

Eos

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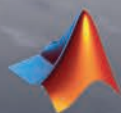
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Where Science Connects Us

This month, *Eos* is meeting the moment "Where Science Connects Us" with deep dives into the state of the geoscience profession ("Eight Ways to Encourage Equality, Diversity, and Inclusion Discussions at Conferences," p. 13), some ATLAS-sized enthusiasm for a comet ("How an Interstellar Interloper Spurred Astronomers into Action," p. 16) as well as research updates ("Tracing Black Carbon's Journey to the Ocean," p. 30) and quirky queries (whither Planet Y, p. 8).

AGU's annual meeting is in New Orleans this year, and our feature story, a forward-looking analysis of the ways hurricane forecasting has grown in breadth and depth since Hurricane Katrina (p. 22), is a great read for those attending AGU25. It's a great read for those who aren't at the meeting, too—a reminder of the relevance and importance of Earth and space sciences for discovery and solution-based inquiry.

So follow the path of the Mighty Mississippi (just look at the bottom of the page!) as you let *Eos* show where science connects us to Earth, space, and each other.

Caryl-Sue Micalizio, Editor in Chief



On the Cover

Design and illustration
by Mary Heinrichs,
after Harold Fisk's
meander maps of the
Mississippi River

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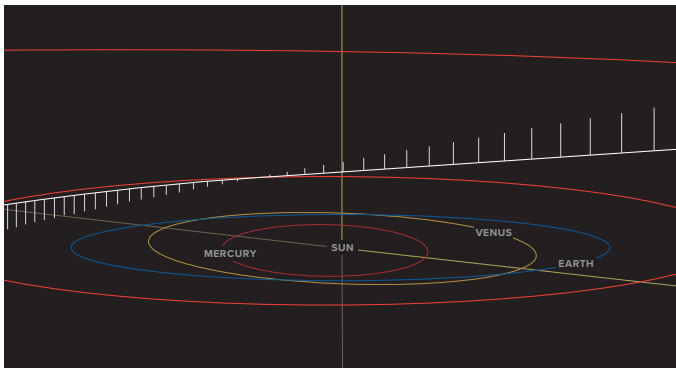
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Janice Lachance, Executive Director/CEO





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Creativity Prize

[1] The team of Maria Cristina Rulli (Polytechnic of Milan, Italy) and Paolo D'Odorico (University of California, Berkeley, USA)

for spearheading novel analyses of the water-energy-food nexus that describe how numerous complex factors interact, providing for better freshwater stewardship in a changing, globalised world.



Maria Cristina Rulli



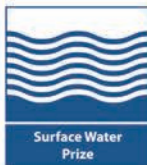
Paolo D'Odorico

[2] The team of Zhiguo He (Zhejiang University, China)

for developing working, versatile soft robots with unprecedented manoeuvrability that have the capacity for numerous underwater research and monitoring applications. Team members include: Pengcheng Jiao and Yang Yang.



Zhiguo He



Surface Water Prize

Qiuhua Liang (Loughborough University, UK) and his team

for developing innovative, open-source, multi-GPU hydrodynamic models to support real-time flood forecasting at high temporal-spatial resolutions. Team members include: Huili Chen, Xiaodong Ming, Xilin Xia, Yan Xiong and Jiaheng Zhao.



Qiuhua Liang



Groundwater Prize

Chunmiao Zheng (EIT, Ningbo, China) and his team

for powerful modelling tools to understand groundwater processes and manage groundwater resources under diverse eco-hydrological and climatic conditions, considering environmental and socioeconomic factors at local and national scales.



Chunmiao Zheng



Alternative Water Resources Prize

Virender K. Sharma (Texas A&M University, USA) and his team

for the effective removal of antibiotics and pharmaceuticals from wastewater through advanced oxidative processes by activated ferrate, which work at high, even enhanced, efficiency in water containing commonly occurring natural organic matter. Team members include: Ching-Hua Huang, Chetan Jinadatha and Radek Zbořil.



Virender K. Sharma



Water Management & Protection Prize

Joseph Hun-wei Lee (Macau University of Science & Technology, China)

for developing unique and highly effective hydro-environmental modelling systems for the sustainable water management of smart cities.



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Volcanic Eruptions in One Hemisphere Linked to Floods in the Opposite One



The band of thunderstorms seen here in the area around northern South America marks part of the Intertropical Convergence Zone (ITCZ), an area of enhanced moisture encircling the globe north of the equator. Credit: NASA/GSFC, Public Domain

Throughout Earth's history, so-called volcanic winters have radically altered Earth's climate. In these events, gases expelled by powerful eruptions form aerosols that reflect the Sun's radiation and prevent it from warming the planet.

But eruptions' effects on Earth systems don't stop with temperature. Large eruptions can have diverse down-the-line impacts such as altered rainfall, damaged crops, and, according to a new study, disrupted seasonal flood patterns (bit.ly/volcano-floods).

"Usually, when we think about volcanoes, we think of them through the lens of changes in temperature," said Gabriele Villarini, a hydroclimatologist at Princeton University and a coauthor of the new study. "The question I had was, 'How about volcanoes and their impact on flooding at the global scale?'"

Villarini and his colleagues simulated the effects of three major volcanic eruptions in Earth's past. Their results, published in *Nature Geoscience*, showed an asymmetric pattern: Major eruptions in the tropics of one hemisphere appeared to coincide with substantial increases in seasonal flooding in the opposite hemisphere. The findings could guide disaster response efforts and offer insight into the possible effects of geo-engineering as well.

The work "builds a bridge between climate modeling work on volcanic eruptions

and the potential impacts on people and societies," said Matthew Toohey, a climate scientist at the University of Saskatchewan who was not involved in the new study.

The work "builds a bridge between climate modeling work on volcanic eruptions and the potential impacts on people and societies."

Opposing Hemispheres

The research team used previous simulations of Earth's climate system to obtain precipitation and temperature data for 5 years after three highly explosive eruptions: Guatemala's Santa María in 1902, Indonesia's Mount Agung in 1963, and the Philippines' Mount Pinatubo in 1991. The scientists also simulated hypothetical control worlds in which those eruptions never happened.

The researchers then used those data in a statistical model to see how flooding pat-

terns might respond. The model reproduced streamflow conditions after the three eruptions and in the hypothetical cases with no eruptions.

When volcanic plumes were confined to one hemisphere, the scientists found, peak stream gauge readings increased in the opposite one. (Such readings have long been an indicator of seasonal flooding.)

Mount Agung's 1963 plume stayed in the Southern Hemisphere. In the year after the eruption, about 50% of stream gauges in tropical Southern Hemisphere basins showed a decrease in peak readings when compared to the noneruption scenario, according to the model. In the Northern Hemisphere, however, about 40% of stream gauges showed an increase in peak flow in the year after the eruption.

The effects of the eruption of Santa María showed a similar pattern: In the 2 years after the eruption, simulated stream gauges in the Northern Hemisphere (where the aerosols were concentrated) had decreased flows, while those in the Southern Hemisphere experienced an abrupt increase.

Mount Pinatubo's eruption plume, however, was more evenly distributed across the Northern and Southern Hemispheres, and its effects were distinct. The simulations showed that in the 3 years after the eruption, Pinatubo's plume decreased flooding



The 1991 eruption of Mount Pinatubo, Philippines, was one of three eruption events studied by researchers investigating links between flooding and volcanic gases. Credit: Dave Harlow/USGS, Public Domain

in tropical regions but increased stream gauge readings in arid areas of each hemisphere.

Eruptions on the Equator

The research team didn't directly identify the underlying reasons for the results, but Villarini said that the volcanic emissions and flood patterns are likely linked via the Inter-tropical Convergence Zone (ITCZ), a band of strengthened precipitation where Earth's trade winds meet.

“If we can make useful predictions about changes in rainfall and changes in streamflow, that can have a real-world impact.”

Gases from volcanic eruptions, especially sulfur dioxide, oxidize to form tiny particles that scatter sunlight, cooling Earth's surface and creating a temperature differential that pushes the ITCZ away from the hemisphere containing the plume. This shift in the ITCZ likely pushes moisture-laden air into the opposite hemisphere, contributing to increased flooding, Villarini said.

Toohey said the results are a step toward being able to predict the potential for unusual flooding or drought across broad areas after a volcanic eruption. “It's important that we keep working in order to understand these processes better, to be able to make better predictions on a finer scale,” he said.

“If we can make useful predictions about changes in rainfall and changes in streamflow, that can have a real-world impact,” Toohey said.

Villarini said understanding the long-term, secondary impacts of volcanic eruptions also has implications for potential geoengineering efforts. Volcanic eruptions scatter aerosols in much the same way that efforts to cool Earth's atmosphere via aerosols would. Possible changes to flood patterns would need to be considered by any aerosol engineering efforts, he said.

By **Grace van Deelen** (@gvd.bsky.social), Staff Writer

What Makes Beaver Ponds Bigger?



Beaver researchers (bottom left) in their natural habitat explore a beaver pond complex in Happy Jack Recreation Area in Wyoming. Credit: Emily Fairfax

In recent years, the North American beaver (*Castor canadensis*) has been increasingly recognized as a valuable on-site engineer that can help communities meet water management goals. Beavers are famously “eager” to build dams, which slow the flow of streams and allow wetland areas to grow.

Until now, however, land managers didn't have a way to estimate how much water beaver reintroduction could actually bring to a habitat. Not every beaver dam results in a sprawling ponded complex; sometimes they result in smaller areas with less water retention than meets the needs of the community.

In a study published in *Communications Earth and Environment*, researchers from Stanford University and the University of Minnesota were able to link the amount of surface water in beaver ponds across the western United States to the features in those landscapes that make beaver ponds bigger (bit.ly/bigger-beaver-ponds).

Big, Beautiful...Beaver Ponds

Beavers often chain together multiple dams and ponds to form beaver pond complexes.

The complexes increase an area's water retention, decrease water temperatures, and provide natural firebreaks. These wetland habitats also give the semiaquatic rodents ample room to roam and allow other species (such as amphibians, fish, and aquatic insects) to flourish.

The advantages of beaver pond complexes aren't going unnoticed—the reintroduction of beavers to the North American landscape is an increasingly popular strategy for land managers looking to naturally improve a waterway.

“Managers need to know where beaver activity—or beaver-like restoration—will store the most water and maximize the environmental benefits, such as providing cooling and enhancing habitat quality,” said Luwen Wan, a postdoctoral scholar at Stanford and the new study's lead author. “Our models highlight the landscape settings where ponds grow largest, helping target nature-based solutions under climate stress.”

While improving water retention is a goal of many watershed management projects, especially in the increasingly drought-prone western United States, the researchers also

emphasized that creating the largest possible ponds isn't the right solution for every area.

"Bigger ponds are not always better," said Emily Fairfax, a coauthor of the study and an assistant professor at the University of Minnesota. Fairfax explained that larger ponds are great when the goal of the project involves water retention, but smaller ponds could be a better fit for a project in which the goals are pollution removal or increasing biodiversity. "It's worth thinking about what we are actually asking of these beavers. And is that reasonable?"

"Our models highlight the landscape settings where ponds grow largest, helping target nature-based solutions under climate stress."

How to Design a Dream Stream

Speaking on the main findings of the study, Wan said that she and her colleagues "found a clear link between the total length of beaver dams and the size of the ponds they create." In addition, they observed that the biggest ponds were found "where dams are longer, stream power is lower to moderate, and woody vegetation is of moderate [6–23 feet, or 2–7 meters] height."

Included in the study were 87 beaver pond complexes across the western United States, encompassing almost 2,000 dams. Using high-resolution aerial imagery from the National Agriculture Imagery Program (NAIP), the team connected the observed ponded area to different landscape measurements like soil characteristics, stream slope, and vegetation metrics.

The researchers chose NAIP imagery for its high spatial resolution and ability to cover large areas (visiting every beaver pond in the field would take too much time). Wan noted that although NAIP aerial imagery was the right fit for this project, it isn't perfectly beaver proof. The imagery is updated every 2–3 years during the growing season, which may introduce some errors, like missing ponds even when dams have already been constructed.

Using remote sensing to predict where beaver reintroduction would be a successful match to the needs of a watershed isn't a new idea. One frequently used model mentioned in the study is the Beaver Restoration Assessment Tool (BRAT). BRAT allows researchers to identify how many dams a given stream would likely be able to host. "That's really important information to have," said Fairfax, "but that doesn't tell us how big the dams are, or how much water they could be storing."

When Beavers Aren't Best

Findings from this study will also be helpful when selecting sites for beaver dam analogues (BDAs). These human-made structures are alternatives to beaver reintroduction that mimic beaver dams to achieve the same ecosystem benefits the beavers would bring. They are often the right tool when a waterway is too degraded to host a beaver population.

BDAs raise water levels and allow the preferred foods of beavers (such as willows and alders) to take root, giving "a little push" to the process of reestablishing a beaver population, explained fluvial geomorphologist and associate professor Lina Polvi Sjöberg of Umeå University in Sweden. Polvi Sjöberg was not involved in the new study.

Fairfax added that BDAs are a useful tool but are not equivalent to actual beaver dams. With beaver dams, a living animal is always present, so land managers can count on the "maintenance staff on-site" to constantly update and monitor the waterway.

The Beavers Are Back in Town

North American beaver populations are still on the rebound from a long history of trapping and habitat loss that came with European colonization of the continent. "We are at maybe 10% of the historic population, and we actually don't know if it's still growing," Fairfax said. Modern threats to beaver populations include highways and artificial dams, she added, which prevent beavers from freely moving to places they once inhabited.

Not everyone is quick to welcome North America's largest rodent back to their neighborhood with open arms. Though public perceptions of beavers are shifting from pest to watershed management partner, the potential for contention still remains. Beavers occasionally build their dams in less-than-ideal locations, a situation that can result in flooded private properties and damaged infrastructure. The study noted that

human influence (like trapping and land use conflicts) is a factor that land managers must consider but is not captured in statistical models.

"It's worth thinking about what we are actually asking of these beavers. And is that reasonable?"

Beavers Worldwide

The researchers found what makes beaver dams bigger in the western United States, but scientists have said it will be important to replicate this study in different regions of North America, especially as beaver habitat expands northward as a result of climate warming.

"North American beavers are all one species, *Castor canadensis*. A beaver in Arizona is the same species as a beaver in Alaska. They all have the same instincts," said Fairfax, "but beavers also do learn and adapt to their environments pretty strongly."

