orange colors represent deeper to shallower depths) along the axis of the NAMOC. South of the survey area, the approximate axis of the NAMOC is shown in red. ER = Eirik Ridge, FC = Flemish Cap, HS = Hamilton Spur, NFLD = Newfoundland, OB = Orphan Basin, OK = Orphan Knoll. Bottom: Also shown are depth (blue) and gradient (red) profiles along the axis of the NAMOC, from northwest to southeast, generated from the newly acquired multibeam data. The 1,200-kilometer mark referenced in the text is indicated in the map and the graph.*

gins. Such systems, discovered in the past 20 years, have become major players in global estimates of hydrocarbon resources [e.g., *Zhang et al.*, 2019].

Just as rivers are formed by the erosive action of water currents, submarine channels are formed by erosive turbidity currents. Turbidity currents comprise dense, sediment-laden flows that travel down sloped seafloors under the force of gravity [*Meiburg and Kneller*, 2010], often at speeds of up to 20 meters per second (72 kilometers per hour, or about 10 times the average speed of the Gulf Stream, the fastest moving ocean current).

On the modern seafloor, deepwater submarine channels longer than 100 kilometers are generally found in association with deep-sea fans made of sediments from major river systems. In addition to the Bengal Channel, which lies seaward of the Ganges and Brahmaputra rivers, examples include channels and fans seaward of the Amazon, Congo, Indus, Mississippi, and Nile rivers.

One of the longest, if not the longest, submarine channels in the world, however, is associated not with sediment sourced from a river or deep-sea fan but, rather, with outwash from melting glaciers. The Northwest Atlantic Mid-Ocean Channel (NAMOC) wends its way for more than 3,800 kilometers from Hudson Strait—which connects Hudson Bay to the Atlantic—in the north, through the Labrador Sea, and around the Grand Banks of Newfoundland before terminating at the northern limit of the Sohm Abyssal Plain, just east of Newfoundland Ridge (Figure 1). Although first observed in 1949 and subsequently studied and mapped further through the 20th century using technologies of the day [e.g., *Ewing et al.*, 1953; *Hesse et al.*, 1996], many questions about its formation remain unresolved because of the absence of detailed knowledge of its morphological and structural features.

Submarine channels, despite being major features in ocean basins, sometimes do not appear on regional bathymetric charts because grid sampling of complex bathymetric data sets—the technique by which most modern charts are rendered—is too coarse to adequately capture the relatively narrow channels. The NAMOC, for example, which is generally less than 5 kilometers wide, was not imaged on the 2008 version of the General Bathymetric Chart of the Oceans (GEBCO) when the chart was produced from a 60-arc-second (roughly 1,850-meter) sample interval grid. To map the full extent of these channels in detail, therefore, researchers cannot rely on generic legacy data sets but must have dedicated surveys.

The principal objective of expedition 102 on the German R/V *Maria S. Merian* (MSM102) in summer 2021 was to use multibeam bathymetric sonar to map morphologic details over much of the length of the NAMOC (Figure 1). Such detailed mapping not only helps answer questions about the NAMOC itself but also will lead to better understanding of the physical processes involved in deep-sea sediment transport, allow for detailed comparisons of submarine channels and terrestrial river systems, and offer opportunities to examine the roles of turbidity currents, the Coriolis force, sediment mass failures, and other factors in producing such critical and scientifically interesting features.

Formation of the NAMOC in the Labrador Sea

The Labrador Sea, located between Canada's Labrador coast and Greenland and home to the portion of the NAMOC mapped during the MSM102 expedition (Figure 1), began forming roughly 60 million years ago as seafloor spreading in the Atlantic propagated northward. Spreading in the Labrador Sea ceased about 40 million years ago [*Roest and Srivastava*, 1989] and was followed by tectonic compression that led to deformation and shoaling of the basin. The basin's modern surface, however, largely resulted from Pleistocene glacial epochs over roughly the past 2.6 million years. As evidence of these glaciations, glacial till extends to the outer shelf and uppermost slope along most of the eastern Canadian continental margin [*Piper et al.*, 2012; *Shaw et al.*, 2014].

It is believed that the most profound influences on the basin's modern geomorphology resulted from high sediment fluxes that caused intensified hyperpycnal and turbidity current flows during glacial melt episodes over the past 60,000 years, especially commencing about 20,000 years ago during the collapse of the Laurentide Ice Sheet, which covered most of present-day Canada and the northern United States. Because most of this glacial input derived from the North American landmass, the basin has an asymmetric bowl shape. The western side of the basin has a more rounded concave shape, whereas the eastern side has a flatter seafloor abutting a steep gradient along the Greenland margin. The entire basin dips gently, by less than 0.1°, to the south.

Hudson Strait, leading from Hudson Bay at the northern extent of the Labrador Sea, was a major outlet for the Laurentide Ice Sheet throughout the late Pleistocene [*Margold et al.*, 2015]. Its deep shelf break at 600-meter water depth and eroded uppermost slope imply that major ice streams occupied the strait—ice streams that drained much of northern North America. This geographically confined source of sediment at the northern end of the Labrador Sea and the sea's bowl shape and southern dip, which together form a broad funnel, are critical factors in the formation of the NAMOC.

Mapping NAMOC

Scientists and crew aboard the R/V *Maria S. Merian* sailed from Emden, Germany, on a 7-week expedition between late July and early September 2021 to map roughly 2,000 kilometers of the NAMOC in greater detail than ever before. The objective was to follow the axis of the channel and run a series of orthogonal profiles to image its morphology and structure, from just east of Orphan Knoll to the northern extent of the Labrador Sea (Figure 1).

Protocols enforced because of COVID-19 limited the ability of several of the expedition's proponents to participate, but otherwise, few obstacles were encountered. Conditions were remarkably calm, which was unusual for the Labrador Sea, and there was no time lost to bad weather, although overcast skies and frequent fog were typical.

The *Merian* is equipped with a hull-mounted multibeam bathymetric mapping system with a maximum beam coverage of 150°, meaning that on a single pass, it can map a swath of seafloor up to 7 times as wide as the water is deep. Each swath consists of a maximum of 432 beams; thus, during MSM102 enough data were acquired to allow, at a minimum, a depth sounding every 100 meters (i.e., producing a 100- × 100-meter grid for the entire data set). In addition, coincident data were acquired with a subbottom profiler that yielded submeter vertical resolution and allowed imaging to 100 meters below the seafloor.

Several remarkable characteristics of the NAMOC were immediately apparent from complete mapping of the northern half of the channel during MSM102 together with transit data from other expeditions that crossed portions of its southern extent. These observations shed light on the NAMOC, its formation, and how it compares with other submarine channels. They also raised interesting questions with implications for pro-

JUST AS RIVERS ARE FORMED BY THE EROSIVE ACTION OF WATER CURRENTS, SUBMARINE CHANNELS ARE FORMED BY EROSIVE TURBIDITY CURRENTS.

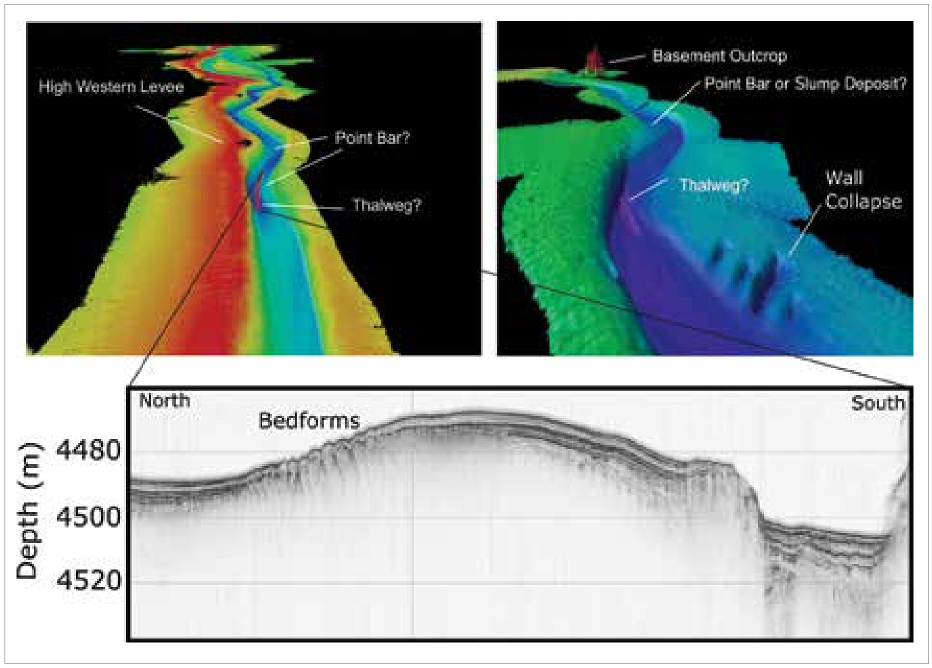


Fig. 2. Top: Perspective views looking north along the NAMOC show slight meander bends, possible point bars, the discontinuous nature of the thalweg, and channel wall collapse structures. Both images show the high western levee. Bottom: A subbottom profile along a possible point bar in the top left image shows bedforms on the surface and parallel layered (i.e., not cross-bedded) stratigraphy.

cesses that control sediment transport, carbon burial, and other processes of the deep ocean.

The River Analogy

Comparisons between deep-sea channels and river systems are common in the literature. However, there are fundamentally different physical processes at play. The sediment-laden turbidity currents that form subsea channels, such as the NAMOC, are aperiodic [*Meiburg and Kneller*, 2010], and many of their properties, including their downslope velocities, are largely dictated by flow volume and the density contrast between the flow and the ambient fluid (seawater) in addition to the gravitational force acting along the seafloor gradient. As the front portions of turbidity currents are known to hydroplane, the bed substrate (seafloor) has little bearing on the nature of these flows, which as a result show their highest velocities close to the seabed.

In contrast, river flows continuously erode their channels and are dictated entirely by gravity (gradient), channel dimensions, flow volume, and the roughness of the riverbed substrate. The ambient fluid (air) is not a significant factor because the density of air is so low that it does not affect the flow of water. Because of bed friction, river currents are generally fastest toward the top surface of the flow. There are other distinctions, of course, but the conclusion is that although deep-sea channels and rivers have analogous characteristics, these features likely result from different hydraulic and sedimentologic processes.

ALTHOUGH DEEP-SEA CHANNELS AND RIVERS HAVE ANALOGOUS CHARACTERISTICS, THESE FEATURES LIKELY RESULT FROM DIFFERENT HYDRAULIC AND SEDIMENTOLOGIC PROCESSES.

The NAMOC shows features that appear similar to point bars and thalwegs within the channel (Figure 2), both common features of river systems. Point bars in river systems have tabular, cross-bedded internal structures, but profiles of these deposits within the NAMOC show no such evidence. Detailed mapping during the MSM102 expedition showed that these point bars are predominately composed of material from channel levee collapses (i.e., submarine slumps). The collapsed material appears to have been reworked by subsequent turbidity currents, which is apparent from their elongated shape with surficial bedforms, while at the same time forcing subsequent currents into a narrow region of the main channel opposite the deposit.

This forcing effect appears to create thalweg-like features amid the otherwise flat-bottomed profile of the channel. The wall collapses may thus bear some responsibility for creating meanders in the NAMOC (Figure 2), which in turn result in its "thalweg" consisting of short, discontinuous segments. In comparison, thalwegs in river channels are typically continuous. These intriguing features require additional research that specifically addresses the physical processes that created them [*Azpiroz-Zabala et al.*, 2017].

Rivers and submarine channels are both known to construct channel levees. The banks of the NAMOC are lined with levees tens of meters tall; however, the western levee is consistently higher than the eastern by as much as 50 meters for much of its entire length (Figure 3). This characteristic feature resulted from the Coriolis force, which caused suspended sediment that overtopped the channel to preferentially deposit on the western side as Earth rotated beneath the cloud of suspended sediment. (The Coriolis force does not influence channel levee deposition in rivers on land.) The NAMOC levee asymmetry was observed when the channel was discovered and was first ascribed to tectonic tilting of the basin. New data from MSM102 permit a continuous comparison of levee heights along the NAMOC, which will allow finite quantification of the Coriolis effects because the channel crosses some 20° of latitude.

