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SCIENCE NEWS BY AGU

CONNECTING OVER CLIMATE

Scientists from seemingly disparate fields ally to solve Earth's grand challenges.

AGU
ADVANCING EARTH AND SPACE SCIENCES

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From the Editor

To mitigate the far-reaching effects of climate change, scientists aren't working alone, and they're not working in silos.

The authors of this month's opinion are candid about it: "Glacier Intervention Research Isn't Just for Glaciologists." Read about potential approaches to glacier intervention and some of the social, economic, and ethical implications to be weighed when studying them on page 14.

Meanwhile, in "How Volcanologists Can Improve Urban Climate Resilience" (p. 18), a scientist and an urban sustainability expert outline how volcanologists have developed approaches to practical challenges they face in helping communities be more resilient to hazards. The authors then explain how these same approaches can support municipalities in adapting their infrastructure to climate change.

Finally, don't forget our Climate Resilience word search on page 32, and make your own connections.

On the Cover

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Janice Lachance, Interim Executive Director/CEO

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A Seychelles Shoreline Resists the Rising Sea

Despite consistently rising sea levels, most of Aldabra Atoll's shoreline hasn't changed since 1960. Credit: Hansueli Krapf/Wikimedia Commons, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

With global sea levels projected to rise by 44 centimeters by the end of the century, atolls such as Aldabra—a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site in Seychelles and home to the world's largest population of giant tortoises—may be at risk of sinking into the ocean.

A new study, however, shows that despite consistently rising sea levels, most of Aldabra's shoreline hasn't changed since 1960 (bit.ly/Aldabra-shoreline).

Aldabra's (Mostly) Stable Shoreline

An atoll forms when corals attach to the margins of a volcanic island or platform in the ocean. Over time, the volcano is eroded and subsides into the sea, leaving a ring-shaped reef. Winds and waves deposit crushed coral from surrounding reefs on top of the ring, forming islands that rise above sea level. Four large islands ring Aldabra's central lagoon: Grand Terre, Malabar, Picard, and Polymnie.

Most of the world's coral atolls are found in the Pacific and Indian oceans. Well-known atolls include Maldives, a popular tourist destination, and Bikini, which the United States used as a nuclear test site until the 1950s. Aldabra has the distinction of being one of the highest atolls, with an average height of 8 meters. For comparison, the average elevation of Maldives is 1 meter.

Their low elevation makes atolls especially vulnerable to rising sea levels.

"Atolls are dynamic and have adapted to grow vertically with changing sea levels over hundreds and even thousands of years," Annabelle Constance, a conservation and spatial ecologist at the Seychelles Islands Foundation and first author of the study, wrote in an email to *Eos.* "However, this balance relies on the availability of loose sediments from nearby coral reefs."

As reefs deteriorate in increasingly hot, acidic oceans, those sediments are becoming scarce, making it harder for atolls to keep up with rising sea levels.

In the new study, researchers from the University of Zurich and the Seychelles Islands Foundation traced changes on Aldabra's shorelines, using aerial and satellite images from 1960 to 2011. The results were surprising.

Constance noted that "61% of the shoreline remained unchanged, while the areas that did change averaged about 25 centimeters per year—lower than the global average for atolls." This rate of change includes both erosion and accretion: Stretches of shoreline that were eroded lost an average of 25 centimeters per year, whereas accreting areas gained land at the same rate.

The authors also noted local differences. Aldabra's outer shoreline, which borders the open ocean, changed at an average rate of 15 centimeters per year. The inner shore, which encircles the atoll's central lagoon, changed at the much higher rate of 32 centimeters per year.

> **"We need to preserve these unique ecosystems to ensure their continued resilience."**

Shoring Up Against Rising Sea Levels

Aldabra's remarkable resilience is likely due to its geologic history, explained Paul Kench, a coastal geomorphologist at the National University of Singapore who was not involved in the study.

"The key difference is that much of the shoreline has been above sea level for the last 125,000 years and has become lithified (cemented)," Kench wrote in an email to *Eos.*

This historic cementation explains why the atoll's inner and outer shorelines change at different rates: Much of the outer, ocean-facing shore consists of solid limestone ridges, whereas the inner shore features more loose sediments that haven't had time to lithify. "This affords the ocean shoreline greater resistance to the impacts of sea level change," Kench wrote.

A lack of human habitation has probably contributed to Aldabra's ability to stay above water. Mangroves on the atoll were harvested for timber until Aldabra became a protected site in the 1970s. Since then, the shoreline of one of the atoll's islands, Picard, has accreted up to 161 meters as flourishing mangrove forests have trapped and retained sediment. The study's authors suggested that reducing such destructive activities as logging and construction could help shore up other atolls against rising sea levels.

"Our research shows that Aldabra's resilience to sea level rise is likely linked to its high protection status. This serves as a crucial lesson, especially now, when a significant tourism development within the Aldabra group of islands just started," Constance wrote, referring to the planned construction of a luxury resort on Assomption Island, around 30 kilometers south of Aldabra. "We need to preserve these unique ecosystems to ensure their continued resilience."

By **Caroline Hasler** (@carbonbasedcary), Science Writer


SCALABLE CARBON FLUX MONITORING.
UNPRECEDENTED SIMPLICITY.
INTRODUCING THE
CARBON NODE
Until now, questions about CO_2 flux in an ecosystem have always come easier than the answers. The Carbon Node is the next-generation eddy covariance monitoring solution that's simple to set up, designed for scalability, and gives you processed, actionable data in just minutes. So you can find the answers we're all looking for.
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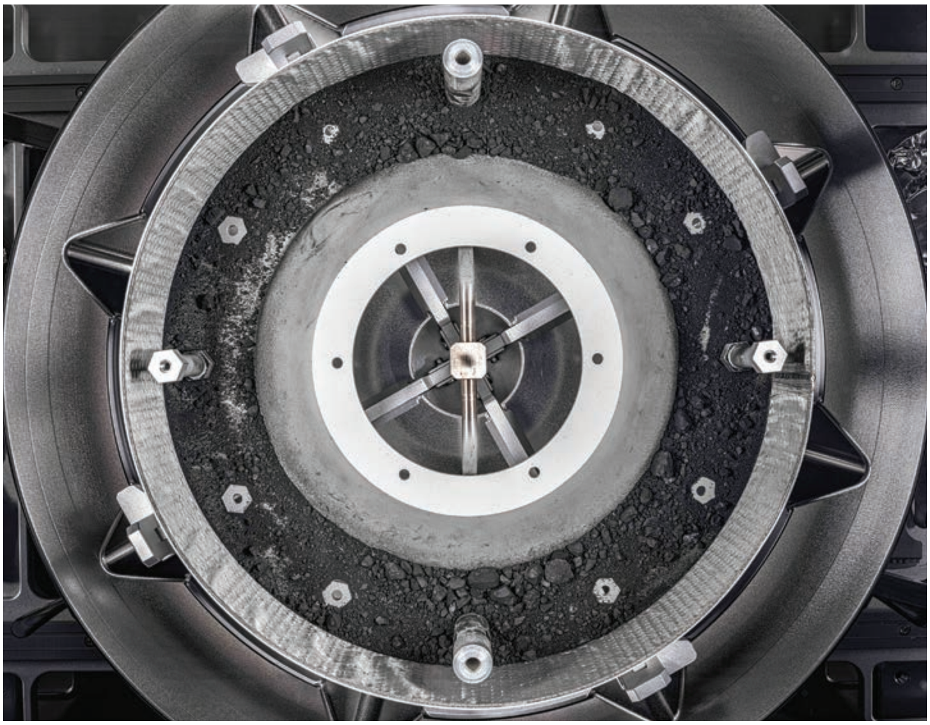
Life's Building Blocks Found in Bennu Samples



OSIRIS-REx's Touch-and-Go-Sample-Acquisition-Mechanism collected more than 120 grams of regolith from asteroid Bennu. Credit: NASA/Goddard/Erika Blumenfeld & Joseph Aebersold, Public Domain

Regolith samples from asteroid Bennu contain many of the essential building blocks of life. These molecules include 14 of the 20 protein-building amino acids found in Earth life, all five of the nucleotide bases found in DNA and RNA, and ammonia. The samples also contain sodium-rich salts, suggesting that Bennu's parent body contained enough water to produce brines.

"Bennu contains many precursor building blocks of life, along with the evidence that it comes from an ancient wet world and contains materials that point to Bennu having traveled from the coldest regions of the solar system," Nicky Fox, associate administrator of NASA's Science Mission Directorate, told reporters during a media call in January.

"I do want to emphasize that their findings do not show evidence of life itself," Fox cautioned, "but they do suggest that the conditions necessary for the emergence of life were likely widespread across the early solar system. This, of course, increases the odds that life could have formed on other planets."

Brewing Bennu Tea

Bennu is a carbon-rich asteroid about 500 meters wide that orbits about 168 million kilometers from Earth. It's a pile of rubble loosely held together by gravity rather than a solid hunk of rock and is thought to have started out as part of a larger asteroid that originated in the outer solar system.

> **"We found a really complex soup of organic molecules."**

NASA's Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission visited Bennu in 2020.

The spacecraft collected 121.6 grams of regolith from the asteroid's surface and returned to Earth in September 2023. The NASA mission team has been carefully curating the returned samples and doling out small portions for scientific analysis. At every stage of the process, scientists exercised extreme care not to expose the samples to Earth's atmosphere or other terrestrial contaminants, lest any potential discoveries be tainted.