She added that beavers will make use of the materials available to them, such as a colony in Yukon, Canada, that has been observed using rocks as dam-building material. "Whenever we build a model that describes what beavers are doing, there is a chance that it's going to have a strong geo-spatial component to it," Fairfax said.

Polvi Sjöberg agreed, stating that she hadn't seen many studies using remote sensing methods to estimate the suitability of a stream for beaver reintroduction outside of the western United States. Putting things into a wider perspective, she added that some defining features of the American West, like the semiarid climate and large expanses of undeveloped public land, aren't applicable to other regions of the world.

In an email, Wan said the next steps from this study include further exploring beavers' ponded complexes across larger areas and "quantifying the ecosystem services these ponds provide, such as enhancing drought resilience."

By **Mack Baysinger** (@mack-baysinger.bsky.social), Science Writer

Cyclones Affect Heart Health for Months After They Subside

After a tropical cyclone passes through an area, governments take stock of the damage. NOAA, for instance, lists the costs associated with damaged buildings and roads and reports any injuries or deaths attributed to the storm.

However, research suggests that storms can also have hidden, long-term consequences for human health.

In a new study published in *Science Advances*, scientists report that cyclones, also known as hurricanes and typhoons, produce a significant uptick in hospitalizations due to cardiovascular disease for months after they subside (bit.ly/cyclone-health). In addition, the potential at-risk populations are growing as a result of climate change intensifying cyclones and driving them into temperate regions such as Canada and New Zealand.

“This research supports the historically overlooked indirect health risk and burden of tropical cyclones.”

“This research supports the historically overlooked indirect health risk and burden of tropical cyclones and suggests the need for extending public health interventions and disaster preparedness beyond the immediate cyclone aftermath,” said Wenzhong Huang, an environmental epidemiologist at Monash University in Australia and the lead author of the new study.

Heart Problems Spike After Storms

Previous studies have examined possible connections between cardiovascular disease and cyclones, but most have focused on a single health center and single storm in the United States.

“For our study, we encompassed multiple tropical cyclone events across decades and across multiple countries and territories with diverse socioeconomic contexts,” Huang said. “We also analyzed much longer post cyclone periods.”

The researchers tracked cardiovascular disease–related hospitalizations of more than 6.5 million people across Canada, New Zealand, South Korea, Taiwan, Thailand, and Vietnam from 2000 to 2019. They identified 179 locations that experienced cyclones and documented how many days storms hit each area. The team then examined hospital records to see whether more people were admitted for heart problems after cyclones, tracking patients for up to a year after each storm.

The results revealed that hospitalizations associated with heart health jumped by 13% for every additional day a location was hit by a cyclone. The biggest spike in hospitalizations didn’t occur immediately after the cyclones but, rather, came 2 months after they passed, and the increased risk of hospitalization didn’t subside until 6 months later.

“I didn’t expect that the risk would persist that long,” Huang said.

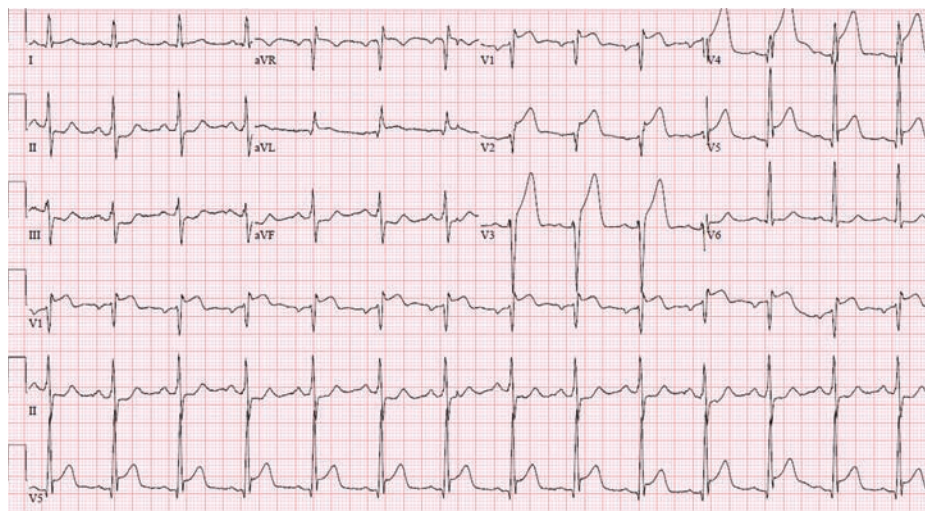
The health burden also fell unevenly across populations. Men, people in their 20s through 50s, and those in disadvantaged communities had the highest risk. In fact, cardiovascular risks after cyclones fell during the study period in wealthier areas while rising in poorer areas. This result suggests that improved health care access and disaster preparedness have benefited only some populations, with Thailand and Vietnam seeing the most cyclone-related heart problems. In total, strokes and ischemic heart disease

(in which blood vessels supplying the heart are narrowed) were the most common maladies reported.

Naresh Kumar, an environmental health scientist at the University of Miami who studies the health effects of cyclones but was not involved in the new study, was not surprised by the findings. According to his own extensive research on hurricanes in Florida and Puerto Rico, “there is not a single disease that’s not touched upon by hurricanes,” Kumar said.

“I didn’t expect that the risk would persist that long.”

But he would have liked the authors of the new study to narrow down the mechanisms driving up cardiovascular health risk after cyclones. The possible causes are abundant. In the months following a cyclone, people increase their use of generators, which produce pollutants; eat more calorie-dense canned foods; can’t exercise or access prescription medicines as easily; and are under immense psychological stress—all of which can increase their risk of cardiovascular dis-



This is what a heart attack looks like. Heart health risks peak 2 months following a hurricane and don’t return to normal until after 6 months. Credit: Coutinho et al., 2018, <https://doi.org/10.7759/cureus.2523>, CC-BY 3.0 (bit.ly/ccby3-0)

ease. Meanwhile, regular health care services are often disrupted, so preventive care is limited.

Understanding these mechanisms is critical because current disaster response systems vastly underestimate the health burden of tropical storms, researchers have said. “We are still scratching the surface in terms of characterizing the health effects of hurricanes,” Kumar said.

“There is not a single disease that’s not touched upon by hurricanes.”

Huang said untangling the most significant contributors to increased risk following a cyclone is the next phase of his research. “I want to understand and investigate the candidates underlying this risk pattern,” he said.

As part of this process, Huang also aims to identify the reasons behind the elevated risk in some populations, such as working-age men. The research could help public health officials target interventions to high-risk populations and monitor cardiovascular health in the months following cyclones.

The Worsening Exposure to Storms

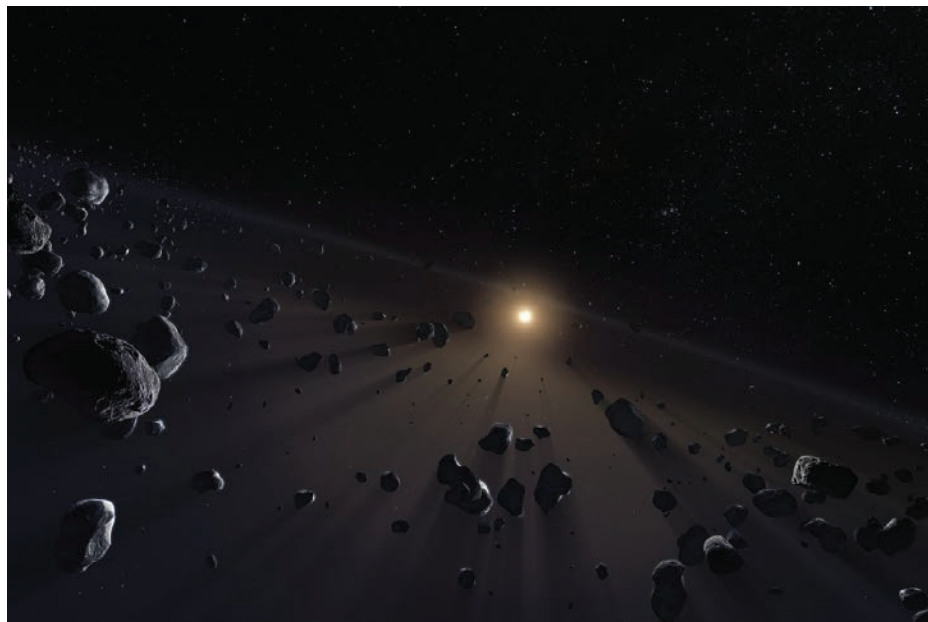
Answering the question of why more people suffer from heart problems after cyclones is becoming increasingly important to policymakers as more communities come under threat. Warmer oceans are fueling more intense storms with higher wind speeds and longer durations, while rising sea levels worsen storm surge flooding that can prolong recovery.

Climate change is also pushing tropical cyclones poleward into regions that have historically experienced few severe storms, such as eastern Canada and New Zealand.

“Places that historically experienced fewer cyclone events could have much higher risk,” Huang said, suggesting that such regions may be inadequately equipped to respond to major storms. “We need to focus on these regions to better prepare for the growing risk.”

By **Andrew Chapman** (@andrewchapman.bsky.social), Science Writer

A Survey of the Kuiper Belt Hints at an Unseen Planet



The Kuiper Belt is home to rocky, icy bodies left over from the formation of the solar system. Credit: ESO/M. Kornmesser, CC BY 4.0 (bit.ly/ccby4-0)

Scientists think they’ve uncovered evidence of a new planet, the first to be discovered in nearly 2 centuries.

Following an analysis of the orbits of bodies in the Kuiper Belt, a team has proposed that an unseen planet at least 25 times more massive than Pluto might reside there. These results were published in *Monthly Notices of the Royal Astronomical Society* (bit.ly/Kuiper-Belt-Planet).

The Kuiper Belt is a doughnut-shaped swath of space beginning just beyond the orbit of Neptune and extending to roughly 1,000 times the Earth–Sun distance. It’s home to untold numbers of icy, rocky objects, including Pluto and other so-called Kuiper Belt objects such as Arrokoth.

Everything in the Kuiper Belt can be thought of as cosmic debris, said Amir Siraj, an astrophysicist at Princeton University and the lead author of the new paper. “It represents some of the leftovers from the formation of our solar system.”

And most of those leftovers are small: Pluto is the most massive known Kuiper Belt object, and it’s just 0.2% the mass of Earth.

But over the past decade, scientists have hypothesized that something substan-

tially larger than Pluto might be lurking in the Kuiper Belt. Evidence of that unseen world—a so-called Planet Nine or Planet X—lies in the fact that six Kuiper Belt objects share curiously similar orbital parameters and are associated in physical space. A nearby, larger planet could have shepherded those bodies into alignment, researchers have proposed.

“Neptune has a really strong grasp on the outer solar system.”

Planes, Planes, Everywhere

Siraj and his colleagues recently took a different tack to look for a massive resident of the Kuiper Belt: They analyzed a much larger sample of Kuiper Belt objects and focused on their orbital planes. One might expect the average orbital plane of Kuiper Belt objects to be the same as the average orbital

plane of the planets in the solar system, said Siraj. But a planet-mass body in the Kuiper Belt would exert a strong enough gravitational tug on its neighboring Kuiper Belt objects to alter measurably the average orbital plane of the Kuiper Belt, at least in the vicinity of the planet. Siraj and his collaborators set out to see whether they could spot such a signal.

“This is really expected to be a game changer for research on the outer solar system.”

The researchers extracted information about the orbits of more than 150 Kuiper Belt objects from the JPL Small-Body Database managed by NASA’s Jet Propulsion Laboratory in Pasadena, Calif. Of the several thousand known Kuiper Belt objects, the team homed in on that subset because those objects aren’t gravitationally influenced by Neptune. Neptune is the playground bully of the outer solar system, and the orbits of many Kuiper Belt objects are believed to be literally shoved around by gravitational interactions with this ice giant. “Neptune has a really strong grasp on the outer solar system,” said Siraj.

The researchers calculated the average orbital plane of their sample of Kuiper Belt objects. At distances of 50–80 times the Earth–Sun distance, they recovered a plane consistent with that of the inner solar system. But farther out, at distances of 80–200 times the Earth–Sun distance, they found that their sample of Kuiper Belt objects formed a plane that was warped relative to that of the inner solar system. There was only a roughly 4% probability that that signal was spurious, they calculated.

Meet Planet Y

Siraj and his collaborators then modeled how planets of different masses at various orbital distances from the Sun would affect a simulated set of Kuiper Belt objects. “We tried all sorts of planets,” said Siraj.

By comparing those model results with the observational data, the researchers deduced that a planet 25–450 times more massive than Pluto with a semimajor axis in the range of 100–200 times the Earth–Sun distance was the most likely culprit.

There’s a fair bit of uncertainty in those numbers, but the team’s results make sense, said Kat Volk, a planetary scientist at the Planetary Science Institute in Tucson, Ariz., not involved in the research. “They did a pretty good job of bracketing what kind of object could be causing this signal.”

To differentiate their putative planet from Planet X, Siraj and his colleagues suggested a new name: Planet Y. It’s important to note that these two worlds, if they even exist, aren’t one and the same, said Siraj. “Planet X

refers to a distant, high-mass planet, while Planet Y denotes a closer-in, lower-mass planet.”

There’s hope that Planet Y will soon get its close-up. The Legacy Survey of Space and Time (LSST)—a 10-year survey of the night sky that will be conducted by the Vera C. Rubin Observatory in Chile—will be supremely good at detecting Kuiper Belt objects, said Volk, who is a member of the LSST Solar System Science Collaboration. “We’re going to be increasing the number of known objects by something like a factor of 5–10.”

It’s entirely possible that Planet Y itself could be spotted, said Volk. But even if it isn’t, simply observing so many more Kuiper Belt objects will better reveal the average orbital plane of the Kuiper Belt. That will, in turn, shed light on whether it’s necessary to think about a Planet Y at all.

Even if his team’s hypothesis is proven wrong, Siraj says he’s looking forward to the start of the LSST and its firehose of astronomical data. “This is really expected to be a game changer for research on the outer solar system.”

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

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Call for Continental Scientific Drilling Proposals

The International Continental Scientific Drilling Program (ICDP) invites proposals for innovative drilling projects that address Earth’s history and global challenges.

Supported by 21 member countries and UNESCO, ICDP provides a platform to investigate key scientific and societal questions across its four core themes: Geodynamic Processes, Geohazards, Georesources, and Environmental Change. Proposals will be evaluated on scientific quality, global relevance, technical and financial feasibility, as well as inclusivity and contributions from early-career researchers.