Channel Morphology and Gradient

New data acquired during expedition MSM102 also allow calculation of a continuous gradient profile (Figure 1). Previously, gradients along much of the NAMOC could only be interpolated using bathymetry collected during discrete crossings of the channel. These new data show, for example, that although the NAMOC has a relatively consistent overall gradient of only about 0.05°, there are subtle deviations that correspond to changes in channel architecture. For example, at about the 1,200-kilometer point in the new bathymetric profile (Figure 1), there is an increase in gradient that corresponds to an initial shoaling of the channel prior to its deepening and the formation of higher-amplitude and broader meander bends. With the new data, it will be possible to conduct detailed modeling of flow hydrodynamics that can be related to channel characteristics.

Currents are typically slow in low-gradient river systems, which also tend to have highly

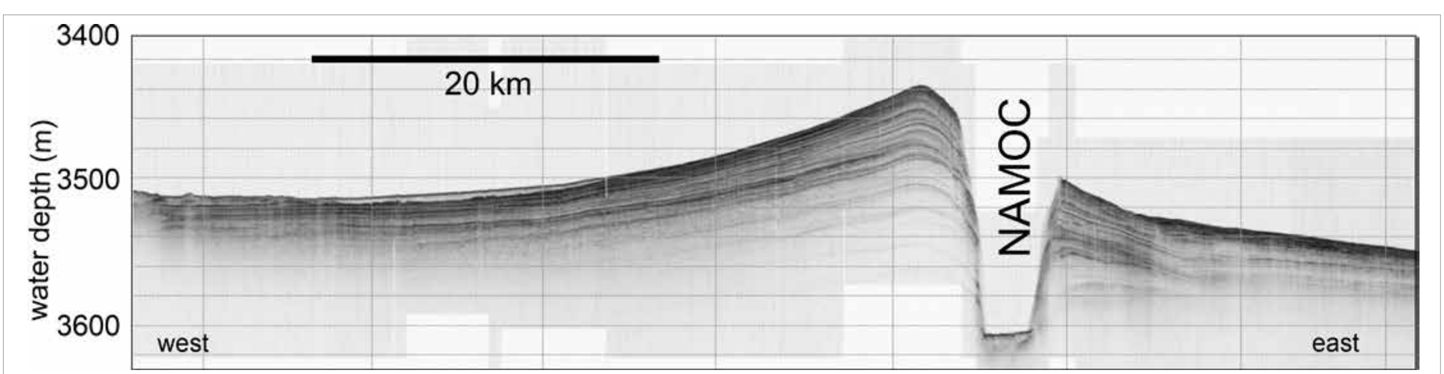


Fig. 3. This ParaSound subbottom profile across the NAMOC shows the general boxlike shape of the channel as well as its high western levee.

meandering paths: The Nile, which is about the same length as the NAMOC and has a similar gradient, is a good example. Similarly, the Congo submarine channel has an overall gradient of just over 0.5° and is highly meandering [*Savoye et al.*, 2009]. It was thus expected that the NAMOC's low gradients should result in significant meandering, yet as we see in the new mapping, it has few meanders, and those it does have are of low amplitude (Figures 1 and 2).

The velocities of flows within the NAMOC have not yet been estimated, but it is possible that velocities were high and that flow velocity is more critical than slope gradient and the Coriolis effect in determining the degree of meandering in submarine channels. As was mentioned previously, density contrasts between turbidity currents and ambient seawater are a major control on flow velocities. If flow velocities were high in the NAMOC system, then high-concentration flows were likely prevalent. Understanding flow concentrations in the NAMOC bears significantly on the objectives of surveying efforts in terms of determining the role of submarine channels in transporting and redistributing critical elements, such as nutrients and carbon, to the deep sea.

One of the more interesting features revealed by the MSM102 survey is the confluence of the NAMOC and the Imarssuak Mid-Ocean Channel (IMOC), which originates along the southern Greenland continental margin (Figures 1 and 4). The data show IMOC to be a shallow, braided system, distinct from the single-channel NAMOC. It's unclear what fundamental differences in these systems generated such vastly different morphologies, but they are presumably related to the sources of the turbidity currents that formed them. Perhaps the IMOC was generated by turbidity currents derived in multiple locations rather than in a confined or point source. Perhaps also the flows were of lower concentration or consisted of different grain sizes. These factors have yet to be investigated but will likely inform us about the regional variability of deglaciation in the North Atlantic.

Scientists studying the NAMOC have already learned a great deal from the mapping collected last summer, yet the characteristics described above reflect only initial observations and interpretations. Much work remains to integrate these data with data from sediment cores and multichannel seismic reflection experiments that were also acquired during MSM102, as well as with existing data. This continuing work is necessary to understanding more completely the geologic history of this unique submarine channel system and the glacial and sedimentary processes that created it.

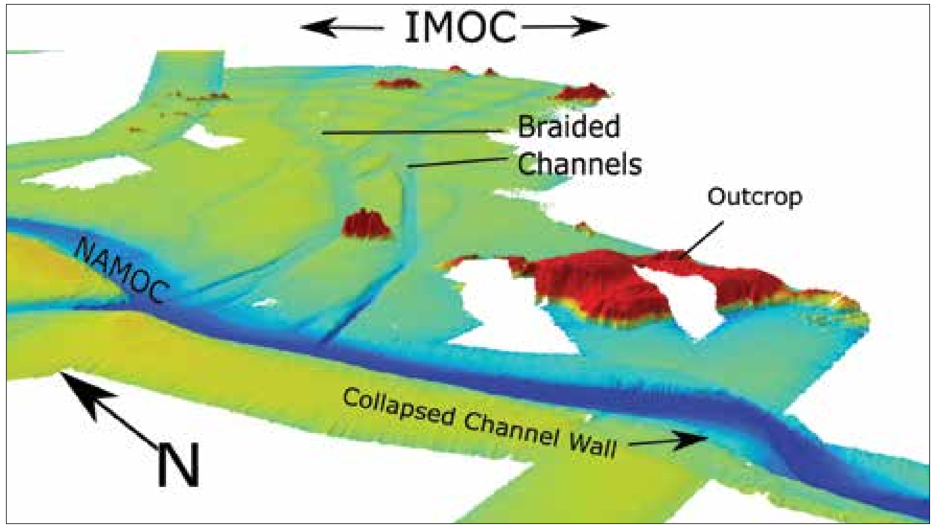


Fig. 4. This perspective view, rendered with multibeam bathymetry data, looks northeast at the confluence of the NAMOC and the Imarssuak Mid-Ocean Channel (IMOC) on the east side of the NAMOC. One of the few tributaries entering the NAMOC from its western side can be seen at far left, as can the braided nature of the IMOC and a channel wall collapse at one of the small meander bends in the NAMOC. See Figure 1 for the location of this site.

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References

Azpiroz-Zabala, M., et al. (2017), A general model for the helical structure of geophysical flows in channel bends, *Geophys. Res. Lett., 44*, 11,932–11,941, https://doi.org/10.1002/2017GL075721.

Ewing, M., et al. (1953), Exploration of the Northwest Atlantic Mid-Ocean Canyon, *Geol. Soc. Am. Bull.*, *64*, 865–868, https://doi.org/10.1130/0016-7606(1953)64[865:EOTNAM]2.0.CO;2.

Galy, V., et al. (2008), Recycling of graphite during erosion: A geological stabilization of carbon in the crust, *Science*, *322*, 943–945, https://doi.org/10.1126/science.1161408.

Hesse, R., et al. (1996), Imaging Laurentide Ice Sheet drainage into the deep sea: Impact on sediments and bottom water, *GSA Today*, *6*(9), 3–9, www.geosociety.org/gsatoday/archive/6/9/pdf/i1052-5173-6-9-sci.pdf.

Margold, M., et al. (2015), Ice streams in the Laurentide Ice Sheet: A new mapping inventory, *J. Maps*, *11*(3), 380–395, https://doi.org/10.1080/17445647.2014.912036.

Meiburg, E., and B. Kneller (2010), Turbidity currents and their deposits, *Annu. Rev. Fluid Mech.*, *42*, 135–156, https://doi.org/10.1146/annurev-fluid-121108-145618.

Piper, D. J. W., et al. (2012), Erosional and depositional features of glacial meltwater discharges on the eastern Canadian continental margin, in *Application of Seismic Geomorphology Principles to Continental Slope and Base-of-Slope Systems*, edited by B. Prather et al., *Spec. Publ. SEPM Soc. Sediment. Geol.*, *99*, 61–80, https://doi.org/10.2110/pec.12.99.0061.

Roest, W. R., and S. P. Srivastava (1989), Sea-floor spreading in the Labrador Sea: A new reconstruction, *Geology*, *17*, 1,000–1,003, https://doi.org/10.1130/0091-7613(1989)017%3C1000:SFSITL%3E2.3.CO;2.

Savoye, B., et al. (2009), Geological overview of the Angola-Congo margin, the Congo deep-sea fan and its submarine valleys, *Deep Sea Res., Part II*, *56*(23), 2,169–2,182, https://doi.org/10.1016/j.dsr2.2009.04.001.

Shaw, J., et al. (2014), Continental shelves of Atlantic Canada, *Mem. Geol. Soc. London*, *41*, 7–19, https://doi.org/10.1144/m41.2.

Zhang, G., et al. (2019), Giant discoveries of oil and gas fields in global deepwaters in the past 40 years and the prospect of exploration, *J. Nat. Gas Geosci.*, *4*, 1–28, https://doi.org/10.1016/j.jnggs.2019.03.002.