Research teams received four small samples for analysis: two of fine- and medium-grained regolith from the main sample collection chambers and two of a fine-grained material that hitched a ride outside the main chambers after it was accidentally scooped up.

"We first made what we call a 'Bennu tea,'" said Danny Glavin, an astrobiologist and senior scientist for sample return at NASA's Goddard Space Flight Center in Greenbelt, Md. "We took samples, we boiled them in water and acids to extract the organic compounds to make this 'tea,' which we then analyzed using several different mass spectrometry techniques to identify the organic molecules."

The analyses revealed that the Bennu samples contained 33 known amino acids, including 14 of the 20 protein-building amino acids used by Earth's life and 19 nonprotein amino acids. The samples also contained high concentrations of ammonia, formaldehyde, carboxylic acids, and polycyclic aromatic hydrocarbons, all of which contribute to biological processes. What's more, the samples also contained all five nucleobases found in DNA and RNA—adenine, guanine, cytosine, thymine, and uracil—along with around 10,000 nitrogen-bearing chemical species.

"We found a really complex soup of organic molecules," Glavin said.

Bennu's concentration of ammonia was about 75 times that found in samples from asteroid Ryugu, which were collected and returned to Earth by the Japan Aerospace Exploration Agency's Hayabusa2 mission in 2020. Bennu's high ammonia levels add to evidence that its parent body originated in the outer solar system, where ammonia ice is more stable, before it migrated closer to the Sun, where ammonia ice would have sublimated.

Bennu's regolith also contained a diverse array of salts, including sodium-rich salts, carbonates, phosphates, and sulfites, which only rarely have been seen in fallen meteorites. Some of the salts were clearly deposited on top of clay materials in veinlike streaks.

"On Earth, these [salt deposits] form in lakes on the surface," said Tim McCoy, a mineral scientist and curator of meteorites at the Smithsonian National Museum of Natural History in Washington, D.C. "That probably wasn't the case on Bennu's parent asteroid.... There [was] something like a muddy surface that had pockets of fluid or veins of fluid, perhaps only a few feet wide, under the surface, and it was within those cracks that the evaporation occurred. Water was lost to the surface, and these minerals were left behind."

These salt patterns, which the team did not expect to find, are consistent with other evidence that Bennu's parent asteroid had enough water for a long enough period in its past to alter its minerology.

Another unexpected find had to do with the way the amino acid structures were oriented, a property known as chirality.

Life on Earth builds proteins almost exclusively from amino acids that twist to the left. In a quirk of fate, most of the amino acids found in past meteorite falls also twist to the left, which led planetary scientists to theorize that meteorites brought at least some of life's building blocks to Earth.

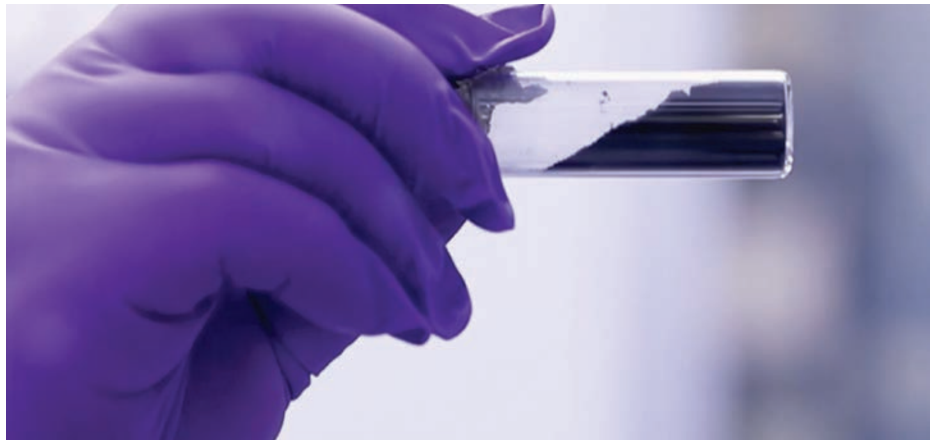
But in the Bennu samples, the amino acids twist to the left and to the right in almost equal abundance.

"I have to admit, I was a little disillusioned or disappointed," Glavin said. "I felt like this had invalidated 20 years of research in our lab and my career. But this is exactly why we explore. This is why we do these missions, right?"

Glavin and his colleagues plan to look at more Bennu samples to see whether more of the asteroid's amino acids have evenly split chirality.

"But for now, the origin of molecular homochirality in life on Earth continues to remain a mystery," Glavin said.

These discoveries were published in *Nature* and *Nature Astronomy* (bit.ly/Bennu-brine, bit.ly/Bennu-organics).



NASA researchers extracted a small portion of their regolith sample to brew "Bennu tea." Credit: NASA Goddard/OSIRIS-REx, Public Domain

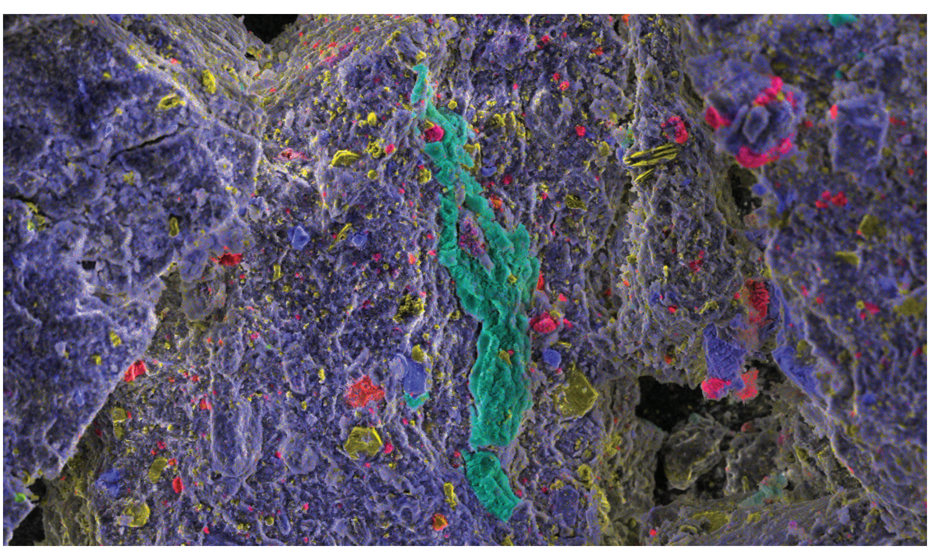
Life's Building Blocks Are Everywhere

"The discovery of brines is crucial for understanding the origin of life in the solar system," said Ahmed Mahjoub, a planetary scientist at the Jet Propulsion Laboratory in Pasadena, Calif. "Salt-rich evaporites create environments ideal for preserving and concentrating organic molecules, including life's building blocks like amino acids and nucleotides."

"I have to admit, I was a little disillusioned or disappointed. I felt like this had invalidated 20 years of research in our lab and my career."

Mahjoub has studied the chemical characteristics of organic material in our solar system but was not involved with these new studies of Bennu. "Similar brines have been detected on Ceres and Enceladus, highlighting their astrobiological significance across the solar system," he said.

Study authors noted that many of these biologically important compounds, including the amino acids and nucleobases, have been detected before in meteorites and comets or remotely detected on bodies in the outer solar system.



This energy dispersive spectrometry map of an unprepared grain of Bennu's regolith shows the placement of briny salt atop clay materials. Phosphorus is shown in green, calcium in red, iron in yellow, and magnesium in blue. A 0.1-millimeter vein of magnesium sodium phosphate (green cluster at center) was formed by evaporation. The phosphate may have played a role in the formation of organic molecules found within the samples. Credit: Natural History Museum, London/Tobias Salge and NASA's Goddard Space Flight Center, Public Domain

"What's so significant about the Bennu findings is that those samples are pristine," Glavin said. The samples were protected from heat damage during atmospheric reentry and from exposure to Earth's atmosphere and biosphere. "All meteorites are exposed to some level of contamination," he said. "The bottom line is, we have a higher confidence that the organic material we're seeing in these samples [is] extraterrestrial and not contamination. We can trust these results."

"We have a higher confidence that the organic material we're seeing in these samples [is] extraterrestrial and not contamination."

That Bennu hosts bioessential material similar to that discovered elsewhere in the solar system confirms that life's building blocks are quite widespread, Mahjoub added.

"These molecules may have formed in molecular clouds through irradiation of simple compounds," Mahjoub said. "Collisions of comets and asteroids with planets and moons could have delivered these organics, potentially contributing to the origin of life. Such impacts may also release prebiotic molecules into space, allowing them to travel to other locations."

Many of the methods that can tease out the subtle signals of complex molecules found in asteroid samples fundamentally change or destroy the material in the process, rendering sample reanalysis impossible—you can't brew the same Bennu tea twice. Because of that, NASA and its partners are preserving around 70% of the returned Bennu samples for scientists to study in the future, as was done with the lunar samples returned by the Apollo missions.

"I cannot wait to see what our future explorers will find as they study these pristine materials in ways that we cannot even imagine today," Fox said.

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

How Much Did Climate Change Affect the Los Angeles Wildfires?

Climate change made the combination of heat, dry climate, and forceful winds that drove January's devastating Los Angeles wildfires about 35% more likely, according to a report published that month by World Weather Attribution (WWA) (bit.ly/WWA-LA-fires).