ICDP applies a co-funding model, typically providing 5–70% of project costs. Since inception, ICDP has invested about US\$ 60 million in more than 60 projects, leveraging over US\$ 240 million from national agencies and other partners. Projects must align with the **ICDP Science Plan** and may also include land-sea drilling in cooperation with IODP.

The proposal system includes **Pre-Proposals**, **Workshop Proposals**, and **Full Proposals**, with the recent addition of the **Fast-track Full Proposal**.

The new Fast-track option allows researchers to bypass earlier stages in order to respond quickly to exceptional, high-impact opportunities requiring immediate support. Updated guidelines are available for resubmitting Pre-Proposals, and dedicated information can be found for geothermal and lacustrine drilling projects.

Proposals must be submitted by **January 15, 2026** to proposal.submission@icdp-online.org. The call is open to Principal Investigators from ICDP member countries, with international collaboration strongly encouraged. Member countries include Australia, Austria, Belgium, China, Estonia, Finland, France, Germany, Iceland, India, Italy, Japan, Netherlands, New Zealand, Norway, South Africa, Spain, Sweden, Switzerland, the United Kingdom, and the United States.

Further details, guidelines, and a video on proposal preparation are available on the ICDP website: www.icdp-online.org/proposals

Nitrogen Needs Could Be Limiting Nature's Carbon Capacity



Red nodules on the roots of an alder tree in Oregon are the result of nitrogen-fixing bacteria. Credit: Steven Perakis

Plants use nitrogen to produce proteins, enzymes, and chlorophyll, all necessary components to perform photosynthesis, in which plants remove carbon from the atmosphere and store it in their leaves, roots, and soil.

However, though the atmosphere is made up of more than 78% nitrogen, the element is unusable for plants in its natural form. Tiny microorganisms called diazotrophs are responsible for “fixing” nitrogen into a form that plants can absorb and use. Diazotrophs live in the soil and in living and decaying plants, creating important partnerships with both naturally growing vegetation and agricultural crops.

Because plants need nitrogen to grow and remove carbon from the atmosphere, understanding the global distribution of biological nitrogen fixation (BNF) is crucial for building accurate climate models.

A new study in *Nature* makes a surprising update to global BNF estimates: Forests, grasslands, and other natural areas may have access to between a quarter and two thirds less biologically fixed nitrogen than previously thought (bit.ly/global-nitrogen). In previous studies, most field measurements of BNF in natural settings were taken from

locations such as tropical forests, where nitrogen-fixing organisms are 17 times more abundant than the global average, creating an overestimation of nitrogen availability. This new work, coauthored by a team of 24 international scientists, examines a broader range of ecosystem types and provides a more detailed picture of the global distribution of nitrogen fixation.

Modernized Mapping

A group of researchers, many of whom are involved in the new study, first published a paper on how to model BNF in 1999, explained lead author Carla Reis Ely, an ecosystem ecologist at the Oak Ridge Institute for Science and Education (bit.ly/BNF-modeling). “But they knew that there were some issues, particularly with data on the abundance of nitrogen fixers, that needed to be addressed.”

The scientists involved with the updated project started by reviewing a compilation of field measurements and distribution data on BNF across natural ecosystems. They found that the sampling bias in past research had produced an overestimation of global nitrogen availability.

Reis Ely said “it makes sense” that scientists hoping to measure BNF would do

their research in places where they know BNF is occurring. “It’s very hard to propose a project where scientists were going to go to a place to measure nitrogen fixation where they know nitrogen fixation is not happening.”

They compiled more than 1,100 existing measurements of BNF rates from natural field sites, ranging from tropical forests to the Arctic. In doing so, they aimed to build a much larger and more representative dataset on how common nitrogen-fixing organisms and their hosts (such as shrubs and mosses) are across various regions and ecosystems. Once they had gathered and organized the measurements of BNF rates from specific sites, they upscaled those rates to estimate and map global nitrogen fixation rates for each of Earth’s biomes.

According to the study’s findings, the amount of nitrogen fixation by microbes in natural environments is approximately 25 million tons lower than previously estimated.

From Forests to Farms—and Beyond

According to the study’s findings, the amount of nitrogen fixation by microbes in natural environments is approximately 25 million tons lower than previously estimated—the equivalent of 113 fully loaded cargo ships. Most of it occurs in tropical forests and drylands, but Reis Ely noted that soils, biocrusts, mosses, and lichens also conduct high amounts of nitrogen fixation.

Though naturally occurring nitrogen fixation is lower than previous estimates, agriculturally based nitrogen fixation has actually been underestimated, the researchers discovered after sorting through thousands of measurements of agricultural BNF. When natural and agricultural datasets were combined, “we found both lower natural nitro-

gen fixation and higher agricultural nitrogen fixation than prior estimates, [indicating] an increasing human signal on this essential process worldwide,” said Steven Perakis, an ecologist with the U.S. Geological Survey at the Forest and Rangeland Ecosystem Science Center and one of the study’s authors.

Crops like soybeans and alfalfa host bacteria that are fixing much more nitrogen than the natural systems that they replaced were fixing. Even though agricultural nitrogen-fixing crops cover only 6% of Earth’s land, they have boosted global nitrogen fixation by 64% since preindustrial levels.

This increase comes with pros and cons: Nitrogen-fixing crops can help feed Earth’s growing population, and they tend to be more eco-friendly than crops requiring chemical fertilizers. But too much nitrogen can upset the nutrient balance in soils and threaten biodiversity by feeding the growth of invasive plants. Further, excess nitrogen can be converted into the greenhouse gas nitrous oxide, and runoff from these soils can leach into groundwater and cause algal blooms.

“Less nitrogen fixation in natural areas could mean reduced capacity [for plants] to uptake carbon from the atmosphere and help mitigate climate change,” Reis Ely said. “On the other hand, if we underestimate how much agricultural nitrogen fixation is happening, we are also underestimating how much excess nitrogen we are adding to natural environments.”

Understanding this balance has implications for estimating nitrogen needs in agriculture as well as for how forests grow and store carbon as carbon dioxide levels rise. “It’s a Goldilocks sort of thing. You want just enough, but not too much, for healthy functioning of ecosystems,” said Eric Davidson, a biogeochemist at the University of Maryland Center for Environmental Science who was not involved in the study.

With this new dataset, researchers can now update their models, which may have been under- or overestimating the nitrogen fixation occurring in natural and agricultural settings. Correct estimates can factor into plans for mitigating climate change. “Could these numbers, these global estimates, change in the future?” Davidson said. “Yes, they could with better understanding. But for the time being, it would appear that this is a significant improvement.”

By **Rebecca Owen** (@beccapox.bsky.social), Science Writer

Bridging Old and New Gravity Data Adds 10 Years to Sea Level Record

As climate change accelerates, it’s more important than ever to understand the individual drivers of sea level rise, from land subsidence and coastal erosion to changes in ocean volume.

For the past 20 years, scientists have had access to high-resolution, satellite-derived maps of Earth’s gravity field, which allows them to calculate fluctuations in global ocean mass.

Recently, geodesists have found a way to extend that record back 10 more years, significantly extending the time frame by which they can consistently measure global ocean mass change.

“This is the first observation-based global ocean mass time series” from 1993 to the present, said Jianli Chen, a geodesy researcher at Hong Kong Polytechnic University in China and a coauthor on the research.

By reconciling older and newer techniques for measuring ocean mass change, the team’s work improves calculations of long-term trends and provides a potential stopgap should satellite data no longer be available.

Shooting Lasers into Space

When scientists measure sea level rise, they consider two main components: how much the ocean’s volume has grown because of changes in water density, which is the ste-

ric component, and how much it has grown because it has gained mass from melted ice, which is the barystatic component.

Past estimates of total ocean mass change have relied on indirect methods like adding up mass loss from ice sheets, glaciers, and land water storage, explained Yufeng Nie, a geodesy researcher also at Hong Kong Polytechnic University and lead researcher on the new study. Mass lost from these areas is assumed to translate to an increase in ocean mass.

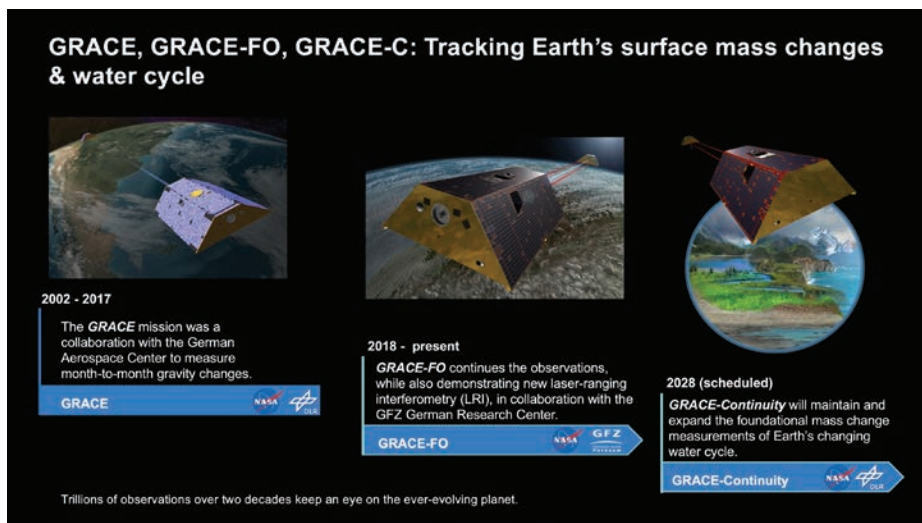
“But these individual estimates are not necessarily consistent, because they are developed by different groups” with different methodologies, Nie said.

In light of this, some researchers adapted satellite laser ranging (SLR), a technique in which scientists bounce ground-based lasers off orbiting satellites to track changes in ocean mass. SLR has been used for decades to measure Earth’s nonuniform gravity field by observing shifts in satellite orbits. A satellite’s altitude depends on Earth’s gravity at any given point on its surface, and gravity in turn depends on the distribution of mass beneath that point. Measuring satellite altitudes thus provides a window into measuring ocean mass changes.

However, one key drawback to using SLR to measure barystatic sea level (BSL) change is that it can measure changes only on very



The European Space Agency’s (ESA) Izaña-1 laser ranging station at Teide Observatory in Tenerife, Spain, sends a green laser into space to detect, track, and observe active satellites. Credit: ESA



The GRACE missions are designed to measure minute changes in Earth's gravity at high spatial resolution. However, there was a coverage gap between the end of GRACE and the start of GRACE-FO, and there may be a similar gap between GRACE-FO and GRACE-C. Credit: NASA/JPL-Caltech, Public Domain

large spatial scales, which limits its application in climate research, Chen said.

"How can you observe, for example, ocean mass change from Antarctic melting using a technique with 4,000-kilometer spatial resolution?" asked Chen.

Enter NASA's Gravity Recovery and Climate Experiment (GRACE) missions. GRACE and its successor, GRACE Follow-On (GRACE-FO), each consisted of two satellites chasing each other along the same orbit, continuously sending laser beams back and forth. Like SLR, this process allowed the GRACE missions to provide maps of Earth's surface mass, but at 10 times the resolution of SLR. And like with SLR, scientists have used GRACE gravity maps to track global ocean mass change.

But GRACE data, too, have their caveats. The first GRACE mission spanned 2002–2017, and GRACE-FO has spanned from 2018 to the present, a short time for understanding long-term trends. What's more, the 11-month gap between GRACE and its successor meant that scientists were not able to calibrate the two satellites with each other, leaving some uncertainty about systemic differences between the missions.

A Near-Perfect Match

Nie, Chen, and their team were able to address both of these caveats by comparing SLR-based measurements of global ocean mass change with those from GRACE and GRACE-FO for the same time period, 2003–2022.

According to gravity maps provided by SLR, barystatic sea level change was 2.16 millimeters per year from 2003 to 2022, while GRACE and GRACE-FO measured 2.13 millimeters per year.

The new analysis showed that SLR and GRACE and GRACE-FO "agree quite well for the long-term trends," Nie said. What's more, researchers found no significant change in the calculation when the data transitioned from GRACE to GRACE-FO. "This gives us confidence that the SLR data, although it is of very low spatial resolution, can be used to tell us the ocean mass variations before 2002," he added.

The researchers were able to extend the time frame of their analysis back to 1993 by using SLR data, and they calculated a barystatic sea level change of 1.75 millimeters per year for 1993–2022. They attribute the lower rate of sea level rise in the past to recent acceleration of ice loss in Greenland.

"Our SLR measurements...can provide a global constraint of the mass changes for the pre-GRACE era," Nie said.

This study was published in *Proceedings of the National Academy of Sciences of the United States of America* in June (bit.ly/satellite-BSL).

"Extending the record of measured BSL using satellite laser ranging back to 1993 is an important achievement," said Bryant Loomis, chief of the Geodesy and Geophysics Laboratory at NASA's Goddard Space Flight Center in Greenbelt, Md. "It allows the disaggregation of total sea level change,

which is measured by altimetry, into its barystatic and steric components."

"The long-term BSL estimate is also useful for assessing the accuracy of previous efforts to quantify the major land ice contributions to BSL prior to the launch of GRACE," he added, referring to the method of adding together mass changes from glaciers, ice sheets, and land water storage. Loomis was not involved in the new research.

Nie, Chen, and their team are working to push the limits of SLR-derived barystatic sea level measurements to smaller spatial scales and lower uncertainties. They hope to demonstrate that SLR data can be used to measure mass change in Antarctica.

GRACE Continuity?

GRACE-FO launched in 2018 and is 7 years into its nominal 5-year mission. The satellites are in good health, and the nearly identical GRACE mission set a good precedent—it lived for more than 15 years. GRACE-FO might well overlap with its planned successor, GRACE-Continuity (GRACE-C), which is scheduled to launch in 2028.

However, recent woes for federally funded science in the United States have put GRACE-C's future in doubt. Although NASA requested funding for GRACE-C for fiscal year 2026 through the mission's launch, NASA's acting administrator, Sean Duffy, recently stated his, and presumably President Donald Trump's, desire to eliminate all Earth science at the agency (including healthy satellites). That cutback would likely nix GRACE-C.

In the near future, both Europe and China plan to launch satellite-to-satellite laser ranging missions that will provide GRACE-like measurements of Earth's gravity, Chen said. However, the loss of GRACE-quality data would hamper climate scientists' ability to accurately track drivers of sea level rise, he added. The SLR-derived measurements demonstrated in this recent research could help mitigate the loss, but only somewhat.