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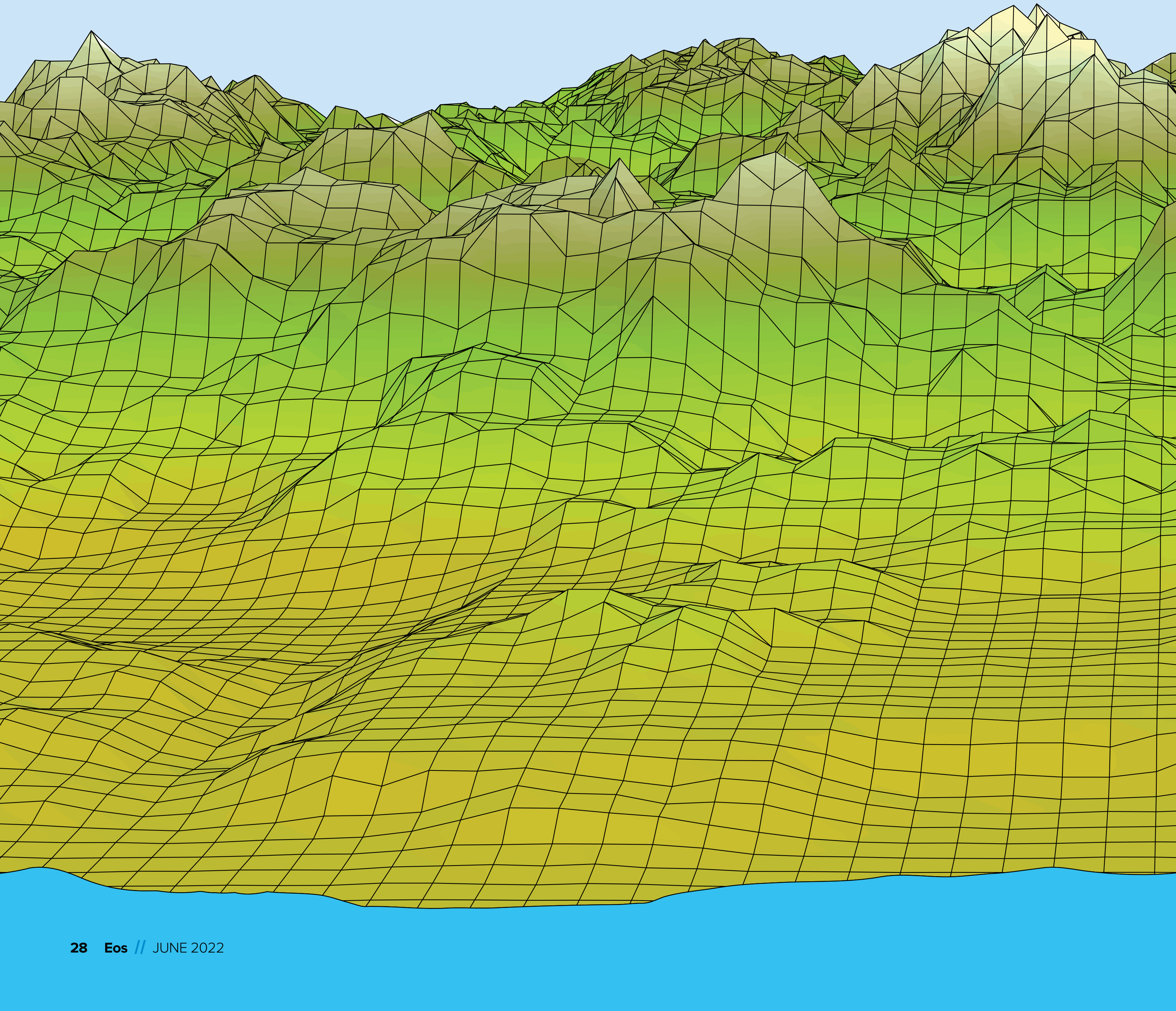
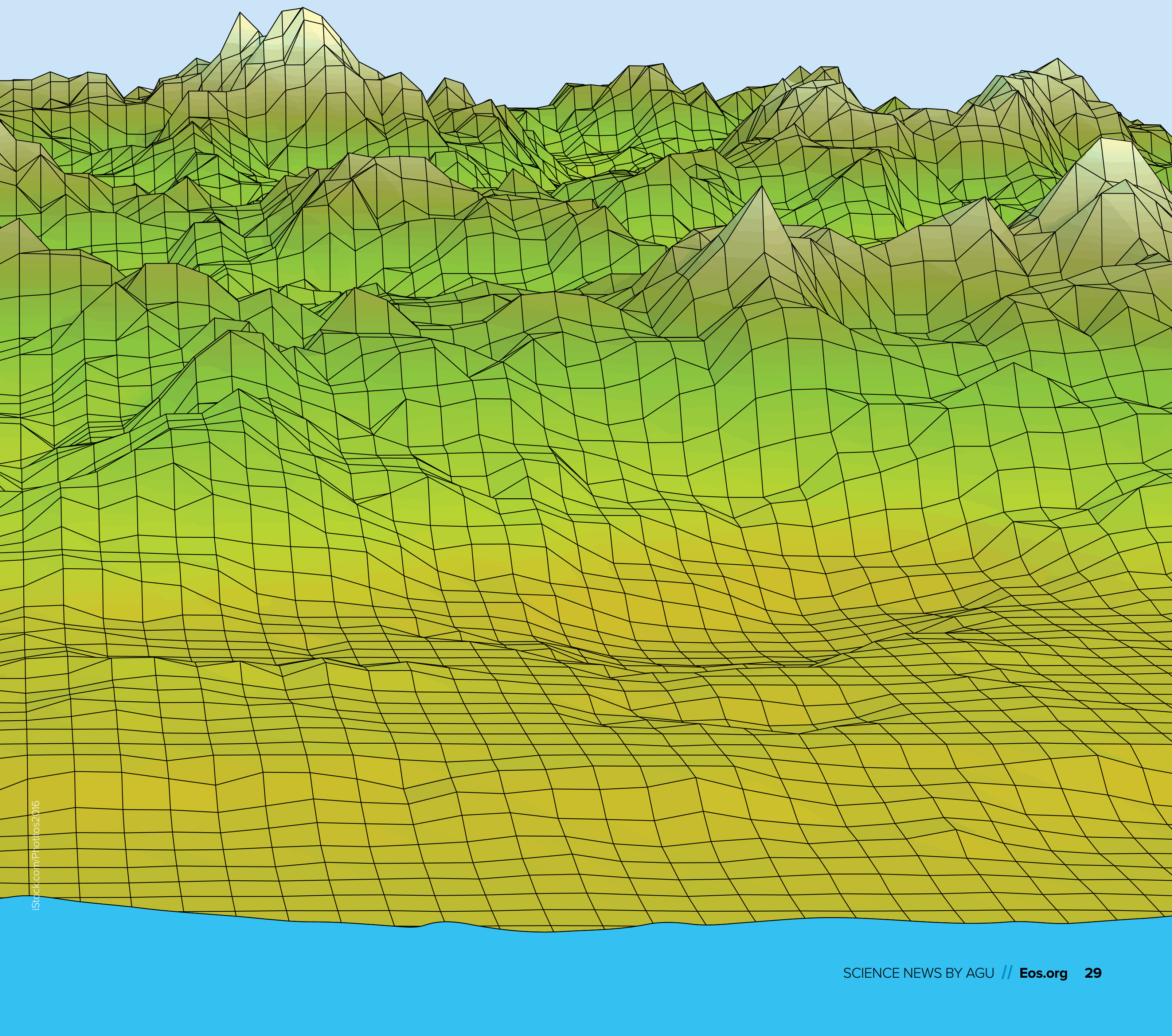
EXPLORING SUBDUCTION ZONE GEOHAZARDS ON LAND AND AT SEA



By Mong-Han Huang, Kristin Morell, Alison Duvall, Sean F. Gallen, and George E. Hilley

A new initiative is bringing scientists together to address fundamental questions about subduction zone geohazards, using the latest advances in observation technology and computational resources.



Earthquakes, landslides, erosion, and storms all interact to shape and reshape subduction zone landscapes, including beaches and cliffs on the coast of Oregon. Credit: ArtTower/Pixabay, Pixabay license

In the complicated regions where tectonic plates converge and landmasses and oceans meet, chains of landscape-shaping events can play out over years or even centuries. Storms and earthquakes dislodge rocks, sediment, and soil. Flooding rivers and strong currents carry these materials downstream and disperse them offshore. Along the way, this debris can carve wider channels, shift the courses of the streams and currents, or dam flows altogether. The resulting geomorphic changes in landscapes and seascapes profoundly affect the safety and livelihoods of tens of millions of people.

Understanding the various types of Earth surface disturbances in subduction zone landscapes and seascapes—and the cascading impacts of these disturbances—has enormous practical importance because the disturbances pose substantial hazards to the ecosystems, communities, and infrastructure in these areas (Figure 1). However, we still lack an adequate understanding of when catastrophic surface disturbances are initiated, where the detritus produced by these events goes, and how long and how far the cascading impacts can extend.

Likewise, uncertainties persist regarding controls on the catastrophic events associated with tectonic convergence of subducting and overriding plates. Unknowns include how and where rock and sediment deform because of this convergence; the amount of convergence that accumulates in subduction zone fore arcs (i.e., between the deep-sea trench and the volcanic arc); and where, how, and why the associated strain becomes localized or not. These knowledge gaps are relevant because strain accumulation and release determine the locations and magnitudes of earthquakes, tsunamis, and seismically triggered mass wasting that may affect population centers (Figure 1).

Accelerating advances in scientific knowledge and technologies are allowing us to address fundamental questions about subduction zone geohazards, one pillar of the Subduction Zones in 4 Dimensions (SZ4D) initiative. SZ4D, which began in 2018, is capitalizing on these advances by engaging a broad group of scientists in a decadal-scale, interdisciplinary research effort. Below we highlight major questions motivating these scientists and also critical developing technologies and key research opportunities to advance our understanding of subduction zone geohazards through this initiative.

ADVANCES IN SCIENTIFIC KNOWLEDGE AND TECHNOLOGIES ARE ALLOWING US TO ADDRESS FUNDAMENTAL QUESTIONS ABOUT SUBDUCTION ZONE GEOHAZARDS.

A Complex Web of Interacting Systems

After major geomorphic events, punctuated and sometimes catastrophic erosional pulses can occur and initiate complicated responses and continuous adjustments in landscapes and seascapes that persist for years to centuries [e.g., *Bruni et al.*, 2021]. Slope failures caused by storms, volcanic sector collapses during eruptions, and earthquake-mobilized debris can dam river channels (Figure 1). These events can lead either to continuous adjustments in channel shape in response to changes in sediment supply or to outburst floods that rapidly alter river channel morphology [e.g., *Cook et al.*, 2018], both of which can damage downstream communities. Large volumes of detritus (e.g., sediment, boulders, trees) delivered to river channels by such subduction zone disturbances, as well as by extreme weather events, can promote widening and sediment infilling of channels, modifying river networks for years to decades [e.g., *Major et al.*, 2016]. These changes in channel morphology can threaten infrastructure built on the banks and floodplains and, by altering a channel's capacity to convey river flows, result in more frequent flooding.

The hazards produced by earthquakes, volcanic eruptions, and geomorphic events reflect the long-term operation of subduction zone processes (Figure 1). For example, deformation of fore-arc crust can modify and be modified by sediment transport systems, build climate-altering topography, and produce ground failures [e.g., *Bhattacharya et al.*, 2018]. Sediment transport can change the hazards posed by megathrust earthquakes, as delivery of sediment to the ocean trench might affect slip behavior and earthquake recurrence in a subduction zone [*Lamb and Davis*, 2003]. The redistribution of surface loading due to both long-term and event-driven erosion can affect the stress on upper plate faults, promoting more frequent earthquakes [*Steer et al.*, 2020].

Volcanic and magmatic processes likewise build topography (Figure 1) [e.g., *Karlstrom et al.*, 2018], sometimes producing eruptions, lava and debris flows, and other hazards in the process. Furthermore, the ascent of magma through crust can alter the crust's thermal state, producing rheological changes that can redistribute deformation throughout subduction zone systems. Communities within these landscapes are especially vulnerable to these hazards, the effects of which can be compounded by longer, more intense storms resulting from human-driven climate change.

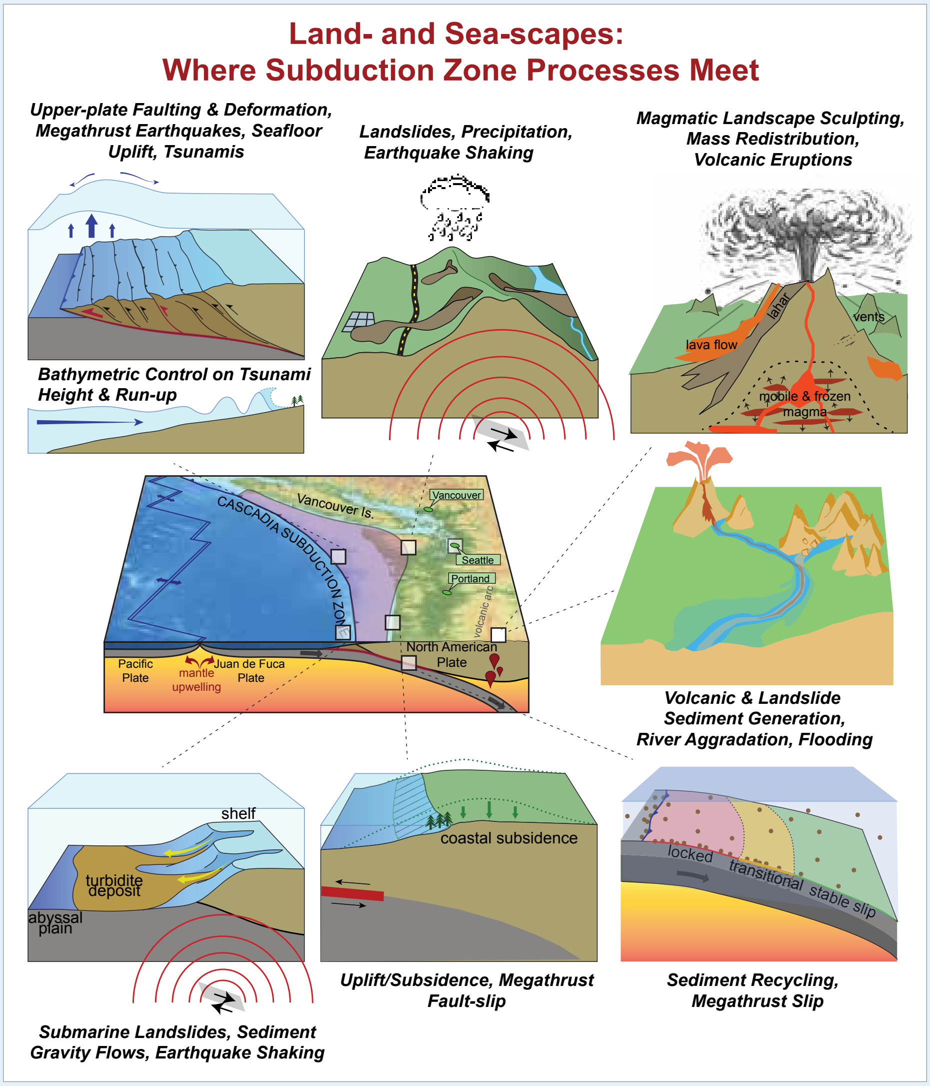


Fig. 1. Subduction zone landscapes and seascapes, such as those along the Cascadia subduction zone (center diagram), are shaped by many processes occurring above and below ground that create hazards for vulnerable populations living in the vicinity of subduction zones. Clockwise from top left: Earthquakes along megathrusts or upper plate faults can cause tsunamis, whose runup on land is controlled in part by coastal bathymetry; precipitation and earthquakes can cause mass wasting events like landslides; subduction zone volcanoes can reshape landscapes and cause many hazards, for example, from lava flows, lahars, and ashfalls; volcanic processes can also send large amounts of sediment and debris down rivers, posing threats from river aggradation and flooding; sediments transported down deep-sea trenches can contribute to slip (i.e., earthquakes) along megathrust faults; fault slip can lead to rapid uplift or subsidence of coastal areas; and earthquake shaking can cause submarine landslides, which may cause tsunamis and damage underwater infrastructure. Credit: U.S. Geological Survey