The study, conducted by nearly three dozen researchers at institutions in Europe and the United States, examined the Fire Weather Index, which incorporates meteorological factors such as temperature, relative humidity, wind speed, and precipitation to estimate fire danger. Researchers compared the index and resulting likelihood and intensity of fires in a 2025 climate to what they might have been under preindustrial conditions, in which the global mean surface temperature was approximately 1.3°C cooler.

The factors that led to the Los Angeles fires are expected to coincide, on average, every 17 years, whereas in preindustrial conditions they may have occurred together only every 23 years.

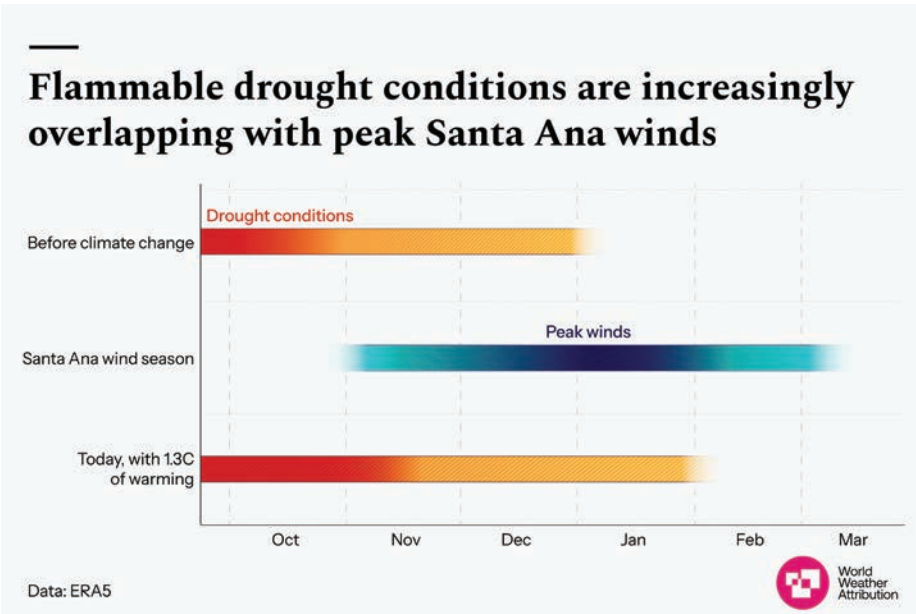
The Palisades and Eaton Fires in Los Angeles County burned nearly 40,000 acres, claiming at least 29 lives and more than 16,000 structures.

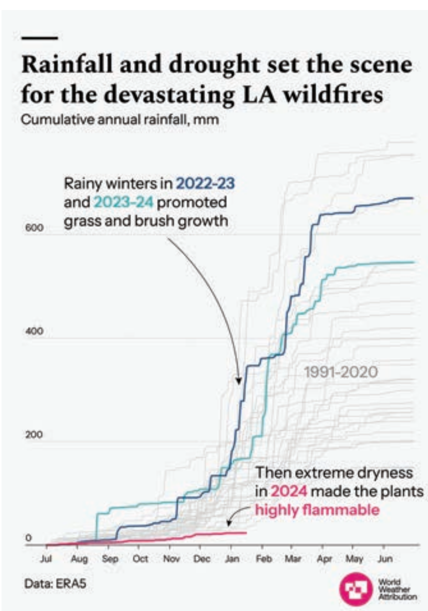
What ignited the first flames of these fires is not yet known, but they were fanned by what Chad Thackeray called "a recipe for disaster." Thackeray is a climate scientist at the University of California, Los Angeles (UCLA) who was not involved in the new study.

"The impact of these fires and the timing of these fires in the core of what should be the wet season differentiate this event as an extreme outlier."

Water years 2022–2024 brought Los Angeles to a 2-year rain total not seen since the highs of 1888–1890, leading to a buildup of vegetation. Then a record-breaking heat wave in summer 2024 dried out that vegetation, and Southern California's rainy sea-

A firefighter battles the Palisades Fire in Los Angeles. Credit: Cal Fire/Flickr, CC BY-NC 2.0 (bit.ly/ccbync2-0)





World Weather Attribution

son, usually experienced between November and March, was unusually delayed. Between 1 May 2024 and 25 January 2025, the region experienced just 0.8 centimeter of rain. Thackeray said the total is normally closer to 15 centimeters. Then came dry Santa Ana winds, which flow toward the coast in the region between October and March.

"While Southern California is no stranger to high-impact wildfires, the impact of these fires and the timing of these fires in the core of what should be the wet season differentiate this event as an extreme outlier," said John Abatzoglou, a climatologist at the University of California, Merced, in a statement. "This was a perfect storm of climate-enabled and weather-driven fires impacting the built environment."

The Role of Climate Change

According to the report, California's dry season has grown about 23 days longer since the preindustrial era. This increase, the researchers said, is attributable to climate change, but their study did not quantify exactly to what degree.

A longer dry season means there is increasing potential for overlap between the dry season, when there is a lot of brush to burn, and the peak of the Santa Ana winds, which can speed the spread of fires.

Southern California has the most volatile hydroclimate in the United States, usually experiencing either extremely high or extremely low amounts of precipitation, said Sasha Gershunov, a research meteorologist at the University of California, San Diego's Scripps Institution of Oceanography. Gershunov was not involved in the study.

Previous research has shown that "climate whiplash," or transitions between the two extremes, has also grown more common in a warming climate. "Very wet years with lush vegetation growth are increasingly likely to be followed by drought, so dry fuel for wildfires can become more abundant as the climate warms," said Theo Keeping, a climate and environmental scientist at the Leverhulme Centre for Wildfires, Imperial College London, in a statement.

However, Gershunov added, the rainy season has never arrived so late in the 150 years' worth of records that exist for the region.

"I can't say that this winter precipitation is so late because of climate change, but I can say that it's consistent with what we expect for a warmer future," he said. "And even in a warmer future, this would still be extreme as far as how late the precipitation is."

The researchers' observational analysis showed that low rainfall from October to December is about 2.4 times more likely now than in the preindustrial climate. As with the extended length of the dry season, the researchers attribute this general shift to climate change but did not determine the quantitative impact of climate change on low rainfall in this study.

What's Next?

The study projected that if the world warms by another 1.3°C by 2100, fire-prone conditions will grow another 35% more likely.

The authors noted that their reported numbers, which have not yet been peer reviewed, have a high level of uncertainty, in part because Southern California has an inherently volatile hydroclimate. But their collective analysis in the form of observational results and climate modeling points to the same conclusion: The conditions most conducive to fire activity are growing more common as the climate warms and will continue to do so under further warming.

The findings align with a separate report issued by a team of UCLA researchers, including Thackeray and two of the researchers on the WWA study, that suggested that the fires were made larger and more intense by climate change because the vegetation in the region was 25% drier than it otherwise would have been (bit.ly/UCLA-LA-fires).

"Without a faster transition away from planet-heating fossil fuels, California will continue to get hotter, drier, and more flammable," said Clair Barnes, a statistician at Imperial College London and a WWA researcher, in a statement.

By **Emily Dieckman** (@emfurd), Science Writer

Ice Core Records Shed Light on a Volcanic Mystery

Despite volcanoes' ability to alter global climate and the fact that records of eruptions date back thousands of years, some recent major eruptions have gone relatively unnoticed.

Researchers have now used ice core records to pin down the identity of a large volcanic eruption that occurred in the 19th century. The culprit is an edifice known as Zavaritskii on a remote island between Japan and the Russian Far East, the team deduced. This discovery resolves a long-standing volcanic mystery and highlights the importance of ice cores to volcanology.

In the early 1830s, temperatures in the Northern Hemisphere temporarily dropped by 0.5°C–1.0°C, according to tree ring and instrumental records. Such widespread cooling is a common signature of a large volcanic eruption because the sulfur dioxide belched by the eruptions catalyzes the formation of aerosols, which scatter sunlight.

But determining which volcano blew its top is difficult. There is no satellite imagery from the 19th century to mine, and historical observations of volcanic eruptions are generally limited to populated locales.

"We really don't have a great understanding of Earth's volcanic record," said Will Hutchison, a volcanologist at the University of St Andrews in the United Kingdom.

Zavaritskii Caldera is located in the Kuril Islands between Japan and the Russian Far East. Credit: NASA

"We really don't have a great understanding of Earth's volcanic record."

Hot Volcano, Cold Ice

To identify the volcano responsible for the eruption, Hutchison and his team turned to ice cores.

The precise timing of a volcanic eruption can be gleaned from the composition of air bubbles trapped in ice. An eruption's chemical signature shows up in several ways, but "the key evidence is the sulfur spike," Hutchison said. And there's a lot of sulfur present starting around 1831 in ice cores extracted from both the Northern and Southern Hemispheres.

It's not surprising that a large eruption detected in ice cores from disparate locations would have affected our planet's climate, said Katharine Cashman, a volcanologist at the University of Oregon in Eugene who was not involved in the research. "It is these bipolar signals that are of particular interest because they are most likely associated with global climate impacts."

Previous research showed that the sulfur peak around 1831 is more than 6 times stronger in the Greenland ice record than in the Antarctic ice record, however. "It's quite a skewed signature," said Hutchison, and that's good evidence that the eruption occurred in the Northern Hemisphere.

Records in Glass

Another clue to the eruption's provenance came from tephra—bits of glassy volcanic ash—found in several Greenland ice cores. Ash from eruptions in the tropics is rarely transported to polar regions, so the eruption likely occurred in the midlatitudes, Hutchison said. But there are plenty of midlatitude Northern Hemisphere locales that are volcanically active. Alaska, Iceland, and Russia's Kamchatka Peninsula all fit that bill. "These are all the kind of classic sources," Hutchison said.