"There's no way SLR can reach the same [resolution] as GRACE," Chen said. "We can only use SLR to see the long-term, the largest scale, to fill the gap. But for many of GRACE's applications—regional water storage or glacial mass change—no, there's no way SLR can help."

By **Kimberly M. S. Cartier** (@astrokimcartier .bsky.social), Staff Writer

Eight Ways to Encourage Equality, Diversity, and Inclusion Discussions at Conferences

Conferences are key enablers of community building within and outside of academic ecosystems, bringing together groups of individuals with different perspectives, experiences, and backgrounds. They can also provide safe and constructive environments for open discussions of cultural issues important to scientific communities, including those related to equality, diversity, and inclusion (EDI, also known as DEI) [Hauss, 2021; Zierath, 2016].

Such discussions, which likely would not occur on a broad scale outside of meetings [Oester *et al.*, 2017; Barrows *et al.*, 2021], are particularly valuable in geoscience and climate research.

These fields are notably lacking in diversity, and within them, hearing the voices of marginalized groups is crucial for guiding effective evidence-informed public policy [Standing and Lidskog, 2021; Bernard and Cooperdock, 2018; Colquhoun and Fernando, 2020; Dowe *et al.*, 2021]. Involvement in conference EDI programming by a wide swath of the scientific community can also help to ameliorate the academic “minority tax” that often disproportionately burdens scientists from underrepresented groups with the responsibility for driving change.

Many conferences now include EDI-related sessions [e.g., Fiedler and Brittani, 2021]. However, encouraging broad engagement with EDI- and community culture-focused sessions—both those looking inward at academia and those looking outward at how science affects society—at conferences remains a challenge.

On the basis of our experiences organizing these types of sessions and the current literature on best practices, we propose eight changes that organizers and conveners can implement to boost attendance in, engagement with, and useful outputs from such discussions.

These approaches group into three themes: focusing attention on EDI programming, facilitating open and productive discussion, and emphasizing evidence and solutions.

Focusing Attention on EDI Programming

1. *Be thoughtful about scheduling.* A key part of generating wider engagement with EDI sessions is signaling that they are priorities for organizers and all attendees (especially



Participants walk through the poster hall at AGU's Annual Meeting 2024 in Washington, D.C. Credit: AGU

those in leadership roles), rather than ancillary topics of interest only to marginalized groups. Meeting conveners can do this through effective scheduling of EDI sessions, which can enhance attendance and engagement [Burnett *et al.*, 2020].

A key part of generating wider engagement with equality, diversity, and inclusion (EDI) sessions is signaling that they are priorities for organizers and all attendees

Specifically, we advise against holding these sessions at the start or end of a day, when attendance tends to be lowest, especially for those with caregiving responsibilities. Likewise, organizers should be cognizant of how placing these sessions at the very end of conference programs may result in sparse attendance, unintentionally portray the session topics as less valuable to the community, and reduce their effectiveness in influencing change.

Instead, we suggest that conveners schedule EDI-related sessions during the main program alongside prominent scientific programming and use plenary and keynote talks to highlight and support discussions of EDI.

2. *Optimize physical placements.* In addition to careful scheduling of EDI sessions, organizers should consider how to maximize attendees' opportunities to engage with related posters and talks by designating optimal locations for content sharing. EDI-related issues have an advantage over many scientific topics in that they are relevant to all attendees; hence, placing them in central, easily accessible locations where they are more visible can spur additional attention and discussion. Additional suggestions for placing EDI posters include displaying them outside main poster halls (e.g., in reception areas), allowing them to be presented multiple times (e.g., once in an EDI session and once in a science session), and fully integrating them into scientific poster sessions to help normalize conversations around culture in science.

Facilitating Open and Productive Discussion

3. *Create welcoming and respectful spaces.* Considering how personal issues related to EDI can be, it is crucial that conferences establish robust and agreed-upon codes of conduct and norms for related discussions, as well as mechanisms to enforce them if needed

[e.g., Favaro *et al.*, 2016]. Such frameworks help to ensure that conferences are spaces where attendees can present their ideas freely while being accountable for their contributions. The code of conduct and norms should also make clear that reasonable and respectful challenges of ideas (and recognition of how the conduct of these discussions affects others) are encouraged when discussing issues of community culture, in the same way they are in discussions of scientific ideas.

Common terminologies for use within EDI discussions can also help to overcome differences in the meanings of words or concepts among countries and languages [Fernando *et al.*, 2024], which can be especially important at climate and geoscience research conferences, given their international attendance.

Many conferences group all EDI-related contributions into large catchall sessions, which can make it challenging for attendees to identify best practices relating to specific aspects of EDI.

4. *Avoid additional costs for attendees.* Many conferences limit attendees to giving a single oral presentation, which can force them to choose between presenting their science (which often is more highly rewarded in academic systems) or their EDI-related work or experiences. Best practices have been showcased by some organizations, such as AGU, which now allows presenters to contribute two abstracts to its annual meeting. Nonetheless, the cost of submitting an additional abstract to a conference can impose a significant financial constraint on researchers, especially if they must pay for poster printing in cases where only one oral contribution is permitted.

When reviewing EDI- and community-focused abstracts, organizers should consider dispensing with single oral abstract submission rules, waiving fees for these abstracts, or issuing small registration-fee rebates (e.g., \$50) to partially cover poster printing costs.

5. *Group EDI contributions by topic.* EDI encompasses a wide range of specific sub-topics, from school education to inclusion in graduate programs and beyond. However, many conferences group all EDI-related contributions into large catchall sessions, which can make it challenging for attendees to identify best practices relating to specific aspects of EDI.

Organizers should solicit enough EDI contributions that they can group them by theme. Especially at larger conferences, having themes will help organizers reach the critical mass of posters and talks needed to hold parallel sessions focusing on different issues (e.g., one about geoscience education in schools and another about accessible field-work), hence maximizing the potential for useful discussions. The United Kingdom's Royal Astronomical Society, for example, has demonstrated best practices in its larger meetings by soliciting contributions to specifically organized EDI sessions that are integrated into the main conference program but have different focuses (e.g., outreach, supporting students and postdocs).

Emphasizing Evidence and Solutions

6. *Encourage sharing of data and applicable lessons.* A major benefit of conferences is the opportunities they offer to develop new ideas in groups and to identify and optimize existing solutions that can be applied in new settings. Science departments and institutions often run dedicated programs to widen participation, increase diversity, and improve inclusivity. Many of these programs include elements for monitoring and evaluating their success. However, they—and the qualitative and quantitative data they produce—are rarely discussed or presented in conference settings, limiting chances for shared identification of lessons learned and where else such lessons can be applied.

To call attention to the scientific basis behind effective EDI interventions, organizers should explicitly encourage contributions that showcase institutional programs and their evaluations. This encouragement might include asking presenters to share data reflecting how their intervention had positive outcomes or, conversely, why it was ineffective (and what lessons can be learned as a result).

Organizers could also provide guidelines for how to present EDI work and outreach programs such that intervention successes and best practices can be shared clearly and potentially scaled for use in other institutions (e.g., by explicitly addressing issues

of funding, time and added labor costs, and other logistical requirements).

Furthermore, organizers should consider optimal formats for engagement around this information. Standard lecture-style talks, for example, may be less effective than town halls, open discussions, or breakout working groups.

Making an effective case that broad interventions are needed often requires providing quantitative evidence linking individual experiences to systemic and problematic issues.

7. *Encourage presenters to link experience and evidence.* Issues relating to EDI, scientific culture, and the academic community are naturally rooted in individuals' lived experiences, and hence, presentations on these experiences often form a substantial portion of EDI sessions. As powerful as these presentations typically are, making an effective case to scientists and decision-makers (e.g., funding bodies) that broad interventions are needed often requires providing quantitative evidence linking individual experiences to systemic and problematic issues.

Encouraging presenters in EDI sessions to frame their discussions in a scientific light when possible—for example, by presenting a clear synthesis of background literature and an evidence base for the work—can help foster positive reactions and productive decisionmaking for implementing change. Professional associations and conference hosts could, again, provide presenters with best-practices guidelines for discussing EDI topics (e.g., encouraging the use of quantitative evaluation and significance testing), given that many EDI presenters are not social scientists by training.

8. *Provide space and funding for additional community events.* Society and conference leaders should also support their community members and attendees in organizing affiliated EDI-related events that do not fall within the traditional conference programs of talks and posters.

This support could include providing space or other accommodations (e.g., free refreshments) for groups to arrange meetups or social events that encourage community building and a sense of belonging. Or it could entail offering groups the opportunity to add their events to the main conference program, rather than organizing them on the periphery. When possible, support should also be offered for these groups to write and publish summaries of observations and outcomes from their EDI-related sessions—for example, through small grants funding the publication of white papers—to extend the reach and impact of their discussions.

Progressing Toward Greater Engagement

Enacting many of the above suggestions will come with financial, logistical, or workload costs for conference organizers. Waiving or reducing fees for EDI-related abstracts, for example, would reduce revenue and must be balanced against other financial constraints and commitments, such as providing financial support to people who would otherwise be unable to attend.

Nonetheless, some suggestions (e.g., optimizing scheduling and physical placement of sessions and soliciting more EDI-related abstracts) should incur little to no additional financial cost and could be acted upon immediately. Others, such as developing guidelines for effective presentation of EDI talks and posters, will likely require more sustained effort over multiple conference cycles. Outside experts in EDI, for example, from

the diversity committees of professional societies, may be able to help here.

Ideally, conference organizers would adopt all the outlined approaches—and perhaps find additional ways to spotlight and support EDI research and discussions at their events. Considering the many challenges and constraints of conference planning, though, it is important to note that these suggestions for change need not all be acted upon simultaneously. Gradual change, such as tackling the simplest improvements first, still represents progress and should encourage broader engagement in EDI sessions and conversations at scientific conferences.

This engagement is especially vital in the geosciences and climate science, where research often has inherent and significant implications for communities and, hence, where the presence of diverse voices is key to producing effective change.

Acknowledgments

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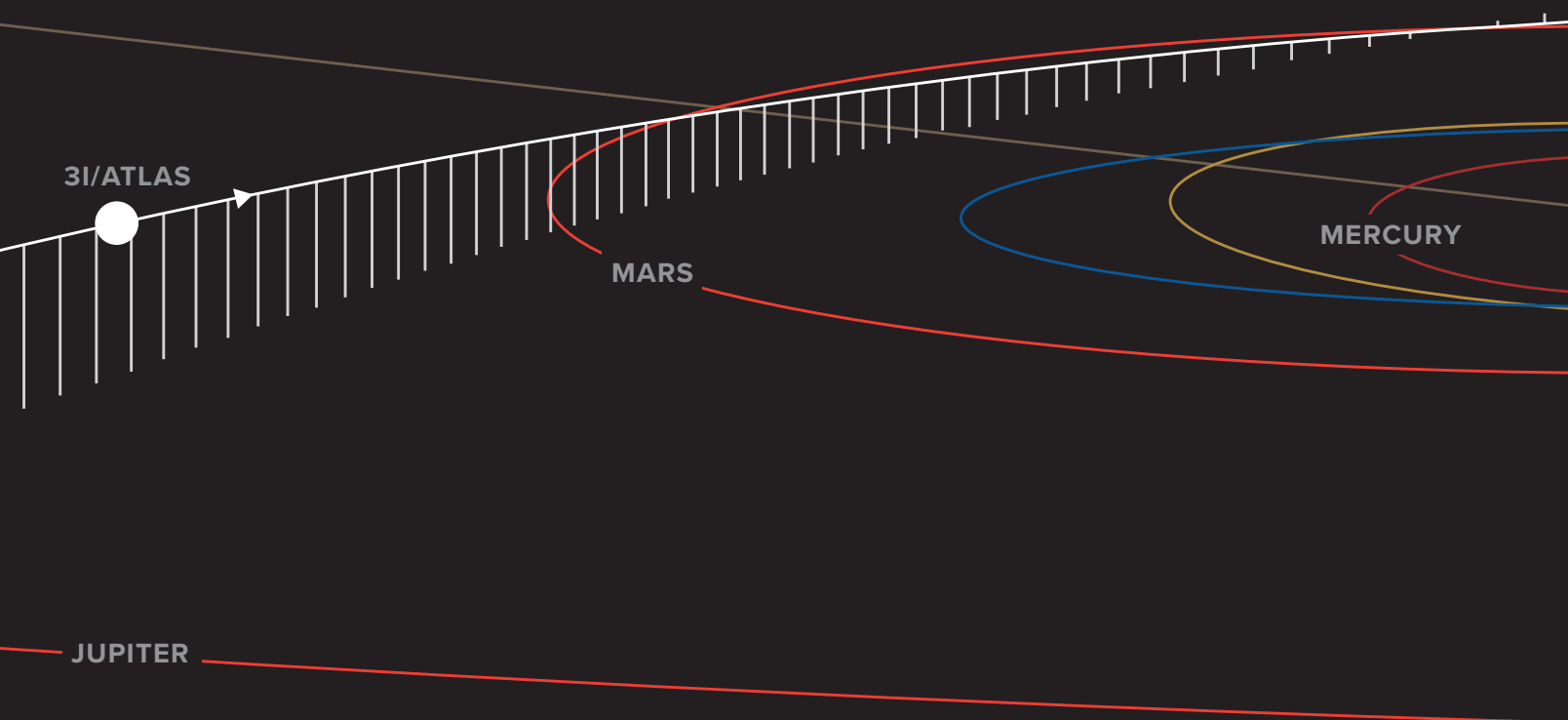
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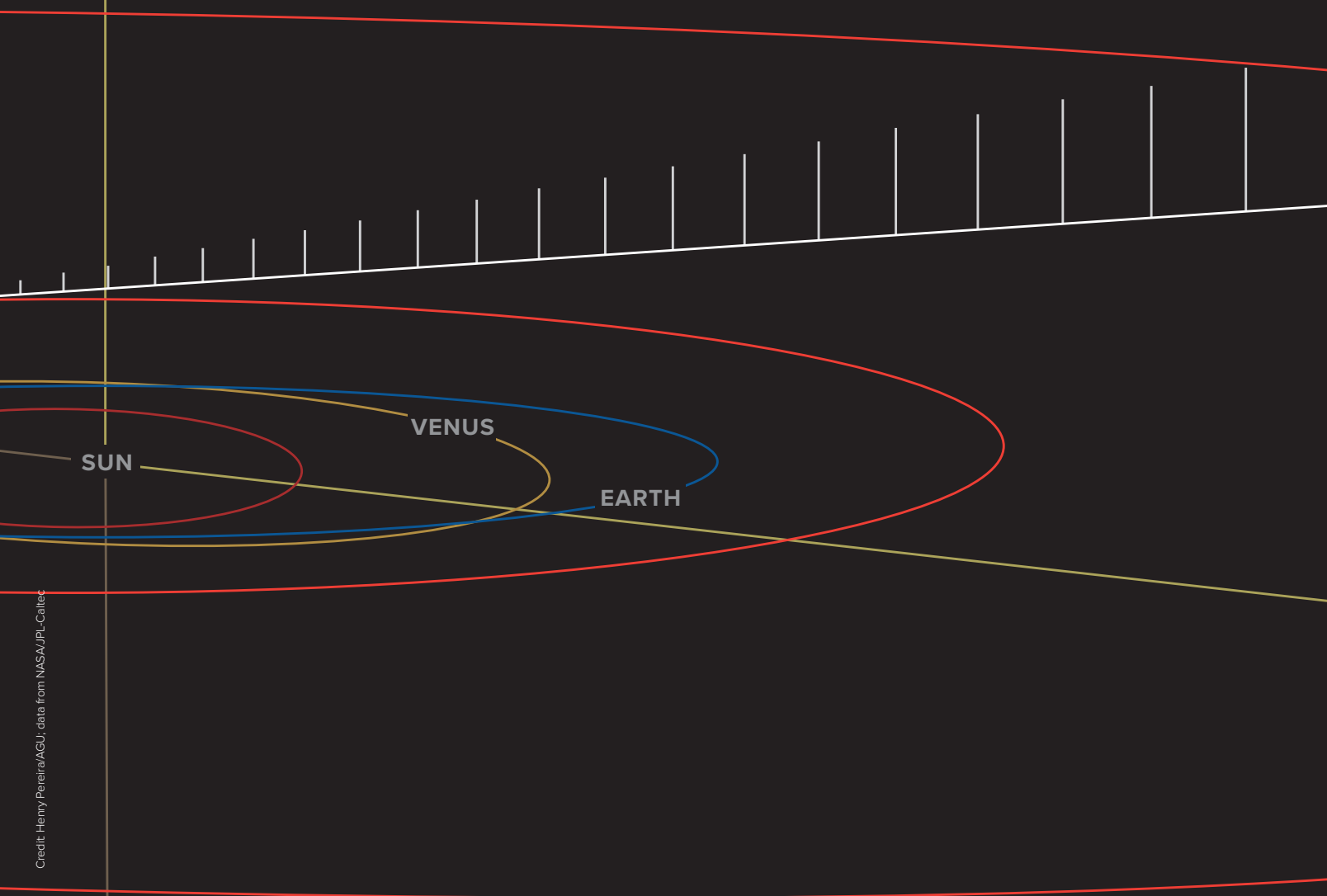
Spurred Astronomers into Action