New Tools for Deeper Understanding

New and emerging technologies allow us to study the processes in and around subduction zones in ways not previously possible, which has enabled a more complete and systems-level understanding. Advances in repeat mapping of Earth's surface using high-resolution remote sensors aboard satellites, aircraft, drones, and submarine craft have revealed details of the initiation and long-term impacts of these events and of the transports of material they cause. Various types of sensors, including multispectral imagers, interferometric synthetic aperture radar (InSAR), and lidar, provide diverse data, with each type suited to particular landscapes, seascapes, and conditions.

High-resolution, repeat spaceborne imaging methods (e.g., InSAR and lidar) now allow us to locate where and when mass failures are initiated and, in some cases, to characterize rates of motion of transported materials (Figure 2) [*Elliott et al.*, 2016; *DeLong et al.*, 2012]. Suborbital plane and drone-based platforms, coupled with computer vision developments, allow images collected by simple camera systems to be used to build ultrahigh-resolution topography. This capability can help rapidly and cheaply characterize downstream effects, such as changes in river location and widespread deposition of sediment within rivers, produced over large areas by disturbances. Low-cost environmental sensor networks—measuring, for example, rainfall and soil moisture—allow for near-real-time monitoring and measurement of environmental conditions that also enable a better understanding of the triggering of mass wasting events and sediment transport. New submarine drone technologies, acoustic Doppler current profilers, and seafloor geodetic monuments can capture seascape changes produced by degradation of submarine fault scarps [*Hughes et al.*, 2021] and sediment density currents that may be initiated by earthquake-generated submarine landslides (Figure 1).

These technologies are enabling, for the first time, both detailed and synoptic views of the ways that fore arcs deform in four dimensions, allowing researchers to begin to con-

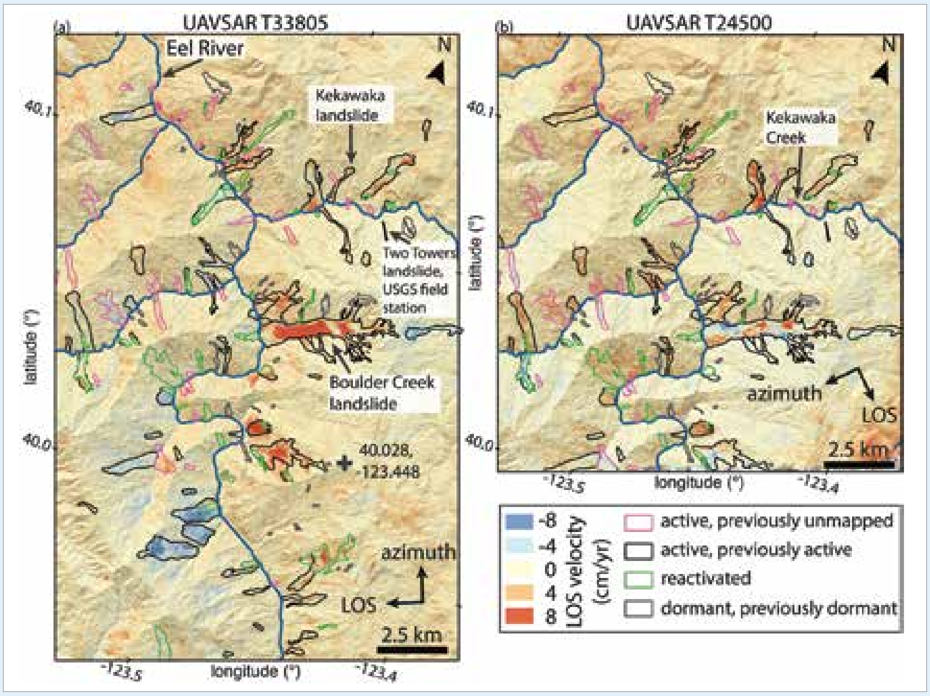


Fig. 2. These average line-of-sight (LOS) velocity maps for two uninhabited aerial vehicle synthetic aperture radar (UAVSAR) flight paths (T33805 and T24500) over part of Northern California each cover the period between April 2016 and February 2018, illustrating the usefulness of the technique for identifying where and when mass failures are initiated and characterizing rates of motion of transported materials. Red and blue shading denotes active deformation, and changes in the activity of the landslides are based on comparison with previously published data. Digital elevation models are from OpenTopography and TanDEM-X. Credit: Handwerger et al. *[2019]*

strain the total energy budget of a subduction zone, which underlies our understanding of how solid Earth and atmospheric processes work together to produce geohazards. Simultaneously, developments in numerical methods and in computer hardware, which now provide petaflop-scale computational resources to researchers (compared with the teraflop-scale computations available 20 years ago), allow accurate simulations of the complex physics of subduction zone disturbances and their cascading impacts.

Combined, these advances allow us to link observations and state-of-the-art numerical models to study the energetics and dynamics of the processes that shape subduction zone landscapes and seascapes. This holistic approach is foundational to better understanding the risks that hazardous tectonic events pose to communities occupying subduction zones.

Two Questions About Subduction Zone Geohazards

Researchers can leverage the suite of new observational technologies, computational capabilities, and model developments available to help investigate two overarching questions about subduction zone surface hazards identified by the SZ4D initiative. First, how do events within Earth's atmosphere, hydrosphere, and geosphere generate and transport sediment across subduction zone landscapes and seascapes? Second, what fraction of a subduction zone's energy budget goes into building and shaping subduction zone landscapes and seascapes? These questions provide a framework for developing testable hypotheses that are of practical importance for understanding the risks of geohazards to humans.

The first question leads us to posit that the frequency with which different sediment-mobilizing drivers occur determines the extent to which these drivers control sediment generation and transport. When storms, atmospheric rivers, or other high-precipitation events mobilize sediments more frequently than do solid Earth events (e.g., earthquake shaking and volcanic unrest), the former will dominate sediment generation and transport [e.g., *Major et al.*, 2021]. Conversely, solid Earth events play a larger role in shaping landscapes when such large storms are infrequent in an area [e.g., *Bruni et al.*, 2021]. Thus, the ratio of the recurrence times of landscape-impacting storms to landscape-impacting solid Earth disturbances determines the relative imprints that atmospheric versus solid Earth processes have on shaping various parts of a subduction zone landscape.

Such framing provides a means of assessing the causes, timings, and locations of hazards and how these hazards might affect humans and infrastructure. It also allows us to anticipate how human-induced climate change alters the distribution of the processes giving rise to these hazards.

Regarding the second question, we might hypothesize that the partitioning of deformation in the upper plate of a subduction zone resulting from stress accumulation is regulated in part by plate motions and by coupling with the lower plate along the subduction megathrust. This partitioning is also regulated by the balance of elastic and inelastic deformation processes in the upper plate, the arrangement of rocks in the upper plate, and the ways in which they deform and flow in response to the weight of the topography [e.g., *Penserini et al.*, 2017].

The partitioning of deformation is important because it affects the locations and scales of potentially hazardous events. For example, absorption of subduction zone convergence between the arc and the trench—and the resulting upper plate deformation (Figure 1)—may manifest as particularly damaging earthquakes because these events often occur closer to human populations than larger events that occur along the subduction megathrust itself.

From Hypothesis to Experiment

Broad working hypotheses and conceptual models can be tested using experiments to explore driving factors in different parts, or segments, of subduction zone systems, holding most conditions constant while systematically varying a single factor. However, such experiments are impractical at the scale and complexity of entire subduction zones.

Fortunately, nature has provided us with opportunities to compare subduction zone segments where many of the relevant factors are known, thereby yielding insights into the effects of different individual factors. Similar to strictly controlled experiments, this approach can also be used to test quantitative models of geomorphic transport and fore-arc deformation within subduction zones.

For example, we might test hypotheses related to our first guiding research question on sediment generation and transport by selecting a pair of subduction zone segments that either have similar solid Earth characteristics or experience similar atmospheric conditions. We can explore the influence of atmospheric events by selecting subduction zone segments that share similar convergence rates, subduction angles (i.e., the angle at which the subducting plate dives below the surface), and available for hazardous earthquakes, volcanic eruptions, and landslides.

The hypothetical experiments described above might be carried out by contrasting, for example, the Cascadia and southern Chilean subduction zone systems. Both have experienced large megathrust ruptures and are situated in temperate climates, and their arc physiographies, their degrees of subduction megathrust coupling, and the presence of a young downgoing oceanic slab in some areas are similar.

NATURE HAS PROVIDED US WITH OPPORTUNITIES TO COMPARE SUBDUCTION ZONE SEGMENTS

frequency-magnitude relationships for large earthquakes and magmatic events but whose climatic parameters (e.g., precipitation, storminess, and temperature) differ. Differences in climatic conditions would presumably manifest within variations in the frequencies, magnitudes, and spatial extents of storms affecting the subduction zone landscapes and seascapes.

In this case, a successful experiment would require field measurements and data that capture the effects of single events and the integrated effects of multiple events. Furthermore, long-term data would be necessary to elucidate how these events combined to produce and transport mass across the subduction zone system over long timescales.

The same data that characterize mass transport can be integrated with data on tectonic convergence and uplift, seismicity, and heat flux to constrain components of the energy budget that are similar or different between subduction zones, thus addressing our second research question. For example, we might identify and compare subduction zone segments that have similar convergence rates, degrees of seismogenic coupling between plates, magmatic fluxes, fore-arc structural complexity, and climate but have different topographies. In this way, we can isolate the interplay between topographic loading and upper plate deformation and magmatism. Such comparisons of natural landscapes may not allow perfect isolation of controlling factors, but they can be augmented by numerical modeling to help constrain the energy

However, the rate of convergence along the southern Chilean subduction zone is far more rapid than along the Cascadia subduction zone. Comparing these zones offers a way, albeit an imperfect one, to investigate systematic effects of variations in the recurrence time of landscape-impacting solid Earth versus atmospheric processes. With a higher convergence rate, the rate of energy addition to the upper plate due to frictional coupling along the megathrust is also plausibly higher in the southern Chilean subduction zone system, indicating another informative comparison between it and the Cascadia system. This example comparison is one of many in which researchers could exploit natural geographic variations in subduction zone properties to advance understanding of subduction zone surface process geohazards.

Putting New Science into Action

Subduction zone landscapes host many communities that are vulnerable to the potent impacts of Earth surface processes operating in these areas. New measurement and modeling capabilities promise to substantially increase our understanding of the phenomena that produce these hazards.