Hutchison and his colleagues analyzed the chemical composition of 45 pieces of tephra extracted from three Greenland ice cores. Each of those shards was only about one tenth the width of a human hair, but the researchers were able to precisely measure the concentrations of elements such as potassium and silicon.

They found that the tephra was a bit of an outlier, chemically speaking. "One of the distinguishing things about it is that it has very low potassium," Hutchison said.

It did not chemically resemble tephra known from Alaska, Iceland, or Kamchatka. The team also ruled out Japan as the site of the eruption because there were no reports of large eruptions there in 1831.

But the Kuril Islands, a disputed archipelago between Japan and Kamchatka, are also volcanic.

"We started getting in touch with people who had been to those islands," Hutchison said.

New Life for Old Samples

One of those people was Breanyn MacInnes, a geologist at Central Washington University in Ellensburg.

MacInnes visited the Kurils, which are about 700 kilometers northeast of Hokkaido, several times for her Ph.D. research from 2006 to 2010. It was quite a journey to get there, MacInnes said. A flight would take her from the United States to Incheon, South

Korea, and she'd then take another flight to the Russian island of Sakhalin. From there, she'd board a research vessel and sail for a day or two to reach the Kurils.

MacInnes collected sediment samples from coastal plains in the Kurils to better understand how tsunamis may have affected local populations. "We dug so many holes," MacInnes said. Those sediment samples invariably included tephra, and MacInnes was more than happy to share them.

"We started getting in touch with people who had been to those islands."

When Hutchison and his colleagues analyzed MacInnes's tephra samples, they found a remarkably good chemical match to their Greenlandic ice core tephra.

In particular, a sample from a caldera known as Zavaritskii on Simushir Island stood out. "The fingerprints matched perfectly," Hutchison said.

And there's evidence that Zavaritskii erupted within the past few hundred years, Hutchison and his colleagues discovered. On Simushir Island, a layer of Zavaritskii's tephra lies on top of Russian artifacts dating from the 1700s to early 1800s. That layering is stratigraphically consistent with an 1831 eruption of Zavaritskii.

A caldera that most of the world has never heard of—let alone could pinpoint on a map—is the likely cause of a measurable blip in Northern Hemisphere temperatures, the researchers concluded. These results were published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/Kurils-eruption).

These findings make sense, Cashman said. However, logical follow-on work would involve digging deeper into the geochemistry of the Zavaritskii tephra. In particular, it would be interesting to determine whether the magma was unusually high in sulfur, Cashman said. If so, the eruption might have had an outsized effect on the planet's climate.

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

U.S. Academic Research Fleet to Add Three Smaller, More Nimble Vessels

At a town hall at AGU's Annual Meeting 2024 in Washington, D.C., the ocean sciences community gathered to discuss the future of U.S. ocean research capabilities. The presenters were clear: Decommissioning of research vessels and a lack of funding for new ones have put ocean scientists in the United States at a global disadvantage. Since the 1980s, the country's Academic Research Fleet has dwindled from 34 vessels to 17.

"If we keep at that pace, we're not going to even be in the conversation for seagoing ocean science," said Paula Bontempi, dean of the University of Rhode Island's Graduate School of Oceanography. "That's a problem," she said.

National Science Foundation (NSF) funding, though, has allowed for construction of a small group of new ocean research vessels. Scientists hope these Regional Class Research Vessels (RCRVs), named for their planned use close to U.S. coasts, will play a small part in bolstering U.S. ocean research capabilities.

Joining the Fleet

The University-National Oceanographic Laboratory System (UNOLS), which is funded by NSF, NOAA, the U.S. Geological Survey, and the U.S. Office of Naval Research (ONR), oversees the operation and outfitting of the 17 vessels currently in the U.S. Academic Research Fleet. These vessels, owned by NSF, ONR, and U.S. universities and laboratories, are a subset of the U.S. Federal Oceanographic Fleet, which also includes vessels owned and operated by NOAA, the U.S. Coast Guard, and EPA.

"If federal budgets don't keep pace to enable science, U.S. expertise in ocean science is largely going to continue to dwindle."

Vessels in the Academic Research Fleet are available to the academic science community for ocean research projects, whereas many of the other vessels in the Federal Oceanographic Fleet have specific missions conducted by the agencies who own the vessels and are not as accessible to academic scientists.

Beginning 15 years ago, subgroups and committees within UNOLS and federal agen-

R/V Taani, *one of three Regional Class Research Vessels that will join the U.S. Academic Research Fleet, was constructed at Bollinger Shipyards in Houma, La. Credit: Darryl Lai, Oregon State University/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)* cies charged with planning for the future of ocean sciences recognized a need for a group of vessels with a wide range of scientific capabilities that could operate in coastal waters and on a lighter budget than some of the fleet's much larger vessels, said Clare Reimers, an ocean biogeochemist at Oregon State University (OSU) who was also a member of the UNOLS Fleet Improvement Committee at the time. Inspired, Reimers spearheaded a proposal to NSF for OSU to lead the development of three new vessels.

Funding for the design, construction, and transition into operation of the three identical RCRVs—R/V *Taani,* R/V *Narragansett Dawn,* and R/V *Gilbert R. Mason*—has been granted in increments, beginning in 2013.

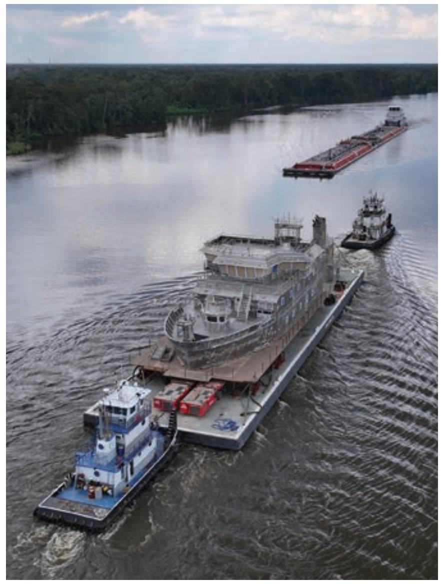
OSU led the design phase and is leading the construction and transition to operation of all three vessels. The university will operate the *Taani* along the U.S. West Coast. The University of Rhode Island, as part of the East Coast Oceanographic Consortium, will operate the *Narragansett Dawn* along the Atlantic Ocean. The Gulf-Caribbean Oceanographic Consortium, including the Louisiana Universities Marine Consortium (LUMCON) and the University of Southern Mississippi, will operate the *Gilbert R. Mason* in the Gulf of Mexico.

"There is a lot of science that is waiting in the wings for these new vessels, and their arrival could not come a minute too soon."

All three vessels are being built by Bollinger Shipyards in Houma, La.

The new vessels will replace three vessels: R/V *Oceanus,* a now-retired vessel once operated by Oregon State University; R/V *Endeavor,* which is currently operated by the University of Rhode Island; and R/V *Point Sur,* an aged ship brought out of retirement in 2015 and currently operated by the University of Southern Mississippi.

The new RCRVs are "going to be extraordinarily capable vessels," Reimers said. The OSU design team plans to include many features that were not available in earlier regional vessels in the fleet, such as a propulsion and navigation system that allows



Part of R/V Gilbert R. Mason *is moved by tugboats during construction. Credit: Darryl Lai, Oregon State University/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)*

the ship to hold position "on a dime," she said.

Each vessel will also have a suite of sonar instruments for deep- and shallow-water seafloor mapping, oceanic and atmospheric sensors that collect data, which are made available to shore-based researchers in real time, and coring capabilities. Many of the instruments are new to any class of research vessel and are the most advanced of their kind, Reimers said.

The *Taani* is about 90% finished and is currently in the water. Shipyard workers are installing its electrical system, after which its major instrumentation will be tested and certified and it will be delivered to OSU. Reimers said she expects delivery in 2026.

Construction of the *Narragansett Dawn* is not far behind—its hull is complete, but its interior needs work, from insulation to electrical equipment to an HVAC (heating, ventilating, and air-conditioning) system.

The *Gilbert R. Mason* is still in pieces that need to be assembled. Reimers expects delivery of the *Narragansett Dawn* to the University of Rhode Island about 5–6 months after delivery of the *Taani* and delivery of the *Gilbert R. Mason* to LUMCON and the University of Southern Mississippi to follow 5–6 months after that.

After construction is completed, each vessel will undergo a year of final outfitting, trials, and training with their crews and then will be available to the scientific community.

"There is a lot of science that is waiting in the wings for these new vessels, and their arrival could not come a minute too soon," said Leila Hamdan, a marine microbial ecologist at the University of Southern Mississippi and principal investigator for the operation of the *Gilbert R. Mason.*

"The expectation is that these vessels will be very important for ocean science for the next 30, 40, maybe even 50 years. And that's worth waiting for," Reimers said.

Investments in Ocean Research

The new RCRVs will "fill a big gap," said Deborah Bronk, a marine scientist at the Bigelow Laboratory for Ocean Sciences and past chair of the UNOLS Council. But another crisis looms in the global class of research vessels—those vessels meant to have global range and carry larger, multidisciplinary teams. Three vessels in the U.S. Academic Research Fleet will reach the end of their service lives by 2027: R/V *Thomas G. Thompson,* R/V *Roger Revelle,* and R/V *Atlantis.*

The ocean sciences community is also facing the loss of the *JOIDES Resolution,* a global class research ship designed for deep-ocean drilling. The *JOIDES* was operated by Texas A&M University on behalf of the International Ocean Discovery Program and funded by NSF before it was retired from the U.S. fleet in 2024.