BY KIMBERLY M. S. CARTIER

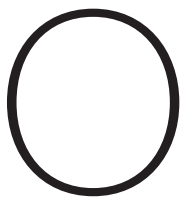


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VALUABLE LESSONS FROM PREVIOUS INTERSTELLAR OBJECTS ALLOWED SCIENTISTS
TO DEVELOP A MORE RAPID RESPONSE WHEN 3I/ATLAS ARRIVED IN JULY.



Credit: Henry Pereira/AGU, data from NASA/JPL-Caltech



n 1 July 2025, astronomers detected a visitor from the deep reaches of space. At the time of discovery, the object was just inside Jupiter's orbit and was zipping across our solar system 4 times faster than the New Horizons probe sped past Pluto. It was first spotted by the Asteroid

Terrestrial-impact Last Alert System (ATLAS) in Chile, which was specifically designed to spot small, fast-moving objects like this. ATLAS sent out a public, automated alert, and when astronomers saw it, they quickly went to work calculating the object's orbit and trajectory.

That's when things got interesting. Backtracking the object's path showed that its origins were not in the Oort cloud, the outermost region of our solar system responsible for most of the comets we see. Instead, the object's journey started a long time ago in a star system far, far away.

The earliest observations of the object—now labeled 3I/ATLAS for being the third confirmed interstellar object (3I)—showed a distinct coma or haze of material surrounding a dense center.

The trajectory of 3I/ATLAS suggests that it will escape the modest gravitational clutches of the Sun in mid-2026, and that time frame has contributed to a flurry of activity among scientists in the emergent field focused on studying interstellar objects (ISOs). Teams of researchers have secured time on some of the most prominent telescopes around the world and in space, combed through telescope archives for "precovery" images, run computer models and simulations, and released nearly three dozen quick-look research papers in astronomy's preferred preprint repository.

"We knew we were going to get a 3I. We didn't know *when* we were going to get a 3I," said Michele Bannister, who researches small solar system objects at the University of Canterbury in Ōtautahi-Christchurch, Aotearoa New Zealand.

The speed of discoveries about this interstellar visitor outpaced efforts made when the first and second interstellar objects were discovered: 1I/'Oumuamua in 2017 and 2I/Borisov in 2019. One ISO

"ASTRONOMERS ARE ALWAYS TRYING TO USE THESE FACILITIES AS EFFICIENTLY AS POSSIBLE."

might be a fluke, and two may be a coincidence, but three seemed inevitable. Astronomers took no chances in preparing for the likely arrival of another interstellar visitor.

Teams' carefully laid plans have borne fruit, enabling rapid-response science, close international collaborations, and a united global effort to learn as much as possible about 3I/ATLAS before it disappears forever.

Planning for 3I

The arrival of 'Oumuamua caught astronomers by surprise. It was the first discovery of its kind and wasn't spotted until it was on its way out of the solar system. Researchers had a mere 2 weeks to get all the data they possibly could, taking their best guesses about what telescopes, instruments, and wavelengths would provide the best data on such short notice.

"IT WAS A VERY COMMUNAL PLANNING PROCESS, WHICH I THINK FOR SCIENCE OFTEN DOESN'T HAPPEN SO QUICK AND ON THE FLY."

When something like 'Oumuamua shows up, "you immediately write what's called a director's discretionary [DD] proposal," explained Karen Meech, a planetary astronomer at the University of Hawai'i's Institute for Astronomy. "You scramble, you write a proposal, you submit it. The [telescope] director reads it and makes a decision without a review panel." Bypassing a review panels speeds up the process but is less democratic.

Having found one ISO, researchers started putting in DD proposals every semester in case another one showed up.

When Borisov appeared 2 years later, it was immediately obvious that it was radically different from 'Oumuamua. The way observations were allotted on telescopes was also different—facilities became overwhelmed with the sheer volume of DD proposals, Meech said. That led to duplicate observations and some teams' observations being bumped entirely when a newer, but identical, proposal came in. Telescopes have since worked out those kinks in the system to streamline the DD proposal process.

Anticipating the inevitable detection of a third interstellar object, many ISO observers took a different approach: target of opportunity (TOO) proposals. TOO is a process commonly used in branches of astronomy that study unpredictable phenomena like supernovas, kilonovas, gravitational waves, and gamma ray bursts. Researchers submit observing proposals for short observations of events that could happen at any time. If the event occurs, the team can trigger those telescope observations.

"Most collaborations, including ours, have preapproved dormant programs at the world's largest telescopes ready to be activated when a suitable [ISO] candidate is confirmed," said Raúl de la Fuente Marcos, who researches small solar system objects at the Universidad Complutense de Madrid in Spain. Before 'Oumuamua, "such a discovery was considered highly unlikely. Now all the collaborations that have been involved in early data releases of 3I/ATLAS have such systems."

“Basically, if you give us more than a semester to plan, we will plan,” Bannister said. “Astronomers are always trying to use these facilities as efficiently as possible.”

De la Fuente Marcos and his team imaged and obtained spectra of 3I/ATLAS with the Gran Telescopio Canarias and the Two-meter Twin Telescope, both in Spain’s Canary Islands. Their observing program was triggered a mere 6 hours after 3I/ATLAS was confirmed as an interstellar object, allowing them to observe the comet from 2 to 5 July. Their results, published in *Astronomy and Astrophysics*, were the first to show that 3I/ATLAS’s spectrum is red and dusty, not too dissimilar from dusty solar system comets.

Teddy Kareta’s observations were more serendipitous. Kareta, a planetary scientist at Villanova University in Pennsylvania, already had time scheduled on the NASA Infrared Telescope Facility (IRTF) for 3 and 4 July. He learned about 3I/ATLAS the evening before his observing run and thought, “That’s too cool to be real,” he recalled.

“And then I woke up to about seven text messages, three missed calls, a dozen emails, most of which were saying, ‘Hey, I noticed you’re on the telescope because I checked the schedule— You’re gonna go out, right?’” Kareta said.

But the comet was coming in much faster than past ISOs and from a direction that made it challenging to observe.

“People were coming up with observational plans on the fly,” Kareta said. “I pointed a 4-meter telescope at it for 2 full hours, and I think I got three useful images.”

There were plenty of emails, group chats, and Zoom calls trying to figure out the best telescope and camera settings.

“It was a very communal planning process, which I think for science often doesn’t happen so quick and on the fly,” Kareta said. “It felt more like a readiness exercise than it did like a traditional kind of planning...you need as many hands on deck as possible to make it work at all.”

Kareta and his colleagues’ infrared spectral observations, accepted for publication in *Astrophysical Journal Letters*, suggest that the comet

may have a complex grain size distribution, grain compositions unlike solar system comets, or both.

A Broad Research Umbrella

By its galaxy-traveling nature, 3I/ATLAS quite literally connects comet science with the study of stars, planetary systems, and the galaxy.



COMET 3I/ATLAS “REALLY DID ARRIVE WITH FANTASTIC TIMING.”

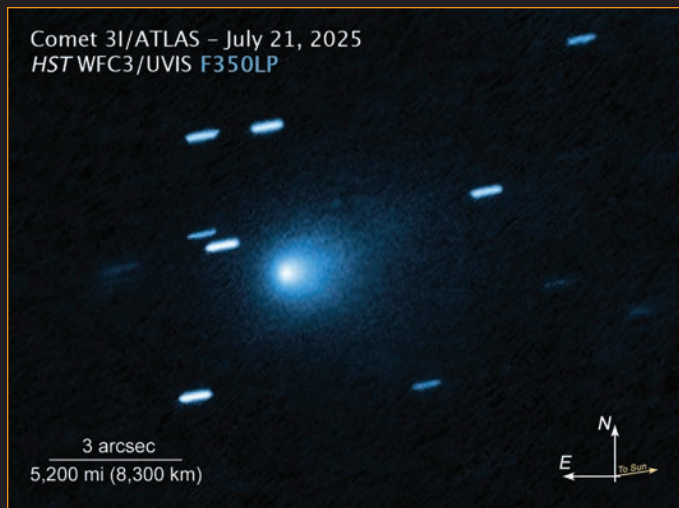


ISO theorists have spent the time since Borisov’s departure working on a computer model that predicts the properties of interstellar objects across the galaxy. They had timed the release of their Ōtautahi-Oxford model for the beginning of science operations of the Vera C. Rubin Observatory and its Legacy Survey of Space and Time (LSST), which is expected to discover dozens of potential interstellar objects.

“We knew that LSST and Rubin were going to find loads, but we just thought this was going to happen in 6 months’ time, not now,” said Matthew Hopkins, who studies both ISOs and galaxy evolution at the University of Oxford in the United Kingdom.



The Gemini South Telescope captured this image of the interstellar comet 3I/ATLAS on 27 August. Credit: International Gemini Observatory/NOIRLab/NSF/AURA/Shadow the Scientist; Image Processing: J. Miller & M. Rodriguez (International Gemini Observatory/NSF NOIRLab), T.A. Rector (University of Alaska Anchorage/NSF NOIRLab), M. Zamani (NSF NOIRLab), CC BY 4.0 (bit.ly/ccby4-0)



Hubble imaged 3I/ATLAS on 21 July. The comet is shedding dust in the direction of the Sun (right) and is haloed by a coma. Background stars are streaked, as the telescope followed the comet's movement. NASA, ESA, D. Jewitt (UCLA); Image Processing: J. DePasquale (STScI), Public Domain

Luckily, the model team, composed of people studying interstellar objects, comets, stars, and galaxy dynamics, was putting the finishing touches on a program that could analyze an ISO's speed and orbital information and predict where in the galaxy it may have come from.



“THERE’LL BE A LOT OF HAPPY ARGUMENTS AROUND ‘WHERE DID THIS FORM IN THE DISK OF ITS HOME STAR, AND WHAT DOES THAT TELL US ABOUT WHAT CONDITIONS WERE LIKE IN THAT PROTOPLANETARY DISK.’”



Comet 3I/ATLAS “really did arrive with fantastic timing,” Hopkins said.

The team jumped into action when the comet’s orbital characteristics were announced. It was detected when it was 670 million kilometers (420 million miles) away, traveling at nearly 60 kilometers per second and coming in at a steep angle. Bannister, part of

Ōtautahi-Oxford’s New Zealand contingent, said that her team was able to share its results so quickly because it had members scattered from western Europe to New Zealand. After working all day, the New Zealanders could hand off the research to European team members, whose day was just starting. By tag teaming the science, they submitted their analysis to *Astrophysical Journal Letters* about 84 hours after the comet’s discovery. (It has since been published.)

“Especially for 3I, given that it was time sensitive, we definitely wanted to share our results as we had them,” Hopkins said.

The Ōtautahi-Oxford model showed that because 3I/ATLAS entered the solar system at a much steeper angle than either ‘Oumuamua or Borisov, it likely came from a different region of the galaxy, a part known as the thick disk. Though most young and middle-aged stars, including the Sun, live in the narrow thin disk of the Milky Way, many older stars live in the thick disk. The trajectory of 3I/ATLAS suggests that it originated from a star system that could be more than 7.6 billion years old. Indeed, its parent star may already be dead.

The age of 3I/ATLAS has intrigued many researchers who study stellar populations, galaxy dynamics, the birth of exoplanetary systems, and astrobiology, fields that are usually disparate and siloed.

“If you’re studying interstellar objects, you’re sitting cleanly at the division between planetary science and traditional astrophysics,” Kareta said. “And I think that means that people from both groups immediately know these are important.”

“Our colleagues who do extragalactic science and supernovae are really excited to help with 3I, and so we’re trying to trigger everything we can on the big telescopes,” Meech said. Her group had been hoping to use the Keck II telescope in Hawaii to obtain high-resolution infrared spectra of the comet, but the telescope had been experiencing technical issues. A student studying kilonovas had TOO time on the nearby James Clerk Maxwell Telescope and donated it.