A concerted effort organized under the SZ4D initiative provides a unique opportunity to take advantage of new capabilities to advance the science of subduction zone systems. The decadal-scale focus of the SZ4D Landscapes and Seascapes group promises to provide a synoptic view of the operation of surface processes and the hazards they create at the scale of an entire subduction zone system—a scale that has never been achieved as part of an integrated scientific effort. Strong stakeholder involvement will also accelerate the pace at which this science can be put into action to reduce the risks of these hazards to vulnerable subduction zone communities by developing partnerships between local stakeholder organizations and community groups.

References

Bhattacharya, S., et al. (2018), Geotechnical and infrastructural damage due to the 2016 Kumamoto earthquake sequence, *Soil Dyn. Earthquake Eng.*, *104*, 390–394, https://doi.org/10.1016/j.soildyn.2017.11.009.

Bruni, E. T., et al. (2021), Stochastic alluvial fan and terrace formation triggered by a high-magnitude Holocene landslide in the Klados Gorge, Crete, *Earth Surf. Dyn.*, *9*, 771–793, https://doi.org/10.5194/esurf-9-771-2021.

Cook, K. L., et al. (2018), Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya, *Science*, *362*(6410), 53–57, https://doi.org/10.1126/science.aat4981.

DeLong, S. B., et al. (2012), Multitemporal ALSM change detection, sediment delivery, and process mapping at an active earthflow, *Earth Surf. Processes Landforms*, *37*(3), 262–272, https://doi.org/10.1002/esp.2234.

Elliott, J., R. Walters, and T. Wright (2016), The role of space-based observation in understanding and responding to active tectonics and earthquakes, *Nat. Commun.*, *7*, 13844, https://doi.org/10.1038/ncomms13844.

Handwerger, A. L., et al. (2019), Widespread initiation, reactivation, and acceleration of landslides in the Northern California Coast Ranges due to extreme rainfall, *J. Geophys. Res. Earth Surf.*, *124*(7), 1,782–1,797, https://doi.org/10.1029/2019JF005035.

Hughes, A., et al. (2021), Quantification of gravitational mass wasting and controls on submarine scarp morphology along the Roseau Fault, Lesser Antilles, *J. Geophys. Res. Earth Surf.*, *126*, e2020JF005892, https://doi.org/10.1029/2020JF005892.

Karlstrom, L., et al. (2018), Magmatic landscape construction, *J. Geophys. Res. Earth Surf.*, *123*, 1,710–1,730, https://doi.org/10.1029/2017JF004369.

Lamb, S., and P. Davis (2003), Cenozoic climate change as a possible cause for the rise of the Andes, *Nature*, *425*, 792–797, https://doi.org/10.1038/nature02049.

Major, J. J., et al. (2016), Extraordinary sediment delivery and rapid geomorphic response following the 2008–2009 eruption of Chaitén Volcano, Chile, *Water Resour. Res.*, *52*, 5,075–5,094, https://doi.org/10.1002/2015WR018250.

Major, J. J., et al. (2021), Effective hydrological events in an evolving mid-latitude mountain river system following cataclysmic disturbance—A saga of multiple influences, *Water Resour. Res.*, *57*, e2019WR026851, https://doi.org/10.1029/2019WR026851.

Penserini, B. D., J. J. Roering, and A. Streig (2017), A morphologic proxy for debris flow erosion with application to the earthquake deformation cycle, Cascadia subduction zone, USA, *Geomorphology*, *282*, 150–161, https://doi.org/10.1016/j.geomorph.2017.01.018.

Steer, P., et al. (2020), Earthquake statistics changed by typhoon-driven erosion, *Sci. Rep.*, *10*(1), 10899, https://doi.org/10.1038/s41598-020-67865-y.

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▶ Read the article at bit.ly/Eos-subduction-zone-geohazards

A SHARPER LOOK AT THE WORLD'S RIVERS AND CATCHMENTS

By Bernhard Lehner, Achim Roth, Martin Huber, Mira Anand, and Michele Thieme

This satellite image of the meandering Mississippi River near Memphis, Tenn., features a false-color overlay that illustrates the river's complexities. Shades of green represent river channels or inundated areas. Credit: U.S. Geological Survey/NASA/Landsat 7, Public Domain

Digital hydrographic maps have transformed global environmental studies and resource management. A major database update will provide even clearer and more complete views of Earth's waterways.

Rivers are the arteries of the planet, providing vital resources as they flow and pulse across landscapes in a vast global network. Rivers and streams convey sediments and nutrients to fertile valleys and river deltas, create habitat corridors and transportation routes, and deliver life-sustaining freshwater to aquatic and riparian ecosystems and to human populations.

Runoff that collects in headwaters drains into small mountain streams and ultimately accumulates into mighty lowland rivers that discharge into the world's oceans. Along their paths, waterways both influence and are influenced by the landscapes and ecosystems they traverse. Understanding and managing surface water resources therefore require fundamental hydrographic knowledge and monitoring as well as the tools that support mapping and analysis of natural river and drainage characteristics. These characteristics include conditions of climate, landforms, and soils, as well as anthropogenic influences such as water abstractions, pollution, and river fragmentation.

Studies of global and regional freshwater landscapes, and of the status and management of the resources they provide, have progressed profoundly in recent years. Many advancements have been facilitated by the increased availability and accuracy of novel remote sensing imagery and the sophisticated interpretation of these data. Digital representations of rivers and catchments are particularly important and a prerequisite for many water-related assessments and modeling efforts.

In the absence of a universally accepted digital global river network, the HydroSHEDS database [*Lehner et al.*, 2008] has emerged in the past decade as the most fre-

STUDIES OF GLOBAL AND REGIONAL FRESHWATER LANDSCAPES, AND OF THE STATUS AND MANAGEMENT OF THE RESOURCES THEY PROVIDE, HAVE PROGRESSED PROFOUNDLY IN RECENT YEARS.

quently applied global hydrographic mapping product [*Lindersson et al.*, 2020], supporting a large and growing community of users. Soon this community will have access to a new version of HydroSHEDS offering expanded capabilities and promising clearer views of Earth's arteries.

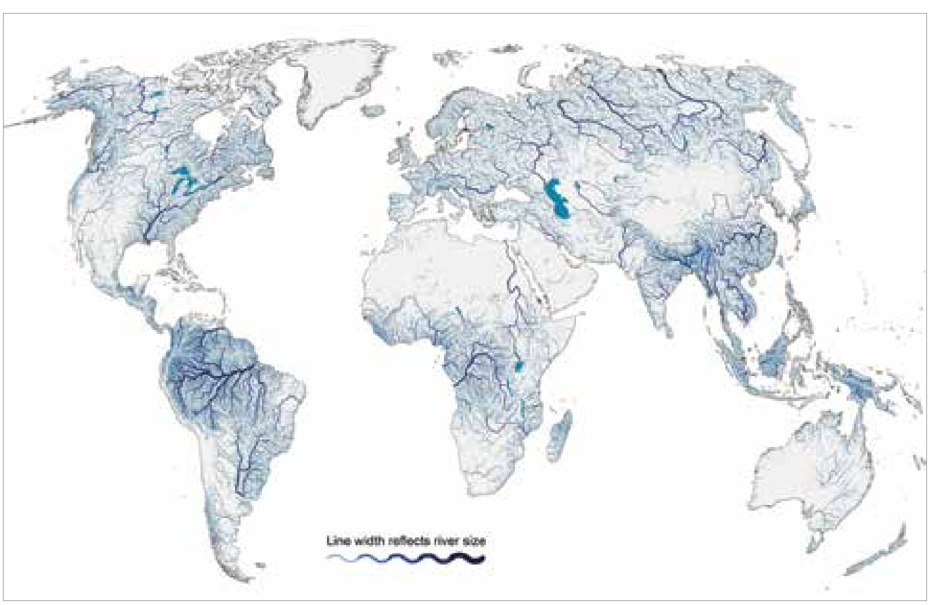

Fig. 1. This map shows the global river network derived from HydroSHEDS version 1. Only large rivers are shown.

Global Data for Freshwater Modeling

Digital hydrographic maps organize information about freshwater landscapes, including rivers (Figure 1), catchments (the land area that drains into a given point in the river network), lakes, and wetlands, into manageable geospatial units. By doing so, they also provide connections between units to allow for upstream and downstream analyses within drainage networks.

River and catchment maps are often derived from gridded digital elevation models (DEMs) by tracing river channels and catchment divides, assuming that the path of water follows topography along lines of steepest descent. The resulting delineations of flow directions, river courses, and catchment boundaries form the foundation of most hydrological models and enable the visualization, analysis, and management of associated river and catchment information.

Since its introduction in 2008, the HydroSHEDS database has transformed large-scale hydroecological research and applications worldwide. Given the HydroSHEDS database's high and modifiable spatial resolution, applications that make use of it span a multitude of scales, from small catchments to large river basins and the entire globe.

HydroSHEDS forms an integral part of many regional or global hydrological and climate change models. It has informed or enabled novel studies and assessments of global biogeochemical cycles and sediment transport from land to the oceans; the dissemination of chemical contaminants and pollution along the global river network; the status of global free-flowing rivers; and patterns of aquatic species ranges and global freshwater biodiversity.

Beyond scientific research, the standardized river network and catchment delineations in HydroSHEDS offer a geospatial framework that serves many management and decisionmaking applications. For example, HydroSHEDS data have been used to support efforts to safeguard societally beneficial aquatic ecosystem services such as water provision and flood control; to assess human health impacts from degrading water quality; to inform conservation planning efforts; and to find strategic solu-

Along their paths, waterways like this river in Iceland both influence and are influenced by the landscapes and ecosystems they traverse. Credit: Jonatan Pie/Unsplash, Unsplash License

tions at the nexus of water, food, energy, and the environment.

The data are used by nongovernmental organizations and national and international institutions to organize and report global water information, including in relation to some of the United Nations' Sustainable Development Goals for water and sanitation. Finally, the data appear in countless online applications for education, community science, and public policy because of the simplicity of mapping and visualizing them in geographic information systems (GIS).

Setting the Standard for Global Hydrography

The first version of HydroSHEDS, which is still in use, was derived from the DEM of NASA's Shuttle Radar Topography Mission (SRTM) at a pixel resolution of 3 arc seconds (roughly 90 meters at the equator). In addition to automatic derivation algorithms, extensive manual inspections and corrections were applied during the creation of HydroSHEDS to ensure a high degree of quality control. Resulting HydroSHEDS products are available at varying resolutions, ranging from 3 arc seconds to 5 arc minutes (roughly 10 kilometers at the equator). Catchment information is offered in nested subbasin structures, making the tool uniquely suitable for applications at scales ranging from individual river basins to countries or the entire world.

Given its wide acceptance as a free and easy-to-use database, HydroSHEDS grew to establish a common standard in hydrographic spatial units (i.e., studies performed using HydroSHEDS all use the same catchment boundaries or river reach units defined therein). Many researchers and users have produced their own data and results, such as on aquatic species distributions, that are interoperable with these standardized units, adding to HydrSHEDS's versatility. Further, the integration of a suite of related data collections and value-added information continues to expand the HydroSHEDS family of products. Foremost among these is the HydroATLAS compilation of more than 50 hydroenvironmental attributes for each of about 8 million river reaches and about 1 million subbasins [*Linke et al.*, 2019].

Amid its remarkable success, however, version 1 of HydroSHEDS has important limitations. In particular, coverage above 60°N latitude (a region largely within the Arctic Circle) is missing from the 3-arc-second product. For coarser products, coverage of this region is of low quality because no underpinning SRTM elevation data were available. Similarly, when version 1 of HydroSHEDS was created, some areas, such as very steep or glaciated mountain terrain, could not be fully resolved because of inherent data gaps or other errors.