In 2022, the Consortium for Ocean Leadership, a Washington, D.C.–based group that advocated for federal funding for oceangoing research, dissolved, leaving ocean scientists "without a voice," Bronk said. In response, Bontempi, Bronk, Hamdan, and others recently formed the Research and Education Coalition for Ocean Sciences (RECOS), an organization that will advocate for federal funding of ocean sciences.

Though private partnerships may increase ship availability, sustained federal investments in academic oceangoing research are needed for the United States to "maintain any role, let alone leadership, in ocean science and the marine space," Bontempi wrote in an email.

"If federal budgets don't keep pace to enable science, U.S. expertise in ocean science is largely going to continue to dwindle," Bontempi said. "An investment in our ocean enterprise as a country is an investment in our shared future."

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

Darker, Less Cloudy Earth Contributed to Record Heat

The Atlantic Ocean has seen significant decreases in cloud cover recently. Credit: Earth Science and Remote Sensing Unit, NASA Johnson Space Center

In a string of ever-hotter years, 2023 stood out: It was the warmest on record at the time (though 2024 has since surpassed it), with temperatures 1.4°C above the preindustrial average and 0.17°C above the previous record set in 2016.

One cause for the spike may have been that Earth was just a little darker than it's been in recent history.

Earth's albedo, a measure of how reflective its surface is, hit a record low in 2023, according to the authors of a study in *Science* (bit.ly/record-low-albedo). That record was due mainly to a dearth of bright, low-level clouds, which reflect more solar radiation than land or ocean. The answers to why these clouds were absent and, crucially, whether the trend will continue are still unclear.

Scientists had pinned most of the heat in 2023 to several factors: an El Niño event, a solar cycle maximum, and ongoing global warming, among other things.

But until now, studies have been unable to attribute around 0.2°C of the anomalous warming. The new research closes that gap and suggests that low-level clouds may be more important to Earth's climate than realized.

"If you lose those clouds, you lose this cooling effect," said Helge Goessling, a paper coauthor and climate physicist at Germany's Alfred-Wegener-Institut. "It's really striking to see how the low-level clouds have changed."

Closing the Gap

Earth takes in energy from the Sun and reemits some of it as both visible and infrared light, a process tracked by a number known as the radiation budget. If Earth absorbs more than it emits, temperatures go up. In recent decades the planet has consistently been absorbing more energy than it loses, gaining an average of 0.76 watt per square meter every year during the 2010s, according to the paper's authors.

> **"If you lose those clouds, you lose this cooling effect."**

Goessling and his colleagues calculated Earth's radiation budget for 2023 and compared it to past years using data from NASA's Clouds and the Earth's Radiant Energy System (CERES) project, which uses satellite observations to track how much energy Earth gains and loses, as well as a global hindcast of climate conditions (ERA5, the fifth-generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis).

The researchers were not surprised to find that Earth absorbed significantly more energy in 2023 than in other years, taking in almost 1 watt per square meter more than the average for the preceding 20 years. Adding the extra energy into a simplified energy budget model, the researchers found it would create 0.23°C of warming—almost exactly the amount previously unaccounted for.

That increase in absorbed energy came from a planetary albedo lower than any recorded going back to 1940. The cause, Goessling said, was clear: clouds.

"If you look at the spatial distribution of where the albedo has been going down and where it has been particularly low in 2023, then it's very obvious that this is correlated with regions where the cloud cover has been changing," he said.

The Future Is (Not) Cloudy

Looking deeper at the ERA5 data, the researchers noted that much of the change in cloud cover came from low-lying clouds, which have a base below 2,000 meters above Earth's surface. These clouds help to cool the surface because they reflect incoming sunlight and allow outgoing infrared radiation to pass through (as opposed to high-level clouds, which trap most infrared radiation in Earth's atmosphere).

2023 saw 1.5% fewer low-level clouds compared to previous years, especially in the Northern Hemisphere. That decrease continues a trend from the previous decade, which saw especially strong declines in low-level clouds over the Atlantic.

"Unscrambling the egg is a challenge."

Why these clouds are disappearing isn't fully known, though it's likely due in part to natural yearly and decadal variations in atmospheric patterns. Some researchers have also argued that a reduction in marine aerosols (associated with regulations limiting shipping emissions) is to blame. Others point to feedbacks from a changing climate.

"Unscrambling the egg is a challenge," said Norman Loeb, a NASA scientist and principal investigator for CERES, who wasn't involved with the research. "Having the correct attribution of what's behind these trends in the energy budget and top of atmosphere radiation, I think that's really important."

If the decrease in low-level clouds comes from more than natural fluctuations, that could mean the influence of feedback effects or marine aerosols on low cloud formation is stronger than currently thought. Both might mean that current climate models are underestimating how much warming will happen in the future, according to Goessling.

Knowing how much warming we're in for is important for designing climate and emissions policies and interventions, so it's crucial to be accurate. As the new study shows, understanding what's happening to the clouds is an important part of that.

"This is kind of crunch time," he said.

Loeb said research into how cloud cover is changing should soon be accelerated. An effort to coordinate new climate models with updated data through 2022 will give the climate science community an easier way to compare results, he said. "We're going to make a lot of progress with this latest set of [data]," Loeb said.

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

Pluto Captured Charon with a Kiss

A composite image of Pluto (foreground) and Charon shows the striking color differences between the two bodies. Credit: NASA/JHUAPL/SwRI

Astronomers have long thought that Charon, the largest moon of Pluto, formed after a collision in the early solar system. New simulations of that encounter have revealed that during a chance meeting in the outer solar system, Charon and Pluto may have become smooshed together in an hours-long "kiss" before settling into a lifelong orbit around each other.

"We were genuinely quite surprised by what we found," said Adeene Denton, a geologist and planetary scientist at Southwest Research Institute in Boulder, Colo., and lead researcher on the study.

That kiss-and-capture process could help settle a long-standing debate about the evolution of the Pluto-Charon system and also explain the evolution of other binary systems beyond Neptune's orbit.

An Unlikely Icy Pairing

In the early years of the solar system's history, chaos reigned, and collisions were common. The history of small impacts is written in the craters that dot the surfaces of bodies from asteroids to planets. Larger impacts left their mark by creating rings, oblong snowmen, and moons—including Earth's.

Even though large collisions used to be common, they did not always result in a pairing. Sometimes two large objects bounced off each other like billiard balls in a so-called hit-and-run collision. Sometimes one object was completely obliterated while the other survived, sometimes the two objects grazed and merged together, and sometimes both objects were partially destroyed but eventually re-formed with one object captured into an orbit around the other.

"The best example that we have for collisional capture of the satellite is the Earth and the Moon," Denton said. Astronomers and planetary scientists have done extensive research into this collision, thanks in large part to centuries of detailed observations of how Earth and the Moon move around each other. In recent decades, lunar samples returned to Earth have shown how the Moon and Earth are geochemically similar, further supporting this theory.

"In the outer solar system, we are not so lucky to have this information," Denton added.

This has presented a challenge to scientists like Denton who have been trying to understand how diminutive Pluto could have survived a similar collisional capture of its largest moon, Charon.

Previous collision simulations have shown that it's exceedingly difficult to form the Pluto-Charon system in the same way that the Earth-Moon system formed.

One reason is Charon's heft: Charon is about 50% the size and 12% the mass of Pluto. Our Moon, on the other hand, is 27% the size and 1.2% the mass of Earth. Charon would have had to travel very slowly or impact at a sharp angle to end up as Pluto's moon—neither scenario is very likely, but astronomers grudgingly accepted that it must have happened that way because it was the only way to make the capture stick.

But Denton realized that past simulations failed to account for the fact that Earth and the Moon are mostly made of rock, whereas Pluto and Charon have a significant amount of ice.

"In the outer solar system, we are not so lucky to have this information."

"If we instead approximate them as geologically realistic bodies made of rock and ice, how does that change the conditions under which Pluto can capture Charon?" Denton asked. The answer, they felt, lies in the material strength of ice compared with rock.

First Came a Kiss, Then Came Marriage

Denton and their colleagues started by incorporating material strength into existing simulations of the Pluto-Charon collision, which were based on the Earth-Moon collision. In the Earth-Moon collision, the speeds and relative masses of the two initial objects meant that once they collided, the debris was entirely molten and behaved like a fluid.

But at the speed and sharp impact angle that had previously been presumed for a Pluto-Charon collision, "the two bodies don't deform as much because they're now behaving like ice and rock would, and not fluid," Denton explained. "Charon would come in and hit Pluto and keep going and leave the system."

When the researchers started exploring other, more typical impact speeds and angles, they found that the material strength of an ice-rock mixture made a big difference. The simulations showed that when proto-Charon struck proto-Pluto, friction within the rock-ice material distributed some of the impact momentum, causing the two objects to become connected for tens of hours—the "kiss." The ice's strength prevented them from fully merging, and eventually, the two objects physically separated but remained in orbit around each other—the "capture."

These results were published in *Nature Geoscience* (bit.ly/Pluto-Charon-kiss).

Explaining Pluto and Its Neighbors

William McKinnon, a planetary geologist at Washington University in St. Louis who was not involved with this research, called the kiss-and-capture mechanism "a variation on a theme" of planetary collisions and added that "the inclusion of strength in the numerical models is an important advance."