“He said, ‘You know what, [the kilonova is] not going to go off in the next 2 weeks. Let’s use it for this,’” Meech recalled. “And so we

got five nights of observations on this object.” Meech and her colleagues are still analyzing those data to understand the abundances of certain gases in 3I/ATLAS’s coma.

The Long-Term Strategy

Several weeks after its initial discovery, it is clear that 3I/ATLAS looks and behaves like a comet. It’s now millions of kilometers closer to the Sun than it was upon detection in early July, and more recent observations, including from the Hubble Space Telescope, James Webb Space Telescope, Very Large Telescope, and more, have shown a dusty coma emitted from the Sun-facing side and the beginnings of a traditional comet tail behind it.

Most of the earliest 3I/ATLAS papers are still undergoing peer review, and Kareta said that more research analyzing July observations will continue to trickle out. Groups that wrote early papers will be going back over their data to put them in context with newer information and provide deeper analyses of those initial quick looks.

However, with the early rush of observations mostly completed, some scientists are turning their attention to what they want to learn about 3I/ATLAS in the coming months.

“A lot of teams are still scrambling to get telescope time,” Meech said.

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**“THE LONGER WE HAVE
TO STUDY IT, THAT MEANS MORE
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BRAINS CAN TAKE A CRACK
AT THE PROBLEM AND...LEAVE
THEIR MARK ON THIS OBJECT.”**

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The comet reached its closest point to the sun, a mere 35% farther than the Earth–Sun distance, on 29 October. Earth had lost sight of it in the Sun’s glare in early September, but by mid–August, 3I/ATLAS had already started outgassing, as predicted. Astronomers were eager to analyze the chemistry of the gases it emitted because that could give clues about its history.

“Stellar encounters this close are actually really rare for interstellar objects,” Hopkins said. This is probably 3I/ATLAS’s first encounter with a star since it was booted out of its own system, and its surface material has likely been frozen in time since then. “We can use that to learn some really cool things about the chemistry of its parent star halfway around the galaxy, even if it’s dead.”

Spectra obtained from 3I/ATLAS’s coma in mid–August showed strong signs of water ice, carbon dioxide, nickel, and cyanide—all expected of a comet emitting a mixture of gas and dust as it heats up. “Typically for comets, the first thing you see is CN, cyanide, not

because it’s particularly abundant but because it interacts so strongly with sunlight,” Meech said.

Indeed, scientists are seeing an object not too unlike a domestic comet, and they’ll continue to monitor its outgassing as it gets closer to the Sun.

The outgassing of carbon monoxide would be particularly telling, as the compound freezes solid only in extremely cold conditions like those that exist in the outer reaches of a star system. So if 3I/ATLAS outgasses carbon monoxide, Hopkins explained, it would be a strong hint that the object may have formed in the coldest outer regions of its system’s protoplanetary disk.

“There’ll be a lot of happy arguments around ‘Where did this form in the disk of its home star, and what does that tell us about what conditions were like in that protoplanetary disk,’” Bannister added.

Still, who knows? “These are representative fragments of star formation elsewhere. There’s no reason that every protoplanetary disk has the same chemical distribution,” Meech said.

Every snapshot researchers get from now until 3I/ATLAS’s departure will help them put together a holistic, time series picture of the comet as it heats up and evolves.

All eyes, and telescopes, will be trained on its predicted point of emergence in late November.

Time Enough for Everyone

The biggest advantage that scientists have with 3I/ATLAS that they did not have with 1I/Oumuamua is time—time not only to make more observations and analyses but to enable the widest participation possible.

‘Oumuamua arrived in October, the middle of the academic semester. Scientists who could respond quickly tended to be senior-level researchers, those with fewer teaching responsibilities, and those at institutions with easier access to telescope facilities, Kareta explained. Early-career scientists, those involved with research programs, or those who had inflexible responsibilities were less able to contribute to the groundbreaking discovery in the two-ish weeks before the object disappeared.

With 2I/Borisov and now with 3I/ATLAS, a monthslong observation window has enabled a larger, more diverse group of scientists from around the world to participate in observing, analyzing, and discussing this discovery.

“The longer we have to study it, that means more people can work on it, more brains can take a crack at the problem and...leave their mark on this object,” Kareta said.

And that can be only a positive thing for this nascent, but growing, field of science.

“We’re 7 years into this field of small-body galactic studies,” Bannister said. “There’s a whole different generation of people coming into this than were involved in 1I and even 2I. That’s really exciting to see.”

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Read the article at [Eos.org](https://www.eos.org)





A NOAA WP-3D Orion Hurricane Hunter aircraft captured this image from within the eye of Hurricane Katrina in 2005. In the 20 years since, hurricane forecasting technology has grown more sophisticated. Credit: PBH/Alamy Stock Photo



HOW RESEARCHERS HAVE STUDIED **THE WHERE, WHEN, AND EYE OF HURRICANES SINCE KATRINA**

Twenty years after one of the country's deadliest storms, scientists reflect on improvements in the ability to understand and predict disasters.

By Emily Gardner

On 28 August 2005, New Orleans area residents received a bulletin from the National Weather Service (NWS) office in Slidell, La., warning them of “a most powerful hurricane with unprecedented strength.” One excerpt of the chilling announcement, issued via NOAA radio and the Federal Communications Commission’s Emergency Alert Service, read,

BLOWN DEBRIS WILL CREATE
ADDITIONAL DESTRUCTION. PERSONS...
PETS...AND LIVESTOCK EXPOSED TO
THE WINDS WILL FACE CERTAIN
DEATH IF STRUCK.

POWER OUTAGES WILL LAST FOR
WEEKS...AS MOST POWER POLES WILL
BE DOWN AND TRANSFORMERS
DESTROYED. WATER SHORTAGES WILL
MAKE HUMAN SUFFERING INCREDIBLE
BY MODERN STANDARDS.

Hurricane Katrina, which caused 1,833 fatalities and about \$108 billion in damage (more than \$178 billion in 2025 dollars), remains the costliest—and among the top five deadliest—hurricane on record to hit the United States.

In the 20 years since the hurricane, meteorologists, modelers, computer scientists, and other experts have worked to improve the hurricane forecasting capabilities that inform bulletins like that one.

Consider the forecast cone. Also known as the cone of uncertainty, this visualization outlines the likely path of a hurricane, with decreasing specificity into the future: The wider part of the cone might represent the forecasted path 36 hours in advance, and the narrower part might represent the forecasted path 12 hours in advance.

“If we were to have a Katrina today, that cone would be half the size that it was in 2005,” said Jason Beaman, meteorologist-in-charge at the National Weather Service Mobile/Pensacola office.

“IF WE WERE TO HAVE A KATRINA TODAY, THAT [FORECAST] CONE WOULD BE HALF THE SIZE THAT IT WAS IN 2005.”

How to Make a Hurricane

The ingredients for a hurricane boil down to warm water and low pressure. When an atmospheric low-pressure area moves over warm ocean water, surface water evaporates, rises, and then condenses into clouds. Earth’s rotation causes the mass of clouds to spin as the low pressure pulls air toward its center.

Storms born in the Gulf of Mexico or those that traverse it, as Katrina did, bene-

fit from the body’s sheltered, warm water, and the region’s shallow continental shelf makes storm surges particularly destructive for Gulf Coast communities.

Hurricanes gain strength as long as they remain over warm ocean waters. But countless factors contribute to how intense a storm becomes and what path it takes, from water temperature and wind speed to humidity and proximity to the equator.

Because predicting the behavior of hurricanes requires understanding how they work, data gathered by satellites, radar, and aircraft are crucial for researchers. Feeding these data into computer simulations helps researchers understand the mechanisms behind hurricanes and predict how future storms may behave.

“Since 2005, [there have been] monumental leaps in observation skill,” Beaman said.

Seeing a Storm More Clearly

Many observations of the weather conditions leading up to hurricanes come from satellites, which offer a year-round bird’s-eye view of Earth.

NOAA operates a pair of geostationary satellites that collect imagery and monitor weather over the United States and most of the Atlantic and Pacific oceans. The mission, known as the Geostationary Operational Environmental Satellite (GOES) program, has been around since 1975; the current satellites are GOES-18 and GOES-19.

When Beaman started his career just a few years before Katrina hit, satellite imagery from GOES-8 to GOES-12 was typically beamed to Earth every 30–45 minutes—sometimes as often as every 15 minutes. Now it’s routine to receive images every 5 minutes or even as often as every 30 seconds. More frequent updates make for much smoother animations of a hurricane’s track, meaning fewer gaps in the understanding of a storm’s path and intensification.

For Beaman, the launch of the GOES-16 satellite in 2016 marked a particularly important advance: In addition to beaming data to scientists more frequently, it scanned Earth with 4 times the resolution of the previous generation of satellites. It could even detect lightning flashes, which sometimes affect the structure and intensity of a hurricane.

The transition to GOES-16 “was like going from black-and-white television to 4K television,” Beaman said.



This image, captured by NOAA’s Geostationary Operational Environmental Satellite-12 (GOES-12) shows Hurricane Katrina shortly after it made landfall, on 29 August 2005. Credit: NOAA/NASA GOES Project, CC BY 2.0 (bit.ly/ccby2-0)



NOAA's GOES satellites, like the one illustrated here, monitor weather over the United States and most of the Atlantic and Pacific oceans. Credit: NOAA/Lockheed Martin, Public Domain

NOAA also has three polar-orbiting satellites, launched between 2011 and 2017, that orbit Earth from north to south 14 times a day. As part of the Joint Polar Satellite System (JPSS) program, the satellites' instruments collect data such as temperature, moisture, rainfall rates, and wind for large swaths of the planet.

THE TRANSITION TO GOES-16 "WAS LIKE GOING FROM BLACK-AND-WHITE TELEVISION TO 4K TELEVISION."

They also provide microwave imagery using radiation emitted from water droplets and ice. NOAA's earlier polar-orbiting satellites had lower resolution at the edges of scans, a more difficult time differentiating clouds from snow and fog, and less accurate measurements of sea surface temperature.

"With geostationary satellites, you're really just looking at the cloud tops," explained Daniel Brown, branch chief of the Hurricane Specialist Unit at NOAA's National Hurricane Center in Miami. "With those microwave images, you can really kind of see into the storm, looking at structure, whether an eye has formed. It's

really helpful for seeing the signs of what could be rapid intensification."

Rapid intensification is commonly defined as an increase in maximum sustained wind speed of 30 or more nautical miles per hour in a 24-hour period. Two periods of rapid intensification were one reason Katrina was so deadly. In the second period, the storm strengthened from a low-end category 3 hurricane (in which winds blow between 178 and 208 kilometers per hour, or between 111 and 129 miles per hour) to a category 5 hurricane (in which winds blow faster than 252 kilometers per hour, or 157 miles per hour) in less than 12 hours.

New Angles

Radar technology has also made strides in the decades since Katrina. Hurricane-tracking radar works via radio signals sent and received by a ground- or aircraft-based transmitter. The signal passes through the atmosphere until it encounters an obstacle, like a raindrop, that bounces it back to the receiver. The amount of time it takes for the signal to return provides information about the location of the obstacle.

Between 2011 and 2013, NWS upgraded its 150+ ground-based radars throughout the United States with dual-polarization technology—a change a 2013 NWS news release called "the most significant enhancement made to the nation's radar network since

Doppler radar was first installed in the early 1990s."

So-called dual-pol technology sends both horizontal and vertical pulses through the atmosphere. With earlier technology, a radar signal might tell researchers only the location of precipitation. Dual-pol can offer information about the type of precipitation, how much is falling, and the sizes of raindrops. It can even help researchers identify debris being transported in a storm.

"That's not something that we had back in Katrina's time," Beaman said. In 2005, forecasters used "much more crude ways of trying to calculate, from radar, how much rain may have fallen."

Radar updates have become more frequent as well. Beaman said his office used to receive routine updates every 5 or 6 minutes. Now they receive updated radar imagery as often as every minute.

Hunting Hurricanes from the Skies

For a more close-up view of a hurricane, NOAA and the U.S. Air Force employ Hurricane Hunters—planes that fly directly through or around a storm to take measurements of pressure, humidity, temperature, and wind speed and direction. These aircraft also scan the storms with radar and release devices called dropsondes, which take similar measurements at various altitudes on their way down to the ocean.

NOAA's P-3 Orion planes and the 53rd Weather Reconnaissance Squadron's WC-130J planes fly through the eyes of storms. NOAA's Gulfstream IV jet takes similar measurements from above hurricanes and thousands of square kilometers around them, also releasing dropsondes along the way. These planes gather information about the environment in which storms form.

A 2025 study showed that hurricane forecasts that use data from the Gulfstream IV are 24% more accurate than forecasts based only on satellite imagery and ground observations.

Hurricane Hunters' tactics have changed little since Katrina, but Brown said that in the past decade or so, more Hurricane Hunter data have been incorporated into models and have contributed to down-to-Earth forecasting.

Sundararaman "Gopal" Gopalakrishnan, senior meteorologist with the NOAA Atlantic Oceanographic and Meteorological Laboratory's (AOML) Hurricane Research Division, emphasized that Hurricane Hunter



The NOAA P-3 Hurricane Hunter aircraft captured this image from within the eye of Hurricane Katrina on 28 August 2005, 1 day before the storm made landfall. Credit: NOAA, Public Domain

data have been “pivotal” for improving both the initial conditions of models and the forecasting of future storms.

With Hurricane Hunters, “you get direct, inner-core structure of the storm,” he said.

Hurricane Hunters are responsible for many of the improvements in hurricane intensity forecasting over the past 10–15 years, said Ryan Torn, an atmospheric and environmental scientist at the State University of New York at Albany and an author of the recent study about the Gulf-stream IV. One part of this improvement, he explained, is that NOAA began flying Hurricane Hunters not just for the largest storms but for weaker and smaller ones as well, allowing scientists to compare what factors differentiate the different types.

“We now have a very comprehensive observation dataset that’s come from years of flying Hurricane Hunters into storms,” Torn said. These datasets, he added, make it possible to test how accurately a model is predicting wind, temperature, precipitation, and humidity.

In 2021, NOAA scientists also began deploying uncrewed saildrones in the Caribbean Sea and western Atlantic to measure changes in momentum at the sea surface. The drones are designed to fill observational gaps between floats and buoys on the sea surface and Hurricane Hunters above.