Similar global hydrographic maps have been developed to improve on these limitations, such as the MERIT Hydro data set [*Yamazaki et al.*, 2019]. However, these products have different technical specifica-

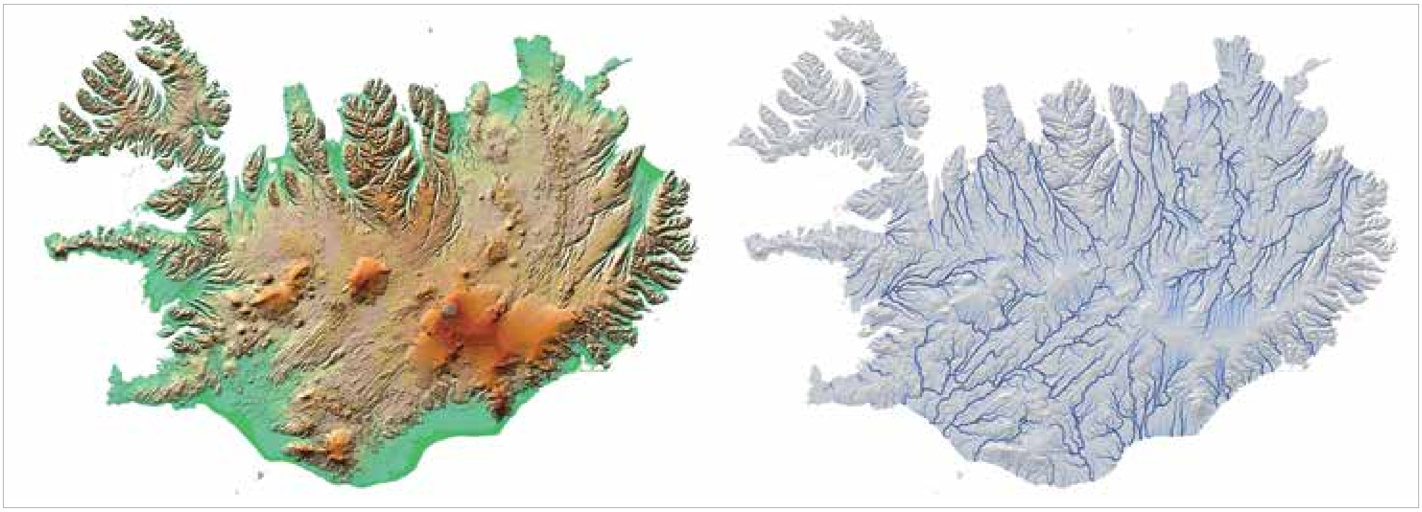

Fig. 2. The TanDEM-X digital elevation model (left) and HydroSHEDS-X derived river network (right) for Iceland are shown here. Only medium to large rivers are depicted.

tions, including differing coastlines and the absence of a nested catchment breakdown. Thus, they are not directly compatible with the existing HydroSHEDS suite of data layers, making updates and transfers of ongoing projects difficult for users.

HydroSHEDS Sharpens Its Vision

HydroSHEDS version 2 (also called HydroSHEDS-X), currently under development (Figure 2), will offer substantial revisions and improvements on version 1 while following the same design characteristics to ensure maximum compatibility between versions and to related products.

The new version is derived from the TanDEM-X (TerraSAR-X add-on for digital elevation measurement) global elevation model, which was created in partnership between the German Aerospace Center (DLR) and Airbus, and is superior to the SRTM DEM in several ways. The elevation data of TanDEM-X were produced at an original resolution of 12 meters, and they cover the entire global land surface area, including northern latitudes. Global TanDEM-X data at 90-meter pixel resolution—and at 30-meter pixel resolution for regions not currently affected by political conflict—were recently licensed for free distribution.

To enhance the quality of results while retaining spatial compatibility, HydroSHEDS-X has been created from the original, nonpublic 12-meter-resolution version of TanDEM-X, yet it will be released at the same 3-arc-second resolution as HydroSHEDS version 1. This approach ensures fully global, homogeneous coverage, including of areas above 60°N latitude, at substantially improved quality due to both the finer resolution of the underpinning DEM and the reduced need to fill data gaps compared with the SRTM data.

To produce HydroSHEDS-X, the original data are being preprocessed and corrected at 3-arc-second resolution with an open-water mask and with novel DLR-provided vegetation and settlement maps (e.g., 3D World Settlement Footprint). These corrections are applied to reduce distortions in elevation caused by vegetation cover, such as in dense forests in riparian areas, and by human-made structures in built-up areas.

WE ENVISION THE UPDATED VERSION OF HYDROSHEDS BECOMING A FOUNDATIONAL OPEN DATA FRAMEWORK THAT WILL ENABLE GLOBAL AND REGIONAL APPLICATIONS IN HYDROENVIRONMENTAL RESEARCH AND FRESHWATER RESOURCE MANAGEMENT.

Following these preprocessing steps, refined hydrological optimization and correction algorithms are applied to derive the drainage pathways. These procedures include improved "stream-burning" techniques that reconcile topographic and hydrographic data to ensure that calculated drainage patterns conform to those observed in the field. The stream-burning techniques incorporate recent auxiliary data products, such as high-resolution terrestrial open-water masks, which improve the tracing of drainage pathways as centerlines in wide river channels and inside large lakes (Figure 3).

In a subsequent processing step, the 3-arc-second river network is then upscaled into coarser-resolution versions (such as 15 arc seconds and 5 arc minutes) for use in global hydrological models. As a hallmark feature, the creation of HydroSHEDS-X is being guided by a high level of manual quality control, including comparisons and alignment with remote sensing imagery and existing regional or local river maps.

Enabling Next-Generation Applications

The main release of the new HydroSHEDS-X database under a free license is scheduled to start this year, with regions above 60°N latitude being completed first (see the HydroSHEDS website for more details).

An important part of the development of HydroSHEDS-X is facilitating the transition of companion data products to be used with the new version. In particular, products such as HydroATLAS will be re-created using HydroSHEDS-X, and information about these transitions—such as tables linking new and old identification numbers of subbasins and river reaches—will be produced so that users can walk their data over to the new format.

Given the longevity and consistency of the original HydroSHEDS product, we envision the updated version becoming a foundational open-data framework that will enable the next generation of global and regional applications in hydroenvironmental research and freshwater resource management.

In particular, we expect the extended coverage of HydroSHEDS-X beyond 60°N latitude to promote novel assessments of climate change implications in Arctic aquatic environments. Also, the improved underpinning elevation data and the resulting overall accuracy enhancements offer new opportunities for high-resolution global applications. For example, HydroSHEDS-X can facilitate a coupling of hydrologic models with real-time remote sensing imagery that allows for monitoring of water availability, water shortages, or flood risk at unprecedented spatial and temporal resolutions worldwide. With its new capabilities, HydroSHEDS-X aims to advance our efforts to tackle pressing questions about the future of Earth's terrestrial landscape and the arteries that carry vital resources through it.

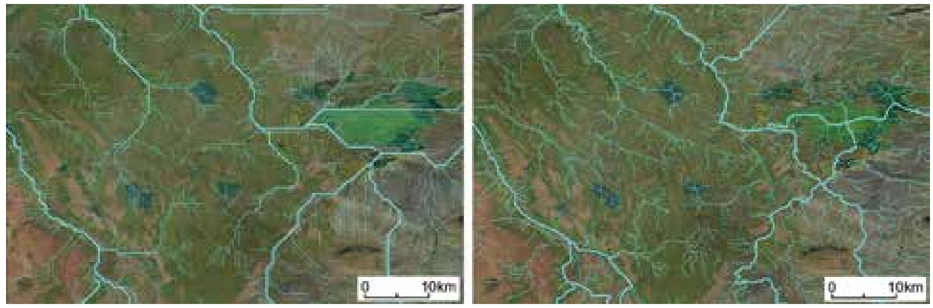

Fig. 3. This comparison of river flow paths in Iceland derived from HydroSHEDS version 1 at 500-meter resolution (the highest resolution available in HydroSHEDS version 1 for this region) (left) and from HydroSHEDS-X at 90-meter resolution (right) illustrates the improved ability of the latter to determine drainage pathways accurately.

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References

Lehner, B., K. Verdin, and A. Jarvis (2008), New global hydrography derived from spaceborne elevation data, *Eos Trans. AGU*, *89*(10), 93–94, https://doi.org/10.1029/2008EO100001.

Lindersson, S., et al. (2020), A review of freely accessible global datasets for the study of floods, droughts and their interactions with human societies, *WIREs Water*, *7*(3), e1424, https://doi.org/10.1002/wat2.1424.

Linke, S., et al. (2019), Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution, *Sci. Data*, *6*, 283, https://doi.org/10.1038/s41597-019-0300-6.

Yamazaki, D., et al. (2019), MERIT Hydro: A high-resolution global hydrography map based on latest topography dataset, *Water Resour. Res.*, *55*(6), 5,053–5,073, https://doi.org/10.1029/2019WR024873.

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Coastal Aquaculture Can Reduce Nutrient Transport

Coastal aquaculture produces many types of seafood, including fish, shellfish, and aquatic plants. An ongoing challenge, however, is understanding the impact of excessive aquaculture on nutrient levels in surrounding waters. Using a combination of field observations and high-resolution mathematical simulations, *He et al.* investigated the impact of aquaculture at Sanggou Bay, located off China's coast in the Yellow Sea.

The main aquaculture technique used in this area is suspended aquaculture, where species of kelp and shellfish hang beneath the water's surface on ropes. In addition to a near-coastal aquaculture area within Sanggou Bay that goes as deep as 10 meters, there is also an offshore aquaculture area that extends to depths of 20–30 meters. By sampling from stations over the whole region, the team found that nutrient concentrations are highest outside the aquaculture area, especially in the near-bottom layer.

To explore the effect of suspended aquaculture on hydrodynamics, the researchers ran numerical experiments with and without aquaculture-induced friction as part of their mathematical model. Their results showed that at the outer boundary of the aquaculture area, aquaculture-induced friction transforms onshore currents in lower layers into offshore currents, which could reduce the transport of nutrients toward the shore. Similarly, the team found that aquaculture-induced friction weakens upwelling, which also could affect the nutrient supply. On the basis of particle-tracking simulations, the researchers estimate that aquaculture-induced friction reduced the amount of high-nutrient water that entered the offshore aquaculture area by 60%.

Suspended aquaculture, used to grow kelp and shellfish at Sanggou Bay in the Yellow Sea, can alter hydrodynamics and reduce the nutrient supply. Credit: Xiaopeng Jiang, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, CC BY-NC-SA 2.0 (bit.ly/ccbyncsa2-0)

Water exchange between the near-coastal aquaculture area and the offshore aquaculture area is mostly unchanged by aquaculture-induced friction, as weakened onshore currents in the top layers are counterbalanced by stronger onshore currents in lower layers. Nutrient transport in the near-coastal aquaculture area is a subject for future study, the researchers say. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006633, 2022) **—Jack Lee,** *Science Writer*

Satellites' Lasers Reveal Changes in Earth's Water Movement

Understanding climate change and its effects on humans, animals, and natural spaces requires studying Earth as a whole, interconnected system. Water movement, in particular, is a process that affects everything from global climate to the smallest habitats.

In 2018, NASA and the GFZ German Research Centre for Geosciences launched the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellites as a continuation of the GRACE mission to study the movement of Earth's water. The two satellites orbit at a consistent distance from each other—in this case, about 200 kilometers. The satellites constantly send each other signals via microwaves and track the other's position within a micrometer's width. Over areas of high mass, the slight change in gravitational pull changes the distance between the two satellites ever so slightly.

These areas of high mass indicate areas with unusual amounts of water, such as the ocean, an ice cap, or an underground aquifer. The standard GRACE-FO data averaged each month tell scientists about the movement of that water. However, water movement doesn't always happen from month to month. The location of water masses can change from day to day or, in some cases, from minute to minute.

Ghobadi-Far et al. set out to test a new instrument on the GRACE-FO satellites that would allow researchers to attain more highly resolved water movement data. The technology, called a laser ranging interferometer (LRI), uses a laser beam rather than microwaves to detect the distance between the two satellites. This technique allows the satellites to track each other's position within a nanometer, which is 1,000 times more accurate than using microwaves.

The researchers analyzed LRI data gathered when GRACE-FO satellites were flying over different, rapidly changing water masses around the globe, including the deep and highly variable Argentine Basin, the Gulf of Carpentaria, and the floodplains and river channels of the Amazon River basin. In all three cases, the researchers demonstrated that LRI data clearly detected the high-frequency ocean variability and rapid water mass variations.