The team found that a kiss-and-capture scenario produced enough collisional debris to form Pluto's minor moons (Hydra, Nix, Kerberos, and Styx), though the moons are so small that the simulations would have had to be thousands of times more powerful for them to be seen, Denton said.

Kiss-and-capture could also help resolve an open question about Pluto's temperature.

Astronomers think that the planet had an underground liquid ocean for most or all of its history, but where it got the heat to sustain that ocean is unknown. Many models of the solar system's formation suggest that Pluto formed much later than planets in the inner solar system, but if it did, it would have missed out on a lot of radioactive materials that could have heated its interior.

But with a kiss-and-capture, "theoretically, you could add a heat source to Pluto from the impact and then sustain heating of Pluto over time as Charon starts to migrate outwards," Denton said.

However, McKinnon cautioned that Pluto's precollision heat is still an important factor to consider in a kiss-and-capture scenario. A warm proto-Pluto or proto-Charon would have distinctly separate layers of rock and ice, whereas cold objects would have a more even mix of rock and ice throughout. That would affect how much of each material's strength came into play during the collision. It would be tough, he said, to gather convincing evidence for kiss-and-capture versus the more traditional graze-and-merge.

"I suppose that definitive evidence for an ocean today on Pluto would argue for an even warmer Pluto in the past, which would argue against kiss-and-capture," he said.

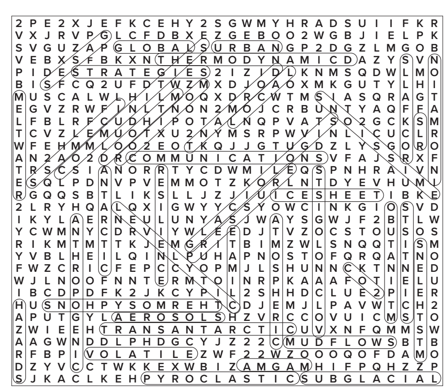
Because a kiss-and-capture depends on the material strength of the colliding objects, it might have happened to other icy objects in the outer solar system. The researchers also simulated the collision of Orcus and Vanth, another pair of co-orbiting icy objects out beyond Neptune's orbit with a mass ratio similar to that of Pluto and Charon. Kiss-and-capture worked for that system, too.

"This process might be something that happens all across the Kuiper Belt, but it might not necessarily be something that's happening, say, in the asteroid belt."

"This process might be something that happens all across the Kuiper Belt, but it might not necessarily be something that's happening, say, in the asteroid belt," Denton said.

The team plans to simulate this kind of collision for other pairs of trans-Neptunian objects like Eris and Dysnomia and Quaoar and Weywot. McKinnon said that seeing kiss-and-capture work for other binary systems in the Kuiper Belt—of which there are many—would help convince him that it happened to Pluto, too.

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



Glacier Intervention Research Isn't Just for Glaciologists

The 2008 painting Breaking News *by artist John Walsh depicts the Polynesian explorer Ui-te-Rangiora sailing amid ice on a southern voyage of discovery. The work reflects how some communities have millennial-scale connections to Earth's deep south. Credit: Antarctica New Zealand*

Humans have been unintentionally engineering the decline of Antarctic ice mass and subsequent sea level rise (SLR) for more than a century. We have done so knowingly since at least the 1970s, when the concept that marine ice sheets could be destabilized by rising atmospheric and oceanic temperatures was introduced, if not since the 1850s, when the warming potential of carbon dioxide (CO_2) was first documented by scientist Eunice Foote.

Rising seas are already displacing communities and are linked to increased flooding, erosion, and saltwater intrusion, causing losses of land, homes, infrastructure, identities, and cultures. The low-probability but high-severity—and therefore high-risk—potential for ice sheets to collapse on the timescale of centuries portends even more drastic changes to coastal communities and ecosystems.

The most logical response to the multidimensional threats of SLR and climate change is to mitigate their root cause. We should rapidly reduce anthropogenic greenhouse gas emissions and strive to return atmospheric CO_2 concentrations to preindustrial levels to diminish both the baseline rate of SLR and the probability of ice sheet collapse.

However, over roughly the past 4 decades—during which scientists have systematically highlighted the adverse impacts of increasing CO_2 emissions on global climate—the rate of CO_2 emissions has doubled. The total greenhouse gas emissions rate, which includes additional gases such as methane and nitrous oxide, increased by 67% over the same period.

We should therefore also plan for a world in which atmospheric CO_2 and other greenhouse gas reductions do not happen fast enough or soon enough. Many scientists are now considering additional means of intervention against rising seas. SLR mitigation tactics with global reach are especially appealing.

Communities contributing the least to greenhouse gas emissions are expected to be the most affected, even within wealthy and high-emission nations [*Khalfan et al.*, 2023]. These communities often have limited resources to construct local seawalls, relocate, or rebuild infrastructure.

With the inequalities inherent in both SLR vulnerability and adaptation in mind, some glaciologists are exploring how intentional glacier interventions could counter glacier mass loss and consequent SLR—that is, how scientists can leverage their expertise to manage, not just monitor, melting glaciers.

Exploring a concept does not imply supporting its implementation. Instead, we argue that, considering the extraordinary stakes of possible ice sheet collapses, potential glacier interventions deserve additional research.

Both advocates and skeptics should examine the feasibility—technical, governance, social, environmental, ethical, and financial—of glacier interventions as well as the consequences of not intervening.

Some glacier intervention research has already progressed along traditional research paths without codesign by affected communities or communities where initial field trials may occur. Most scientists currently debating glacier interventions live and work in the high–gross domestic product (GDP) countries responsible for the bulk of cumulative CO_2 emissions and represent a narrow range of lived experiences. They also work within a dominant research paradigm that is prone to various biases and that tends to treat science, culture, and society as separate spheres in ways that may create rather than reduce risk [*Lewis and Kelman*, 2012].

Thus, we further contend that research into glacier interventions must be codesigned in partnerships involving not only scientists but also current and future rights holders and stakeholders in harm's way, including communities that globally are the most affected by SLR or that have cultural connections to glaciers where field testing may occur. Indeed, these efforts should be led by affected communities from the moment of research inception, according to responsible innovation standards.

What Methods Might Be Used?

Approximately 50% of historical SLR has been caused by thermal expansion of seawater, but this percentage is predicted to drop under all future emissions scenarios studied. Increasing rates of ice flow and melting—caused primarily by atmospheric and ocean warming—and subsequent ice and meltwater flow into the ocean from the Greenland and Antarctic ice sheets mean that these processes will be of greater magnitude in the future and will contribute a larger proportion to SLR.

As of yet, no reasonable glaciological method to limit atmospheric-induced melt over large areas has been developed, but in Antarctica, current (and projected near-future) surface melting is restricted to low-elevation coastal regions. Ocean warming and changes in coastal ocean circulation are the primary causes of Antarctic ice mass loss. If these changes destabilize the margins of marine-terminating glaciers and allow them to slide into the ocean even faster, ice mass loss and consequent SLR could accelerate.

Interventions at sea aim to reduce this ocean forcing or to slow ice flow rates if an instability is triggered. Scientists have modeled reduced marine forcing by simulating the effect of seabed curtains—flexible fabric barriers anchored to the seafloor [*Keefer et al.*, 2023]—in keeping deep, warm ocean water from reaching the edge of an ice sheet. Although research has suggested that this approach could avert ice sheet instabilities in some places, such curtains could not stop a runaway instability once initiated. Instead, they would only modify future ice sheet retreat rates, reducing local mass loss while possibly increasing mass loss elsewhere nearby, but with a net benefit.

Another proposed intervention approach to mitigating SLR finds inspiration in a natural event.

About 160 years ago, the Kamb Ice Stream in West Antarctica suddenly stagnated, with flow in its ice stream trunk slowing from roughly 350 meters per year to a near standstill. The shutdown proceeded in stages associated with changes in meltwater at the interface between the ice and the bed over which it flowed. This process might be intentionally replicated.

Upstream of the Antarctic ice-ocean boundary, ice flow rates depend on subglacial, or basal, meltwater patterns and how they affect resistance provided by underlying materials. That resistance might be increased—and ice flow slowed—by either physically removing water from the basal interface or freezing the basal water in place. Intentionally slowing ice flow would change the balance between mass gain by snow accumulation on the ice sheet surface and mass loss by ice discharge to the ocean. Hence, it could also reduce ice sheet responsiveness to destabilizing marine forcing.

If water were removed via boreholes and pumps, it could be redistributed at the surface via snowmaking machines.

However, keeping ice sheet boreholes open is energy intensive and would require development of environmentally hardened clean power systems. Freezing basal water could be significantly less energy intensive if passive thermosiphons could be used to extract heat from the ice sheet base, but thermosiphons at the required scale have yet to be developed and deployed.

Apart from the technical considerations and challenges, little scientific investigation—theoretical, model based, experimental, or social—has been conducted to understand how intentional glacier slowing would work in practice or what its physical or social consequences would be. We don't know, for example, how many sites or glaciers would need to be targeted with interventions, or for how long, to have a meaningful effect on SLR. We don't know how different spatial patterns of slowing and thickening might play out on longer timescales. We also don't know which communities, human and ecological, would be affected and how.

If ocean warming and changes in coastal ocean circulation destabilize the margins of marine-terminating glaciers, ice mass loss and consequent SLR could accelerate.