Modeling Track and Intensity

From the 1980s to the early 2000s, researchers were focused on improving their ability to forecast the path of a hurricane, not necessarily what that hurri-

cane might look like when it made landfall, Gopalakrishnan explained.

Brown said a storm’s track is easier to forecast than its intensity because a hurricane generally moves “like a cork in the stream,” influenced by large-scale weather features like fronts, which are more straightforward to identify. Intensity forecasting, on the other hand, requires a more granular look at factors ranging from wind speed and air moisture to water temperature and wind shear.

Gopalakrishnan said storms like 2005’s Katrina and Rita “showed the importance of [tracking a storm’s] intensity, especially rapid intensification.”

Without intensity forecasting, Gopalakrishnan said, some of the most destructive storms might appear “innocuous” not long before they wreak havoc on coastlines and lives. “Early in the evening, nobody knows about it,” he explained. “And then, early in the morning, you see a category 3 appear from nowhere.”

Gopalakrishnan came to AOML in 2007 to set up both the Hurricane Modeling Group and NOAA’s Hurricane Forecast Improvement Project. He had begun working on what is now known as the Hurricane Weather Research and Forecasting model (HWRF) in 2002 in his role at NOAA’s Environmental Modeling Center. With the formation of the hurricane modeling group in 2007, scientists decided to focus on using HWRF to forecast intensity changes.

HWRF used a technique called moving nests to model the path of a storm in higher resolution than surrounding areas. Gopalakrishnan compared a nest to using a magnifying glass focused on the path of a storm.

Though a model might simulate a large area to provide plenty of context for a storm’s environment, capturing most of an area in lower resolution and the storm path itself in higher resolution can save computing power.

By 2014, Gopalakrishnan said, the model’s tracking and intensity forecasting capabilities had improved by 25% since 2007. The model’s resolution was also upgraded from 9 square kilometers in 2007 to 1.5 square kilometers by the time it was retired in 2023.

Over time, advances in how data are introduced into models meant that the better data researchers were receiving from satellites, radars, and Hurricane Hunters improved modeling capabilities even further. Gopalakrishnan estimated that by 2020, his office could predict hurricane track and intensity with 50%–54% more accuracy than in 2007.

STORMS LIKE 2005’S KATRINA AND RITA “SHOWED THE IMPORTANCE OF [TRACKING A STORM’S] INTENSITY, ESPECIALLY RAPID INTENSIFICATION.”

NOAA began transitioning operations to a new model known as the Hurricane Analysis and Forecast System (HAFS) in 2019, and HAFS became the National Hurricane Center’s operational forecasting model in 2023. HAFS, developed jointly by several NOAA offices, can more reliably forecast storms, in part by increasing the use of multiple nests—or multiple high-resolution areas in a model—to follow multiple storms at the same time. HAFS predicted the rapid intensification of Hurricanes Helene and Milton in 2024.

Just as they did with HWRF, scientists run multiple versions of HAFS each year: an operational model, used to inform the public, and a handful of experimental models to see which of them work the best. At the end of hurricane season, researchers examine which versions performed the best and begin combining elements to develop the next generation of the operational model. The team expects that as HAFS improves, it will lengthen the

forecast from the 5 days offered by previous models.

“As a developer [in 2007], I would have been happy to even get 2 days forecast correctly,” Gopalakrishnan said. “And today, I’m aiming to get a 7-day forecast.”

NOAA’s budget plan for 2026 could throw a wrench into this progress, as it proposes eliminating all NOAA labs, including AOML (bit.ly/NOAA-budget-2026).

The Role of Communication

An accurate hurricane forecast does little good if the information isn’t shared with the people who need it. And communication about hurricane forecasts has seen its own improvements in the past 2 decades. NWS has partnered with social scientists to learn how to craft the most effective messages for the public, something Beaman said has paid dividends.

Communication between the National Hurricane Center and local weather service offices can be done over video calls rather than by phone as was once done. Sharing information visually can make these calls more straightforward and efficient. NWS

began sending wireless emergency alerts directly to cell phones in 2012.

In 2017, the National Hurricane Center began issuing storm surge watches and warnings in addition to hurricane watches and warnings. Beaman said storm surge inundation graphics, which show areas that may experience flooding, may have contributed to a reduction in storm surge-related fatalities. In the 50-year period between 1963 and 2012, around 49% of storm fatalities were related to storm surge, but by 2022, that number was down to 11%.

Consider the lack of visualization during Katrina in 2005, one of the greatest storm surge disasters our country has seen. We were “trying to express everything in words,” Beaman said. “There’s no way a human can properly articulate all the nuances of that.”

Efforts to create storm data visualization go beyond NOAA.

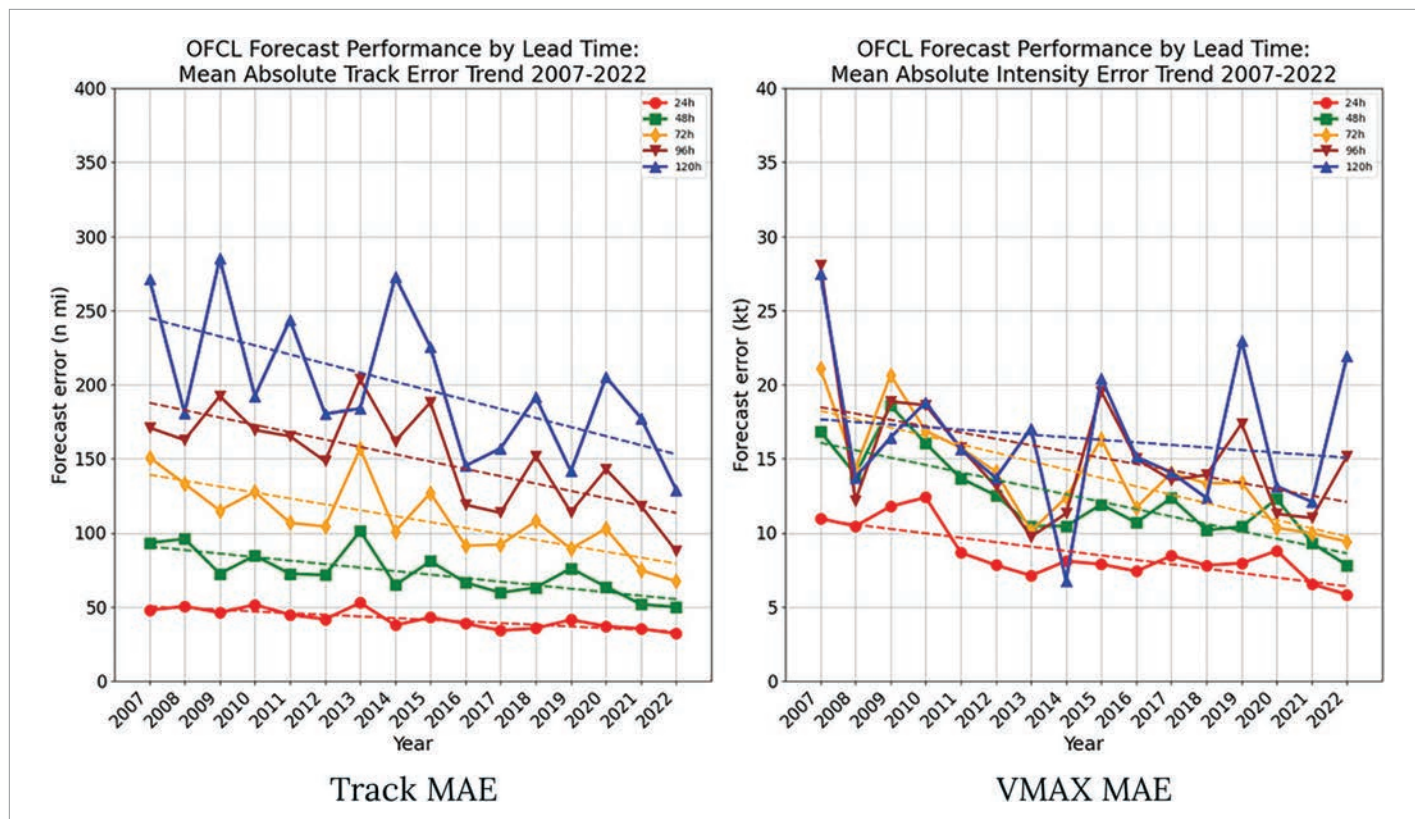
Carola and Hartmut Kaiser moved to Baton Rouge, La., just weeks before Hurricane Katrina made landfall. Hartmut, a computer scientist, and Carola, an information

technology consultant with a cartography background, were both working at Louisiana State University. When the historic storm struck, Hartmut said they wondered, “What did we get ourselves into?”

Shortly after the storm, the Kaisers combined their expertise and began work on the Coastal Emergency Risks Assessment (CERA). The project, led by Carola, developed an easy-to-use interface that creates visual representations of data, including storm path, wind speed, and water height, from the National Hurricane Center, the Advanced Circulation Model (ADCIRC), and other sources.

What started as an idea for how to make information more user-friendly for the public, emergency managers, and the research community grew quickly: Hundreds of thousands of people now use the tool during incoming storm events, Hartmut said. The Coast Guard often moves its ships to safe regions on the basis of CERA’s predictions, and the team frequently receives messages of thanks.

“We know of a lot of people who said, ‘Yes, thank you, [looking at CERA] caused



Since 2007, the National Hurricane Center’s official (OFCL) track forecast errors decreased by 30%–50%, and intensity errors shrank by up to 55%. MAE = mean absolute error; VMAX = maximum sustained 10-meter winds. Credit: Alaka et al., 2024, <https://doi.org/10.1175/BAMS-D-23-0139.1>

me to evacuate,” Hartmut said. “And now my house is gone, and I don’t know what would have happened if I didn’t go.”

Looking Forward

Unlike hurricane season itself, the work of hurricane modelers has no end. When the season is over, teams such as Gopalakrishnan’s review the single operational and several experimental models that ran throughout the season, then work all year on building an upgraded operational model.

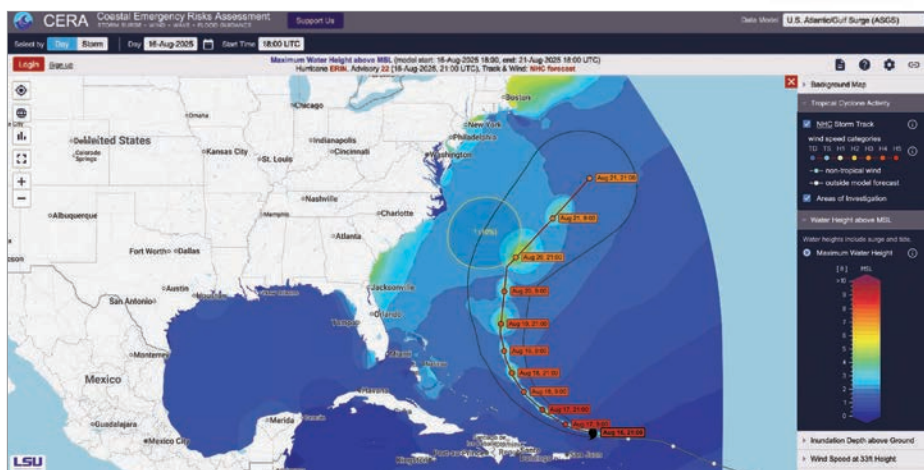
“It’s 365 days of model developments, testing, and evaluation,” he said.

NOAA scientists aren’t the only ones working to improve hurricane forecasting. For instance, researchers at the University of South Florida’s Ocean Circulation Lab (OCL) and the Florida Flood Hub created a storm surge forecast visualization tool based on the lab’s models. The West Florida Coastal Ocean Model, East Florida Coastal Ocean Model, and Tampa Bay Coastal Ocean Model were designed for the coastal ocean with a sufficiently high resolution to model small estuaries and shipping channels.

“WE KNOW OF A LOT OF PEOPLE WHO SAID, ‘YES, THANK YOU, [LOOKING AT CERA] CAUSED ME TO EVACUATE.’”

Though OCL’s models at times outperform NOAA’s models, according to Yonggang Liu, a coastal oceanographer and director of OCL, the tool is not used in operational NOAA forecasts. But it is publicly available on the OCL website (along with a disclaimer stating that the analyses and data are “research products under development”).

The Cyclone Global Navigation Satellite System (CYGNSS) is a NASA mission that pairs signals from existing GPS satellites with a specialized radar receiver to measure reflections off the ocean surface—a proxy for wind speed. The constellation of eight satellites can take measurements more frequently than GOES satellites, allowing for better measurement of rapid intensification, said Chris Ruf, a University of Michigan climate and space scientist and CYGNSS principal investigator.



The Coastal Emergency Risks Assessment tool aims to help the public understand the potential timing and impacts of storm surge. Here, it shows a forecast cone for Hurricane Erin in August 2025, along with predicted maximum water height levels. Credit: Coastal Emergency Risks Assessment

It might seem that if a method or mission offers a way to forecast hurricanes more accurately, it should be promptly integrated into NOAA’s operational models. But Ruf explained NOAA’s hesitation to use data from university-led efforts: Because they are outside of NOAA’s control and could lose funding or otherwise stop running, it’s too risky for NOAA to rely on such projects.

“CYGNSS is a one-off mission that was funded to go up there and do its thing, and then, when it deorbits, it’s over,” Ruf said. “They [at NWS] don’t want to invest a lot of time learning how to assimilate some new data source and then have the data disappear later. They want to have operational usage where they can trust that it’s going to be there later on.”

Whatever office they’re in, it’s scientists who make the work of hurricane forecasting possible. Gopalakrishnan said that during Katrina, only two or three people at NOAA were associated with model development. He credits the modeling improvements made since then to the fact that there’s now a team of several dozen. And more advances may be on the horizon. For instance, NOAA expects a new Hurricane Hunter jet, a G550, to join the ranks by 2026.

However, some efforts at improvement are stalling. The Geostationary Extended Observations (GeoXO) satellite system is slated to begin expanding observations of GOES satellites in the early 2030s. But the 2026 U.S. budget proposal, which suggests slashing \$209 million from NOAA’s efforts

to procure weather satellites and infrastructure, specifically suggests a “rescope” of the GeoXO program.

In addition, hundreds of NOAA scientists, including Hurricane Hunter flight directors and researchers at AOML, have been laid off since January 2025, disrupting hurricane research. (NWS later received permission to rehire hundreds of meteorologists, hydrologists, and radar technicians, as well as hire for previously approved positions.)