This new method allows for observing high-frequency mass changes in the Earth system that cannot be adequately studied using the standard GRACE-FO monthly data, and thus it "broadens the scope of geophysical applications that can be addressed by GRACE-FO satellites data," according to the authors. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2021JB022983, 2022) **—JoAnna Wendel,** *Science Writer*

Innovative Model Elucidates Geothermal Energy Resource

Geothermal energy abounds in Iceland, the North Atlantic island nation with regular, high-profile volcanic eruptions. The island's active magmatism and volcanism support six geothermal plants, which provide more than 25% of the country's electricity. Geothermal energy heats nearly 85% of the homes on the island.

Krafla, in the northern part of the island, is one of Iceland's active geothermal-producing regions. Krafla's high-temperature geothermal system sits in a volcanic caldera, and the plant there has produced power for more than 40 years. However, despite this intensive energy production, a reservoir model of the Krafla geothermal system has not been published in peer-reviewed literature since the 1980s, leaving a data void and potentially untapped resources.

In a new study, *Scott et al.* present a new 3D natural state model of the Krafla geothermal system. To develop the model, the authors inserted data from the extensively drilled geothermal field into a Bayesian framework. Bayesian models digest uncertainty from the input parameters, quantify uncertainty in the results, and use Markov chain Monte Carlo sampling methods to generate statistics.

This model is one of the first to extend to the deep, supercritical roots near the heat source of an exploited geothermal system. The results revealed unexpected contrasts across the drilled area. In the western part of the production field, wells indicate a 0.5- to 1-kilometer-thick liquid reservoir with temperatures that hover around 210°C (410°F). The liquid reservoir sits atop a deeper, even hotter, boiling reservoir. Meanwhile, in the eastern part of the field, boiling conditions extend from the surface to the maximum depth of the wells, approximately 2 kilometers.

The model explains temperature differences across the field in terms of the variable permeability of the region's volcanic rocks and input of heat from the deep magmatic heat source. The model suggests that the extent of the supercritical fluid zone overlying Krafla's magmatic heat source has been underestimated. Therefore, it also indicates the presence of a significant untapped resource in the geothermal field.

The study showcases how advanced statistical modeling and modern data collection can illuminate difficult-to-access energy resources. In addition, the model is a dynamic entity that will improve as more data become available. (*Water Resources Research*, https://doi.org/10.1029/2021WR031254, 2022) **—Aaron Sidder,** *Science Writer*

Biological Crusts Affected by Drought Can Still Stabilize Soils

Biological soil crusts are communities of cyanobacteria, fungi, lichens, and other living organisms that can bind grains together and reduce the susceptibility of soils to erosion by water or wind. Crusts dominated by cyanobacteria, which occur naturally in many drylands, hold promise as a tool to help control erosion and restore degraded land. To date, however, most studies have focused on how individual cyanobacteria species cultured in a lab, rather than the more structurally complex natural communities, respond to changes in their environment.

To help fill this gap, *Bullard et al.* investigated how in situ cyanobacterial crusts in central Australia's Diamantina National Park responded to simulated precipitation in three adjacent dryland environments: sand dune, floodplain, and the area between them (nebkha). The team measured changes in several of the environments' biological and physical characteristics—including photosynthesis, soil moisture, biological crust strength, and each substrate's wind erodibility—following rainfall simulator treatments of 5 and 10 millimeters to crusts experiencing a yearlong drought.

Broken or drought-affected biological crusts, like the one pictured here in Australia's Diamantina National Park, lose their ability to stabilize soils. Credit: David Elliott/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

The researchers found that the cyanobacterial crusts responded rapidly to moisture, exhibiting higher levels of photosynthesis following the 10-millimeter application and displaying a more intense response when air temperatures were warmer. In addition, they found that regardless of the amount of moisture, the air temperature, or the substrate, the spike in photosynthesis was short-lived, returning to background levels within a day.

The wind tunnel experiments revealed that wind is more effective at eroding soil particles following 5-millimeter, rather than 0- or 10-millimeter, treatment of moisture. The authors attribute this result to the impacts of individual raindrops, which cause sand grains to shift toward the surface. Blowing wind entrains these loose grains, and these in turn entrain others, causing erosion.

Collectively, the findings show that drought-affected cyanobacterial crusts can still protect the substrate from wind erosion at the small scales examined in this study. But climate change forecasts indicate that this region will experience more frequent and longer periods of extreme heat and longer intervals between rainstorms. These shifts are predicted to further reduce the crusts' elasticity and alter the species that compose them, potentially putting at risk their ability to stabilize soils. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006652, 2022) **—Terri Cook,** *Science Writer*

ICON Principles Underused as a Natural Hazards Research Tool

Natural hazards have been responsible for hundreds of billions of dollars in economic losses in the 21st century and pose a complex array of risks to human society, infrastructure, and the environment. These hazards—including hurricanes, floods, tornadoes, earthquakes, and plagues—carry a steep human cost as well, claiming more than a million lives over the past 2 decades.

An increasing number of scientific studies explore how a single disaster might affect a single sector of the economy in a specific place. Natural hazards, however, often have overlapping impacts that are themselves influenced by human systems. For example, a flood in a densely populated area will lead to a greater number of human deaths than one in a more sparsely inhabited area. Alternately, a society already dealing with violent unrest and food shortages will be poorly equipped to bounce back after a plague. Focusing narrowly on one effect of one event could fail to capture complex feedback loops that can produce particularly costly or deadly situations.

The amount of damage caused by natural hazards, like this flood in Norristown, Pa., depends on feedback between natural and human systems. An integrated, coordinated, open, and networked (ICON) approach could better capture the interconnected nature of these phenomena, new research suggests. Credit: Michael M. Stokes, CC BY 2.0 (bit.ly/ccby2-0)

According to *Sharma et al.*, using an integrated, coordinated, open, and networked (ICON) approach would help capture such complexity, reducing the toll of these events. In their new study, the researchers discuss opportunities for and challenges of applying ICON principles to natural hazards risk management strategies.

The researchers identify several opportunities to apply the ICON approach to natural hazards, including expanding coordinated modeling efforts, better communication between scientists and stakeholders, and more interdisciplinary research across relevant disciplines, such as engineering, Earth sciences, and social sciences. They argue that these opportunities to use ICON principles could be improved through more systematic data collection and open-source data sharing.

However, barriers remain—different disciplines' lack of shared vocabulary, for instance. A surfeit of frameworks for fostering interdisciplinary collaborations is another example. In addition, the authors highlight accurate scientific communication of uncertainty and risk to the general public as an area of possible improvement. Working through these challenges to implement a more ICON-based approach could improve understanding and decisionmaking regarding natural hazards management and response, the researchers conclude. (*Earth and Space Science*, https://doi.org/10.1029/2021EA002114, 2022)
—Rachel Fritts, *Science Writer*

The Seasonality of Oceanic Carbon Cycling

The ebb and flow of carbon within Earth's systems are complex and ever moving processes. Carbon is a nomadic element, traveling between the atmosphere; the ocean; and the soil, rock, and ice of the planet, changing forms along the way. Much of this cycling takes place in the ocean, partially through a biological carbon pump (BCP). In the BCP, atmospheric carbon is fixed by phytoplankton growing at the surface of the sea. When the phytoplankton die, they sink from the surface to deep ocean waters, carrying their carbon with them. This carbon can remain for hundreds or even thousands of years before returning to the atmosphere.

In the past, the BCP has been treated as a constant, but the variability of sinking carbon particles has been observed in sediment trap sampling over the past few decades. Now, using a global ocean biogeochemical model, *de Melo Viríssimo et al.* look at how the changing seasons can alter the amount and rate of carbon and other nutrients sinking into deep ocean waters.

In particular, they looked at how both the pattern and the strength of the seasonality would affect the sinking speed of carbon particles and their attenuation throughout the water column.

When they compared their modeled seasonal results with nonseasonal scenarios, they found an increase of up to 196% of carbon particle transfer when seasonal variations were taken into consideration.

Although their model was a simplified version of a complicated biogeochemical system, they found that particle fluxes in the BCP are sensitive to the strength of seasonal fluxes, especially in high-latitude regions. The team notes that this study highlights the importance of seasonality on carbon flux, including the sinking speed and the amount of detritus moving through the water column. The team adds that if other researchers assume the BCP is constant, they may be underestimating how much carbon can be sequestered in the ocean.

Future work should collect new observations to unravel how seasonality can affect detrital sinking speeds, according to the authors, who also note that more nuanced inputs of other factors such as water temperature and phytoplankton sizes and species could reveal more details about the BCP related to seasonal fluxes. (*Global Biogeochemical Cycles*, https://doi.org/10.1029/2021GB007101, 2022) **—Sarah Derouin**, *Science Writer*

Health Impacts of Air Pollution from Australian Megafires

From October 2019 to February 2020, fire ripped through the Australian bush with unprecedented intensity, immediately killing 34 people and more than 3 billion animals. In a new study, *Graham et al.* seek to quantify the health impacts of an indirect form of fire damage: the damage caused by poor air quality.

Like car engines, gas stoves, and cigarettes, fires create fine particles with a diameter of less than 2.5 micrometers, called $PM_{2.5}$. High $PM_{2.5}$ concentrations can exacerbate a wide range of medical conditions, from lung disease to cardiovascular disease, even leading to death.

By modeling $PM_{2.5}$ concentrations over southeastern Australia during the period of intense fire activity, the researchers discovered that fire hot spots began to form as early as October and continued to grow over the next 3 months until at least 70% of $PM_{2.5}$ particles in an area stretching from Melbourne to Brisbane stemmed from the fires.

Around 437,000 people were exposed to air with a $PM_{2.5}$ concentration of least 25 micrograms per cubic meter of air, which is substantially more than the 15 micrograms per cubic meter of air that the World Health Organization considers an acceptable level for short-term exposure. At times, $PM_{2.5}$ concentrations increased by more than 3.5-fold because of the fires, the authors estimate.

Using methodology developed by the World Health Organization, the authors estimated that increased $PM_{2.5}$ levels brought on by the fires eventually led to 171 deaths. Sydney and Melbourne bore the brunt of the casualties, with 65 and 23 deaths, respectively, caused by bushfire $PM_{2.5}$, and the rest were scattered throughout the southeastern portion of the country.

This study is the first to simulate $PM_{2.5}$ levels using an air quality model while taking meteorological conditions and atmospheric processes into account. According to the authors, this method is likely to provide the most accurate regional $PM_{2.5}$ exposure estimates to date, which is important, as wildfires are expected to increase as climate change leads to hotter, drier conditions. Public health officials might draw from studies such as this as they strategize about how to keep populations healthy in the new climate era. (*GeoHealth*, https://doi.org/10.1029/2021GH000454, 2021) —**Saima Sidik**, *Science Writer*

The AI Forecaster: Machine Learning Takes On Weather Prediction

According to a 2009 study, U.S. adults look at weather forecasts nearly 300 billion times a year. Reliable forecasts can predict hazardous weather such as blizzards, hurricanes, and flash floods as early as 9–10 days before the event. Estimates value these forecasts at $31.5 billion per year.

Although weather prediction keeps improving from year to year for shorter-term forecasts, forecast skill decreases in the 2-week to 2-month time frame. These longer-timescale forecasts can play a critical role for many sectors, including water conservation, energy demand, and disaster preparedness.

In a new study, *Weyn et al.* set out to improve this subseasonal to seasonal forecasting, as it is known, using a novel approach to weather prediction. Using a convolutional neural network, the authors developed a machine learning system called Deep Learning Weather Prediction (DLWP). The model is trained on past weather data, which differs from standard numerical weather prediction models that create mathematical representations of physical laws. DLWP projects 2–6 weeks into the future for the entire globe.

The authors compared the DLWP model to current state-of-the-art numerical weather models. The evaluation showed that the standard numerical forecasts perform better for short lead times, for instance, 2–3 weeks out. However, the DLWP model compared well when projecting 4–6 weeks down the line.

Although the DLWP model does not yet rival existing models—and cannot currently forecast precipitation—the machine learning approach shows promise, the authors say. For one, the model is computationally more efficient than other approaches. The DLWP model requires only 3 seconds to compute an ensemble forecast consisting of 320 independent model runs. In addition, the model accurately provided a 4.5-day reforecast for Hurricane Irma using total column water vapor and without precipitation. The category 5 hurricane ravaged the northern Caribbean and the Florida Keys in 2017.