Whereas other forms of climate change intervention—from solar radiation management to CO_2 removal—have received substantial attention and have been integrated into mainstream climate change discourses, glacier conservation research is underdeveloped and has not been widely discussed. A small number of groups proposing interventions have published only a few studies, drawing even fewer critical responses [cf. *Moon*, 2018].

Given the existential challenges and risks presented by SLR, many scientists are now suggesting that mitigation options should be investigated, including their positive and negative impacts, as part of holistic assessments of feasibility and desirability.

Considerations of Cost, Legality, Governance, and Justice

The global financial costs of SLR through this century are estimated to be hundreds of billions to trillions of dollars per year [*Brown et al.*, 2021]. The costs of glacier intervention field trials are estimated to be similar to those of existing years-long field campaigns involving large teams drilling holes in ice sheets (e.g., the Antarctic Drilling Project (ANDRILL) and Subglacial Antarctic Lakes Scientific Access (SALSA)), meaning tens of millions of dollars. Potential implementation costs for glacier interventions are highly uncertain, but estimates for the ocean curtain concept suggest that it could cost roughly $10 billion, with annual maintenance of around $2 billion [*Keefer et al.*, 2023].

This level of expense is orders of magnitude more than existing field campaigns but similar to estimates of spending on globally coordinated research during the International Geophysical Year, 1957–1958 [*Koffler*, 1957], and orders of magnitude less than the estimated end-of-century costs of addressing catastrophic SLR for cities, coasts, and ports. Potential sources of financing to cover these costs, either adaptation or intervention research and implementation, are unknown.

SLR hazards and impacts affect low-lying coastal areas without regard for national GDP, but as with other climate change impacts, the highest SLR-related costs relative to GDP fall on lower-income nations [*Brown et al.*, 2021] that have historically contributed far less to greenhouse gas emissions. Planetary-scale SLR thus poses challenges for existing international governance [*Flamm and Shibata*, 2025] and decisionmaking frameworks, including the Antarctic Treaty System (ATS), and raises questions about whether these frameworks can legally and justly oversee potential glacier intervention tests and implementations [*Madani and Shibata*, 2023].

The ATS's ambiguity regarding territorial claims, a legacy of Cold War era realpolitik, may allow engineering interventions on the continent [*Corbett and Parson*, 2022]. But the treaty limits consultative (voting) status in Antarctic governance to nations with the interest and ability to finance and maintain scientific research there. This group of nations, which is responsible for roughly 80% of historical greenhouse gas emissions, excludes one third of the world's population. Moreover, no island nations have consultative status, even though they face existential challenges from rising seas partly because of changes occurring in Antarctica.

Critiques of the ATS's exclusionary approach and inherent coloniality are readily available. Climate science and glaciology are subject to similar critiques. These fields developed within and benefited from systems of European (and later U.S.) imperi-

A field camp on Priestley Glacier sits in front of Lowry Bluff in Victoria Land, Antarctica, in January 2020. Credit: Holly Still

alism and colonial expansion that imposed control and extracted wealth, including scientific knowledge, from occupied lands [*Mercer and Simpson*, 2023].

Given these critiques, glacier interventions in Antarctica and elsewhere would clearly benefit from new approaches to socioscientific systems and science policy governance that provide means of collective decisionmaking, financing, and action. Scientists and others in the high-emissions, high-GDP nations primarily responsible for historical and ongoing global environmental injustice [*Gupta et al.*, 2023] should not be setting the terms and conditions for research into possible intervention options.

The Arctic Council, in which Indigenous representative bodies contribute to all discussions as permanent participants, shows one way forward. A similarly diverse range of traditions and worldviews should be represented with respect to interventions in Antarctica [e.g., *Zurba and Papadopoulos*, 2023].

Preferred pathways forward should minimize harm while maximizing benefits—not least cultural survival—for communities most directly and deeply affected by otherwise unmitigated SLR and by glacier interventions. Support for exploratory research into SLR interventions should thus be organized and led by representatives from these communities.

Under an equitable and just governance structure, glaciologists, atmospheric scientists, oceanographers, social scientists, and others with relevant expertise might work as colleagues or technical consultants to those leading these efforts. In these positions, scientists could contribute knowledge and analyses to evaluate possible interventions and their impacts, using best practices such as clearly quantified confidence ratings (similar, perhaps, to those used by the Intergovernmental Panel on Climate Change). Glaciologists may be best suited to lead the field components of trials or implementations of interventions, if they occur. Should the consensus be that glacier interventions would not achieve required outcomes, the same structure could be applied to consider other proposed interventions.

Protocols and white papers outlining recommended practices for geoengineering and intervention governance and policy formulated by intergovernmental bodies like the United Nations and scientific associations such as the U.K.'s Royal Society, AGU, and the U.S. National Academies may provide guidance for researching and developing interventions that prioritize ethical design and community needs. However, those documents (like this article) cannot in themselves represent the values and priorities of countries and communities that have the most at stake but may not have been involved in writing them.

How Should We Pursue Glacier Intervention Research?

Along with the other dimensions of glacier interventions discussed here, scientists must examine embedded ethical questions. Focusing on questions with yes or no answers, such as "Should we do this research," can result in either/or logical fallacies. We suggest that a better approach is to ask, "How can we pursue research into interventions most ethically?" while considering who stands to benefit and who might be harmed by either action or inaction with respect to research and implementation. The possible benefits and harms involve diverse communities, cultures, and disciplines with their own value systems, social and environmental histories, and priorities.

Planetary-scale SLR poses challenges for existing international governance and decisionmaking frameworks.

Glaciologists and other polar scientists should not suppose they have the sole mandate to pursue research into glacier conservation or the right to block such research without broader consultation. The exclusionary nature of the ATS and traditional Antarctic scientific endeavors must be addressed. Indeed, all practitioners in this new multidisciplinary field of glacial intervention research should be careful of their assumptions about information and perspectives from outside their domain of expertise.

For example, one common reason given for not intervening in Antarctica stems from the popular assumption that the continent is a pristine and unoccupied environment. It is not—because of both scientific activities and the global reach of pollutants. Nevertheless, installing and operating glacier management infrastructure would have further physical impacts and would require impact assessments and conservation planning at a level not currently implemented in the Antarctic. Communities facing different levels of risk from SLR may weigh various intervention priorities differently than the small group of scientists currently debating Antarctic glacier conservation.

A second reason commonly offered for not intervening, and indeed for halting discussions of glacier intervention options altogether, is that the mere possibility of such concepts being applied may reduce motivation to pursue vital emissions reductions. Similar concerns have been raised about the effect of pursuing climate change adaptation research.

Some recent research, including a study assessing the attitudes of roughly 340,000 Facebook users exposed to messaging about geoengineering (specifically solar radiation management), discounts the significance of these concerns, which are akin to suggesting we not study medical interventions because people may be less motivated to make healthy lifestyle choices. On the other hand, the human bias toward intervention, even when not intervening is also an option, is a well-studied phenomenon in both medical and environmental research.

Ultimately, implementing interventions to slow glacier and ice sheet melting and mitigate SLR may not be physically or technically viable. Or some options may prove technically possible but have unacceptable environmental, social, cultural, or geopolitical consequences.

Alternatively, there could be approaches that are technically viable, have significantly fewer negative impacts than not intervening, and can be developed in ways that respect, represent, and advance the interests of the diverse array of communities at risk from SLR. But without thorough, multicultural, and multidisciplinary exploration of the feasibility of glacier interventions, we will not know.

We thus suggest that as research proceeds, Earth scientists and social scientists should work in partnership with and under the leadership of scientists and representatives from the regions and communities that have the most at stake in the face of rising seas while being the least responsible for the conditions causing them.