In general, hurricane fatalities are decreasing: As of 2024, the 10-year average in the United States was 27, whereas the 30-year average was 51. But this decrease is not because storms are becoming less dangerous.

“Improved data assimilation, improved computing, improved physics, improved observations, and more importantly, the research team that I could bring together [were] pivotal” in enabling the past 2 decades of forecasting improvements, said Gopalakrishnan. “These improvements cannot happen as a one-man army. It’s a team.”

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Read the article
at Eos.org



Machine Learning Simulates 1,000 Years of Climate



A new machine learning model simulates weather, such as the low-pressure system over the central United States pictured here, using less computational power than CMIP6 models. Credit: SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

In recent years, scientists have found that machine learning-based weather models can make weather predictions more quickly and using less energy than traditional models. However, many machine learning models are unable to predict weather accurately more than 15 days into the future and, by day 60, begin to simulate unrealistic weather.

The new Deep Learning Earth System Model, or DLESyM, is built on two neural networks that run in parallel: One simulates the ocean while the other simulates the atmosphere. During model runs, predictions for the state of the ocean update every four model days. Because atmospheric conditions evolve more rapidly, predictions for the atmosphere update every 12 model hours.

The model's creators, *Cresswell-Clay et al.*, found that DLESyM accurately simulates past observed climate and creates skillful short-term forecasts. Using Earth's current

climate as a baseline, it can also accurately simulate climate and interannual variability over 1,000-year periods in less than 12 hours of computing time. It generally matches or outperforms models included in the Coupled Model Intercomparison Project Phase 6, or CMIP6, that are widely used in computational climate research today.

The researchers report that DLESyM model outperformed CMIP6 models in replicating tropical cyclones and Indian summer monsoons. It captured the frequency and spatial distribution of Northern Hemisphere atmospheric blocking events, which can cause extreme weather, at least as well as CMIP6 models. In addition, the storms the model predicts are also highly realistic. For instance, the structure of a nor'easter generated at the end of a 1,000-year simulation (in 3016) is very similar to a nor'easter observed in 2018.

However, both the new model and CMIP6 models poorly represent Atlantic hurricane

climatology. Also, DLESyM is less accurate than other machine learning models for medium-range forecasts looking up to about 15 days into the future. Crucially, the DLESyM model simulates conditions only within the current climate, meaning that it does not account for ongoing anthropogenic climate change.

The key benefit of the DLESyM model, the authors suggest, is that it uses far less computational power than running a CMIP6 model, making it more accessible than traditional models. (*AGU Advances*, <https://doi.org/10.1029/2025AV001706>, 2025) —*Madeline Reinsel, Science Writer*

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Lakeside Sandstones Hold Key to Ancient Continent's Movement

Around 1.1 billion years ago, the oldest and most tectonically stable part of North America—called Laurentia—was rapidly heading south toward the equator. Laurentia eventually slammed into Earth's other landmasses during the Grenville orogeny to form the supercontinent Rodinia.

Laurentia's path during that period can be traced thanks to paleomagnetism. By analyzing the orientation and magnetism of rocks in the lithosphere, scientists can approximate the relative position and movement of Laurentia leading up to Rodinia's formation.

The rocks along Lake Superior in northern Wisconsin and Michigan are especially important for tracing Laurentia's movement. These rocks—dominated by red sandstones, siltstones, and minor conglomerates—were deposited during extensive sedimentation caused by the North American Midcontinent Rift and are rife with iron oxides like hematite. Hematite can acquire magnetization when it is deposited, recording where it is in relation to Earth's poles.

Unfortunately, the existing paleomagnetic record is marred by a gap between 1.075 billion and 900 million years ago, limiting our understanding of how, when, and where Rodinia formed.



Scientists studied the Freda Formation, seen here at Potato River Falls in Wisconsin, to learn more about how Earth's landforms have evolved.
Credit: Anthony Fuentes

To fill part of this data gap, *Fuentes et al.* collected new samples from the Freda Formation near Lake Superior, which formed in floodplain environments an estimated 1.045 billion years ago. The authors combined these data with stratigraphic age modeling to estimate a new, sedimentary paleopole, or the position of the geomagnetic pole at a particular time in the past.

Previous studies indicated that for 30 million years, between about 1.11 billion and 1.08 billion years ago, Laurentia moved from about 60°N to 5°N at a rate of 30 centimeters (12 inches) per year. The new study showed that over the following 30 million years, Laurentia's progress slowed to 2.4 centimeters (1 inch) per year as it crossed the equator.

The paleocontinent's slowdown during deposition of the Freda Formation coincides with the onset of the Grenville orogeny, the researchers reported. The results, they say, confirm that modern-style plate tectonics rather than a stagnant single-lid regime—in which the lithosphere behaves as a single, continuous plate rather than as multiple independent plates—was operating during this interval. (*Journal of Geophysical Research: Solid Earth*, <https://doi.org/10.1029/2025JB031794>, 2025) —Aaron Sidder, Science Writer

Tracing Black Carbon's Journey to the Ocean

Whether from a forest on fire or gasoline powering a car, organic matter rarely combusts completely: Remnants such as char and soot can persist in the environment for decades. Over time, as physical and biological processes break down the scorched leftovers, some of the carbon they contain leaches into groundwater, lakes, and rivers, eventually making its way to the ocean.

This carbon, known as dissolved black carbon (DBC), represents the ocean's largest identified reservoir of stable dissolved organic carbon.

Yet the isotopic signature of DBC in the ocean does not match that which rivers alone supply. This discrepancy suggests that one or more unknown sources of DBC enter the ocean that are not accounted for in the global carbon budget.

To address this knowledge gap, *Zhao et al.* conducted six field surveys along China's eastern coast, in the Jiulong, Changjiang (Yangtze), and Pearl River estuaries. By gathering samples during all four seasons, the researchers aimed to quantify changes in DBC and shed light on how it moves through coastal ecosystems toward

the sea. Prior research focused only on individual estuaries and didn't always account for how processes may vary across seasons and tide cycles.

The findings from the new study reveal submarine groundwater discharge (SGD) as a likely missing source of DBC. The scientists observed that as seawater pushed into estuaries during flood tides, DBC levels rose. Conversely, when water flowed out of the estuaries during ebb tides, DBC concentrations fell. They suggest that this pattern occurs because the salty ocean water that mixes into the estuaries during flood tides promotes the release of DBC from groundwater into the water column.

The researchers estimate that globally, SGD contributes approximately 20% of the riverine discharge of DBC that enters the ocean each year. Given the role that DBC plays in carbon sequestration and biogeochemical cycling in the ocean, the findings underscore the importance of including estuarine processes in global carbon models. (*Global Biogeochemical Cycles*, <https://doi.org/10.1029/2025GB008532>, 2025) —Aaron Sidder, Science Writer

Finding the Gap: Seismology Offers Slab Window Insights



An ocean bottom seismometer emerges from the depths in 2021, after collecting 2 continuous years of data. The data were used to detect shallow tremors near the Chile Triple Junction, offering new insights into the development of the Patagonian slab window. Credit: Javier Ojeda

Off the southern coast of Chile, three tectonic plates meet at a point known as the Chile Triple Junction. Two are oceanic plates, the Nazca and the Antarctic, which are separating along an active spreading center and creating a mid-ocean ridge between them. At the same time, both plates—and the ridge—are sliding into the mantle beneath a third plate, the South American.

The Chile Triple Junction is the only place on Earth where an active spreading center is subducting under a continental plate.

Just east of the triple junction, beneath South America's Patagonia region, a gap known as a slab window exists between the subducting oceanic plates. Caused by the subduction of the spreading center, the window exposes the overriding South American plate to hot mantle material from below.

Knowing the size and geometry of this opening is key for parsing the area's complex geology. However, limited offshore observations have left researchers unsure of where the slab window begins.

Recently, a new array of seismic stations deployed on the ocean floor off Chile's coast has boosted opportunities for observation. According to Azúa *et al.*, the new seismic data help to pinpoint the beginning of the Patagonian slab window to just south of the Chile Triple Junction.

The seismic data captured shallow tectonic tremors, a type of slow earthquake that releases energy more gradually than conventional quakes—often over the course of several days. Slow earthquakes are increasingly being studied to enhance understanding of plate boundaries.

Using nearly 2 years' worth of the new ocean bottom seismic data, the research team detected about 500 shallow tremors near the Chile Triple Junction.

When they compared the locations of these tremors with those of previously detected conventional earthquakes, they noticed a distinct gap between where the two types of events occur.

The researchers interpret the gap in seismic activity as evidence of the youngest part of the Patagonian slab window, formed within the past 300,000 years.

Although further research will be needed to confirm and build on these findings, this work represents the first direct evidence of the offshore edge of this hole between the two subducting plates. (*Geophysical Research Letters*, <https://doi.org/10.1029/2025GL115019>, 2025) —Sarah Stanley, Science Writer

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Assistant Professor of Geosciences

The Department of Geosciences in the Fulbright College of Arts and Sciences at the University of Arkansas invites applications for a tenure-track Assistant Professor of Geosciences to start in August 2026. This is a standard nine-month faculty appointment. We seek an outstanding individual specializing in geomorphology and/or Earth surface processes broadly defined. We seek a researcher and teacher who has a well-defined national/international research area with a component anchored to US mid-continent. Teaching duties may include undergraduate and graduate geomorphology courses, natural hazards, an upper-level course in the candidate's area of expertise, and field experiences. The successful candidate will conduct research leading to scholarly publications, integrate research with student mentorship, design graduate and undergraduate courses, and implement new methods of teaching to reflect

changes in the field. Additional duties will include serving on various faculty/student-oriented committees, providing service on campus and in related professional organizations, and participating in faculty governance in the department and on campus. Regular, reliable, and non-disruptive attendance is an essential job duty, as is the ability to create and maintain collegial, harmonious working relationships with others.

Completed applications received by October 15, 2025, will be assured full consideration. Late applications will be reviewed as necessary to fill the position.

Minimum Qualifications:

- Doctoral degree (PhD) in geosciences (or a closely related field) from an accredited institution of higher education conferred by the date of initial appointment
- A demonstrated record of teaching or mentoring at the graduate level and/or undergraduate level
- Evidence of, or a demonstrated potential for, an active research agenda

Preferred Qualifications:

- Strong record of successful publication and external funding in geomorphology and/or Earth surface processes
- A demonstrated potential for developing regional/mid-continent research and/or national/international projects and teaching field experiences
- Strong evidence of the ability to be an active and collegial member of a collaborative faculty team both on campus and in relevant national service organizations

About the Department:

Department of Geosciences is interdisciplinary with expertise in geography, geology, Earth science, geographic information science (GIScience), space and planetary science, and related disciplines. We offer bachelor's and master's degrees as well as a PhD in geosciences (<http://geosciences.uark.edu>). As is common, the candidate may work closely with and/or leverage existing research facilities/programs such as Center for Advanced Spatial Technologies (<https://cast.uark.edu/>), Environmental Dynamics (<https://environmental-dynamics.uark.edu/>), Arkansas Center for Space and Planetary Sciences (<https://spacecenter.uark.edu/>), Arkansas Water Resources Center (<https://awrc.uada.edu/>), Savoy experimental watershed, and analytical facilities (<https://isotope.uark.edu/> and <https://icp.uark.edu/>).

Duties will include:

- 40% Teaching
- 40% Research
- 20% Service

Required Documents to Apply:

Cover Letter/Letter of Application, Curriculum Vitae, List of three Professional References (name, email, business title), Statement of Research Philosophy, Statement of Teaching Philosophy

Optional Documents:

Proof of Veteran Status

Recruitment Contact Information:

Celina Suarez, search committee chair, casuarez@uark.edu

All application materials must be uploaded to the University of Arkansas System Career Site <https://uasys.wd5.myworkdayjobs.com/UASYS>



Assistant or Associate Teaching Professor in Geospatial Engineering

The Department of Earth Sciences and Engineering (ESE) at the Missouri University of Science and Technology (S&T) invite applications for a Teaching Professor (non-tenure track) position in Geospatial Engineering to begin in January or August 2026. The primary responsibility of the successful candidate is to support a recently established Master's degree in Geospatial Engineering. Details about the degree program can be found at <https://ese.mst.edu/academic-programs/geospatial-engineering/>. This position will be filled at the Assistant Teaching or Associate Teaching Professor level. Salary will be commensurate with qualifications and experience.

The applicant for this position will teach a variety of geospatial courses, potentially including but not limited to GIS, intro and advanced courses on Positioning, Navigation, and Timing (PNT), Lidar Principles and Applications, and Remote Sensing. Applicants should be prepared to teach geospatial courses with an emphasis on geoscience and engineering applications. Courses will be offered in both in-person and on-line formats.

The educational requirements may be met through a Ph.D. in geological engineering, geomatics engineering, geophysics, geodesy, civil engineering, electrical engineering, computer science, geography, geospatial or geological sciences, or another closely related discipline, or through a M.S. in one of the above fields with 15 or more years of related industry experience. Evidence of successful teaching and significant experience in either industry or academia are desired.

Interested candidates should electronically submit their application consisting of: 1) a cover letter, 2) a current curriculum vitae or resume, 3) a teaching statement, and 4) complete contact information for at least four references to Missouri S&T's Human Resources Office at: <https://hr.mst.edu/careers/> (under "Academic Careers") using Reference Number 00096282. Acceptable electronic formats are PDF and MS Word. Applications will be reviewed as they are received and will continue to be accepted until the position is filled. For full consideration and early action, apply by October 1, 2025. Questions may be directed to Dr. Jeremy Maurer, Search Committee Chair, at jmaurer@mst.edu, or Dr. Stephen Gao, ESE Department Chair, at sgao@mst.edu. The University of Missouri is an Equal Opportunity Employer. To request ADA accommodations, please call the Office of Equity & Title IX at 573-341-7734.



Dear *Eos*:

At the edge of the Greenland Ice Sheet, glacial meltwater carves new rivers into the Arctic landscape. These icy flows carry sediments, nutrients, and freshwater to the ocean, where they alter ecosystems and carbon cycling.

Here, at Tyroler Fjord in Northeast Greenland National Park, two researchers waded into a

meltwater river to collect samples, capturing the chemical fingerprints of a changing climate. Each bottle of meltwater offers clues about how Greenland's retreating ice is reshaping the Arctic Ocean and, ultimately, our global carbon balance.

—**Henry C. Henson**, Department of Ecoscience, Aarhus University, Aarhus, Denmark; and **Isolde C. Puts**, Umeå Marine Sciences

Centre and Department of Ecology and Environmental Science, Umeå University, Umeå, Sweden

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