Improved weather forecasts from 2 weeks to 2 months in advance could improve disaster preparedness for storms like Hurricane Irma, shown here battering Sint Maarten in the Caribbean. A new machine learning weather prediction system shows promise on this subseasonal time frame. Credit: Netherlands Ministry of Defence, CC BY SA 4.0 (bit.ly/ccbysa4-0)

The researchers said their study represents a significant step forward in the use of machine learning for weather and climate modeling and observed that DLWP was remarkable in its ability to learn physics-based phenomena. They also noted that the model could supplement forecasts in the tropics and in the spring and summer months, where most weather prediction models currently struggle. (*Journal of Advances in Modeling Earth Systems* (*JAMES*), https://doi.org/10.1029/2021MS002502, 2021) —**Aaron Sidder**, *Science Writer*

Road Salts Linked to High Sodium Levels in Tap Water

New research into the effects of deicers on drinking water in Philadelphia raises concerns about transparent communication from water utilities. Credit: Audrey Julienne/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

When snowstorms hit, deicing agents such as road salts and brine help keep streets and walkways open. However, some deicers release sodium and chloride into the surrounding environment. Links between elevated sodium intake and human health risks, such as high blood pressure, are well established. The effects of deicers on drinking water, however, have been less clear.

Now, evidence reported by *Cruz et al.* supports a link between deicers and elevated sodium levels in drinking water, with concentrations in the Philadelphia region sometimes surpassing recommended limits for people on sodium-restricted diets. The new study adds a public health perspective to research that has focused primarily on the harmful effects of deicers on freshwater aquatic animals, including amphibians and benthic macroinvertebrates.

The researchers evaluated weekly levels of sodium and chloride in municipal tap water in three homes in the Philadelphia region from November 2018 through March 2019. Each home was located in a different municipality and received water from a different supplier.

Sample analysis revealed that sodium and chloride levels peaked in late winter for all three sites, just after major snowfall and snowmelt events. Concentrations were higher for sites located downstream of areas with relatively higher density development. In line with earlier research, these results suggest that deicers contribute to temporarily elevated sodium levels in drinking water supplies.

The researchers also found that sodium levels occasionally rose to 6.4 times the guideline of 20 milligrams per liter of water recommended by EPA for adults restricted to 500 milligrams of sodium per day. Calculations suggested that at peak concentrations, adults with no sodium restrictions would reach up to 18.8% of their recommended daily limit through tap water alone, and adults on a low-sodium diet (up to 1,500 milligrams per day) would reach up to 33.3% of their limit.

These findings, in combination with a review of sodium reporting data from 40 U.S. cities, suggest the need for water utilities to provide real-time public information on sodium exposure risk. Future research could address potential links between winter sodium peaks and increased risk of hypertension and heart problems. (*GeoHealth*, https://doi.org/10.1029/2021GH000538, 2022) **—Sarah Stanley,** *Science Writer*

Potential of Leaking Modes to Reveal Underground Structure

Uncovering the geologic structure beneath Earth's surface is important for a variety of reasons, including identifying natural resources and studying earthquake hazards. Scientists image Earth's subsurface by observing seismic waves that travel through our planet.

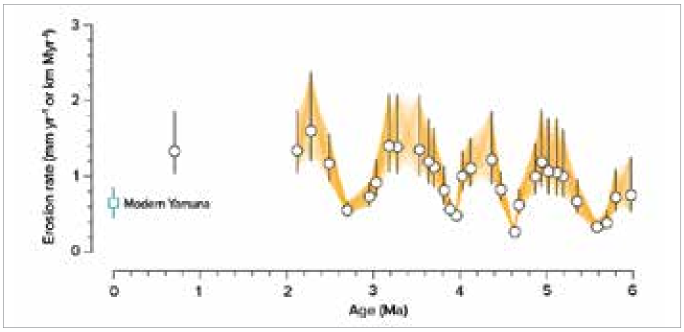
When an earthquake occurs, several types of waves radiate from the event's source. *P* and *S* waves move through the interior, and Love and Rayleigh waves (known as surface waves or normal modes) move across Earth's surface. The speeds at which these waves travel and how each type is scattered in the subsurface can reveal a wealth of information about underground structure.

To study seismic waves, scientists generally must wait for earthquakes, which are unpredictable, or create their own using explosives. In the past couple of decades, however, researchers have developed additional ways to study the subsurface noninvasively by using ambient noise the constant hum of sounds made by people and natural processes, like mining activities or waves crashing on a beach.

In a new study, *Li et al.* demonstrate the possibility of imaging the subsurface using not only normal modes produced by ambient noise but also another naturally occurring type of seismic wave called leaky, or leaking, modes. Leaky modes can occur when a seismic wave is "trapped," bouncing back and forth between two layers of rock. When energy escapes from this bouncing wave, it creates a separate wave referred to as the leaky mode. Compared with normal modes, which are more sensitive to *S* wave velocity structure underground, leaky modes are more sensitive to *P* wave velocity structure.

The authors looked at 1 month of ambient noise picked up by a dense array of seismometers called the Large-n Seismic Survey in Oklahoma (LASSO). Studying both normal and leaky modes extracted from the seismic data, they calculated the speeds at which the waves had moved through the subsurface. Those speeds, in turn, are specific to properties of the rocks below, such as their density and elasticity. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL096032, 2022) **—JoAnna Wendel,** *Science Writer*

Himalayan Erosion Driven by Tectonics, Not Climate?

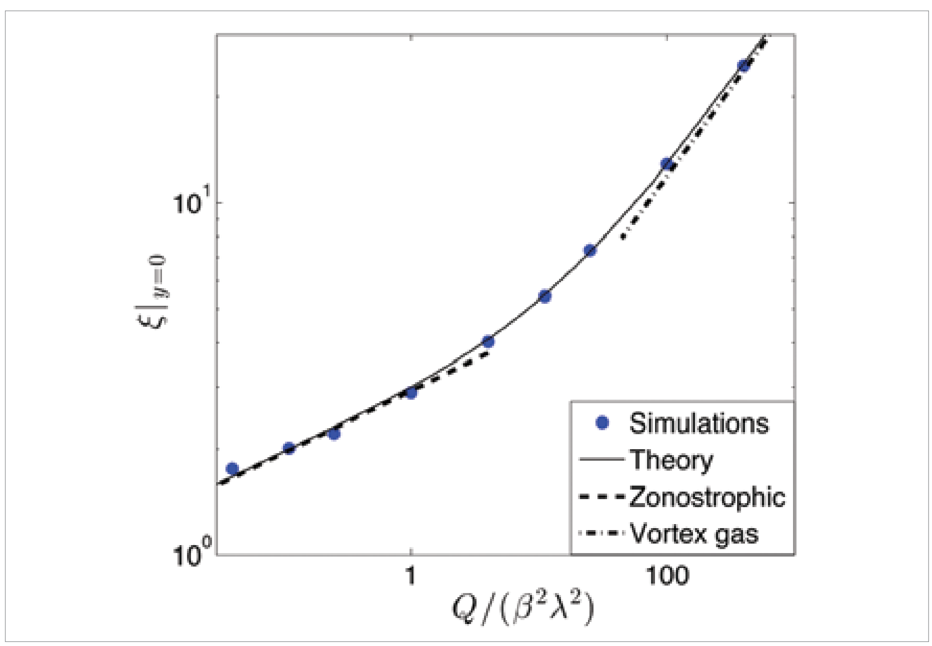


Erosion rates in the northwestern Himalayas, reconstructed from measurements of cosmogenic isotopes in sediments, plotted against sediment depositional ages show a roughly 1-million-year periodicity and an increase in rates toward the present. Orange lines illustrate the results of Monte Carlo uncertainty modeling. Credit: Mandal et al.

It is widely accepted that both climate and tectonics play a role in shaping mountain landscapes, but uncertainty remains about the nature and relative importance of these roles. *Mandal et al.* report erosion rates from the northwestern Himalayas for the past 6 million years based on measurements of cosmogenic beryllium-10 in Siwalik Group sediments shed from the mountains. They propose that the roughly 1-million-year cyclicity in erosion rates evident in their data set results not from a climate driver but from an emergent phenomenon related to tectonic accretion of material to the Himalayas. In an accompanying Viewpoint, *Codilean and Sadler* point out that determining accurate erosion rates with cosmogenic nuclide measurements is difficult, but they note that the data set raises interesting questions about the roles of tectonics and climate in active settings. The proposal from Mandal et al. will generate debate and stimulate more study of how specific sets of processes affect the coupled tectonic-climate system. (https://doi.org/10.1029/2021AV000487 and https://doi.org/10.1029/2021AV000539, 2021) **—Peter Zeitler**

Extracting Order From Turbulence

On rotating planets, differential heating between the poles and the equator gives rise to turbulent instabilities. These instabilities manifest as transient disturbances (e.g., Earth's midlatitude storms) that transport enthalpy poleward, thereby lessening the temperature gradients and quenching the instabilities. Scientists have long sought to understand how the resultant temperature gradients, along with other properties of the system, depend on the degree of destabilization. *Gallet and Ferrari* develop a scaling law that quantifies these dependencies and shows how meridional temperature gradients respond—weakly—to changes in the forcing. Their scaling theory bounds the utility of the long-standing but ultimately incorrect hypothesis that eddies relax temperature gradients to a state of marginal stability. These new results provide a fully nonlinear benchmark for numerical methods used to simulate geophysical flows, for guiding thinking about the behavior of less idealized flows, and for inspiring aspiring theoreticians. As *Vallis* points out in a companion Viewpoint, extracting order from turbulence is often seen as academic hardscrabble, which makes the fertility of Gallet and Ferrari's accomplishment all the more remarkable. (https://doi.org/10.1029/2020AV000362 and https://doi.org/10.1029/2021AV000523, 2021) **—Bjorn Stevens**



This figure shows the criticality parameter (ξ), whose increase measures how temperature gradients depart from their marginally stable value, as a function of the nondimensional heat flux ($Q/(\beta^2\lambda^2)$). The success of the theory and two asymptotes are shown in comparison to direct numerical simulations over a very large range of heat fluxes. Credit: Gallet and Ferrari

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As an internationally recognised research professional, you will lead the research unit and its 40 or so employees, together with the group leaders. This varied and highly responsible role will include coordinating and promoting research by the entire unit as well as leading projects of your own. You will foster the targeted practical implementation of scientific results and nurture close cooperation with relevant stakeholders. You will also be responsible for securing third-party funding for research projects and for maintaining cooperation with authorities and organisations at national and international level.

You are at an advanced stage of your academic career, have many years of research experience, as well as an outstanding scientific track record on the cryosphere and its interactions with the environment. You have extensive experience leading research groups and managing interdisciplinary research projects and possess a motivational and team-oriented management style. You are also inclusive, have excellent negotiating skills, and speak at least one of Switzerland's national languages, as well as being fluent in spoken and written English.

Please send your complete application to Clemens Güdel, Human Resources SLF, by uploading the requested documents through our webpage. Applications via email will not be considered. For questions about the position, please contact **Prof. Dr Beate Jessel, WSL Director (tel. +41 44 739 2224)**. For administrative queries, contact **Ms. Susanne Jost, Head of HR (tel. +41 44 739 2370)**. The WSL strives to increase the proportion of women in its employment, which is why qualified women are particularly called upon to apply for this position.

Greetings from the Arctic!

We are here with three aircraft operating from Kiruna, Sweden, and Longyearbyen, Svalbard, to investigate how air masses transform when they enter (or leave) the Arctic. We have been flying for 3 weeks using various instruments in the visible to the microwave spectral range, as well as an in situ sensor. Mika the Polar Fox, who explains Arctic amplification to kids (see https://mias-klimatagebuch.de/), is with us and enjoys the fascinating view of the sea ice.

Wish you could do the same.

See https://halo-ac3.de/ for more information.

—**Michael Schäfer,** University of Leipzig, Leipzig, Germany; and the **HALO-(AC)³ Team,** Kiruna, Sweden