Acknowledgments

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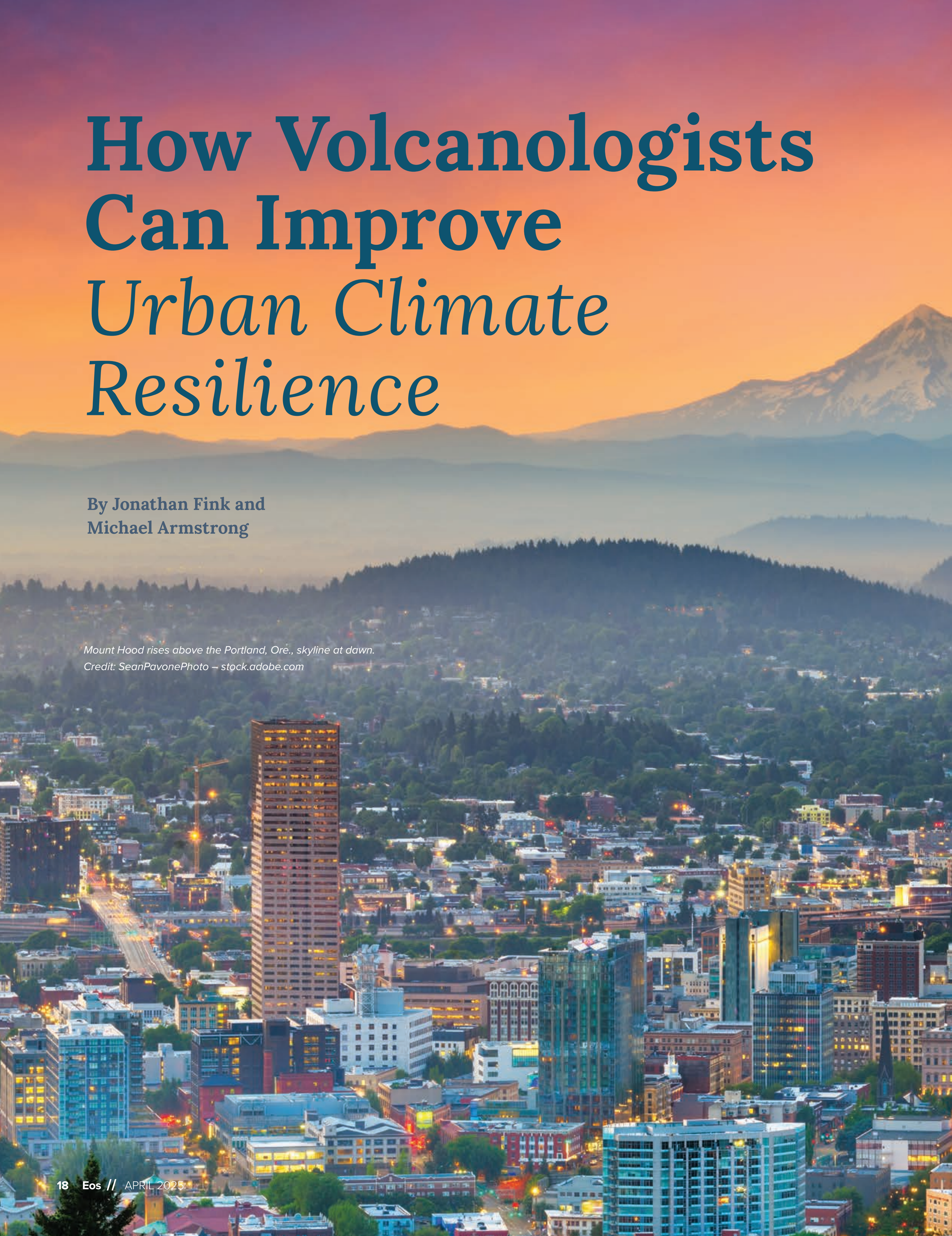
How Volcanologists Can Improve *Urban Climate Resilience*

By Jonathan Fink and Michael Armstrong



Mount Hood rises above the Portland, Ore., skyline at dawn. Credit: SeanPavonePhoto – stock.adobe.com

City-level strategies to cope with climate change can benefit from the insights of volcano scientists, who have long customized hazard information and communications for local communities.

The cities of the Pacific Northwest have long been incubators for novel environmental policy. Governments in Portland, Ore.; Seattle, Wash. and Vancouver, B.C., for example, were among the first to enact urban growth boundaries [Nelson and Moore, 1993; Hepinstall-Cymerman et al., 2011], climate action plans [Rutland and Aylett, 2008; Affolderbach and Schulz, 2017], and clean energy policies.

These cities also share similar geologic settings—active volcanoes dominate their eastern skylines, and to the west, a subduction zone hidden offshore threatens potentially catastrophic earthquakes. This juxtaposition of openness to policy innovation and experience living beside active tectonic hazards hints at a previously unrecognized way that cities, in this region and beyond, could learn and apply important lessons about resiliency to other risks—by learning from scientists at the world's volcano observatories.

Volcanoes and earthquakes pose distinct risks in the Pacific Northwest and elsewhere, but like urbanizing areas everywhere, these regions also now face unprecedented climate threats. Each city must deal with its own unique mix of intensifying dangers from extreme heat, wildfire and smoke, wind, ice, rising seas, and flooding. Combinations of these hazards, many of which are occurring at scales and frequencies beyond those experienced by community members and leaders, are overwhelming the capacities of municipal governments to prepare, respond, and recover.

Among the biggest challenges—and opportunities—for cities trying to increase their resilience is customizing lessons learned elsewhere to their specific situations

Few local governments have the expertise on staff to adapt and respond adequately in real time to rapidly changing and compounding disasters [*Fink and Ajibade*, 2022]. Nor do they have the budgets needed to educate the public about the increasing breadth and severity of climate-related risks or to invest in sufficient physical and social infrastructure to protect residents from catastrophic impacts.

Among the biggest challenges—and opportunities—for cities trying to increase their resilience is customizing lessons learned elsewhere to their specific geographic, demographic, political, and economic situations.

This is where the approaches of volcanologists can help.

A Model for Mapping Local Risk

Unique among groups that monitor natural hazards, volcano observatory staff and their collaborators—as one of us (J.F.) has been for nearly 50 years—must understand the range of risks concentrated in a particular geographic setting. Teams and centers that track seismicity, landslides, debris flows, tsunamis, hurricanes, tornadoes, or floods typically work in multiple sites across regional, national, or global scales.

Most volcano observatories, some of which date back to the mid-1800s, are positioned within sight of one or more specific volcanoes that are the focus of their

Mount Hood rises beyond the skyline of Portland, Ore. Credit: Jeff Hintzman/Flickr, CC BY-ND 2.0 (bit.ly/ccbync2-0)

Wildfire smoke hovers over Portland on 9 September 2020 during an especially destructive fire season in Oregon. Credit: Tedder/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

attention. Staff at these observatories must apply knowledge learned from other volcanoes, and from general theory about volcanic hazards, to the particular conditions of their site to assess and forecast local risks.

This need to customize forecasts extends down to metropolitan and even neighborhood scales.

For example, parts of Tacoma, Wash., are built on mudflow deposits from past eruptions of Mount Rainier, whereas suburbs of Seattle less than 30 kilometers north sit on consolidated pyroclastic flows from that same volcano.

Naples, Italy, offers another example: Residents in the eastern part of the city have to worry about explosive products coming out of Mount Vesuvius, whereas western neighborhoods near the Phlegraean Fields face bigger threats from volcanic gases, ground uplift, and groundwater contamination. Strategies for alerts and evacuations, as well as public education needs, can thus vary widely from one local community to another.

The same is true of urban climate risks, which can differ dramatically block by block, depending on such variables as elevation, tree cover, construction practices, zoning, and proximity to water. For instance, the city of Tacoma has mapped resilience to sea level rise on a block-by-block basis, showing areas likely to be inundated according to different climate scenarios.

To help convey geographically variable risks from volcanic activity, observatory volcanologists produce detailed hazard maps specific to the volcanoes they focus on. These maps could serve as models for the emerging practice of urban climate risk mapping. Volcano hazard maps may, for example, delineate areas subject to mudflows, dome collapse events, or gas emissions, providing communities with locally relevant advance information. Similar maps of urban areas could indicate the most likely or most impactful climate-related hazards on a neighborhood or even block scale, or they could highlight where multiple hazards could lead to compound effects.

City dwellers have difficulty imagining dangers from climate change that they have never confronted.

Crucially, volcano observatories monitor, map, and communicate risks that do not respect municipal, state, or even national boundaries (e.g., mudflows from Mount Baker in Washington can affect the suburbs of Vancouver, B.C.). This border-agnostic approach offers a valuable model for preparing for and responding to climate threats, which are experienced across jurisdictions but are often treated piecemeal by local governments.

Bringing the Hazards Home

Another parallel between volcano observatories and city resilience offices is that staff of each must sometimes alert the public about events that are outside the scope of the community's prior lived experience.

Before volcanoes have awakened after long hiatuses, like Mount St. Helens did in 1980 or Mount Pinatubo did in 1991, few if any nearby residents worried about or prepared for eruptive dangers.

Similarly, city dwellers have difficulty imagining dangers from climate change that they have never confronted. Ten years ago, for instance, residents of Portland—as we both are—likely would not have foreseen temperatures reaching 108°F, 112°F, and 116°F on three consecutive days as they did in 2021. (Prior to the heat dome event that year, the previous recorded high was 107°F, in 1981.) Likewise, we probably would not have foreseen extended periods of smoke-filled air that the U.S. EPA designated as "unhealthy for sensitive groups"—before 2015, Portland had never seen such conditions—or wildfires encroaching on the metropolitan area, as they did in 2017 and 2020. Similar trends of historically anomalous conditions occurring more often are playing out in a growing number of cities around the world.

The late filmmakers Katia and Maurice Krafft, volcanologists famed for their prolific and up-close documentation of active eruptions, recognized this problem of communities' unpreparedness for natural hazards after the 1985 eruption of Colombia's Nevado del Ruiz. That event killed 22,000 people, despite geologists having issued warnings a month earlier about the kinds of mudflows that ultimately buried the town of Armero [*Voight*, 1990]. The Kraffts afterward dedicated their lives to making films to help vulnerable populations better appreciate the unfamiliar dangers associated with infrequent but potentially deadly volcanic eruptions.

Using the relatively unsophisticated editing tools of the 1980s and 1990s, the Kraffts superimposed footage from violent volcanic eruptions onto distant landscapes and cityscapes familiar to local populations to grab their attention and elicit more visceral reactions than spoken lectures or written reports could.

Today's urban resilience offices must do similar work for their residents threatened by novel climate extremes. To achieve this, they can take advantage of powerful technologies like virtual reality (VR), augmented reality (AR), and lidar-equipped smartphones, as well as popular social media platforms, all of which are now being used to supplement traditional assessment tools for volcanic hazards. For example, VR and AR have been used to communicate volcanic risk to local populations and tourists visiting Mount Vesuvius and the ruins of Pompeii [*Solana et al.*, 2008]. And VR combined with gaming software engines has allowed analysis of drone-based mapping of otherwise inaccessible areas of the Greek island of Santorini, where the Minoan civilization settlement was destroyed by volcanic eruptions around 1600 BCE [*Tibaldi et al.*, 2020].

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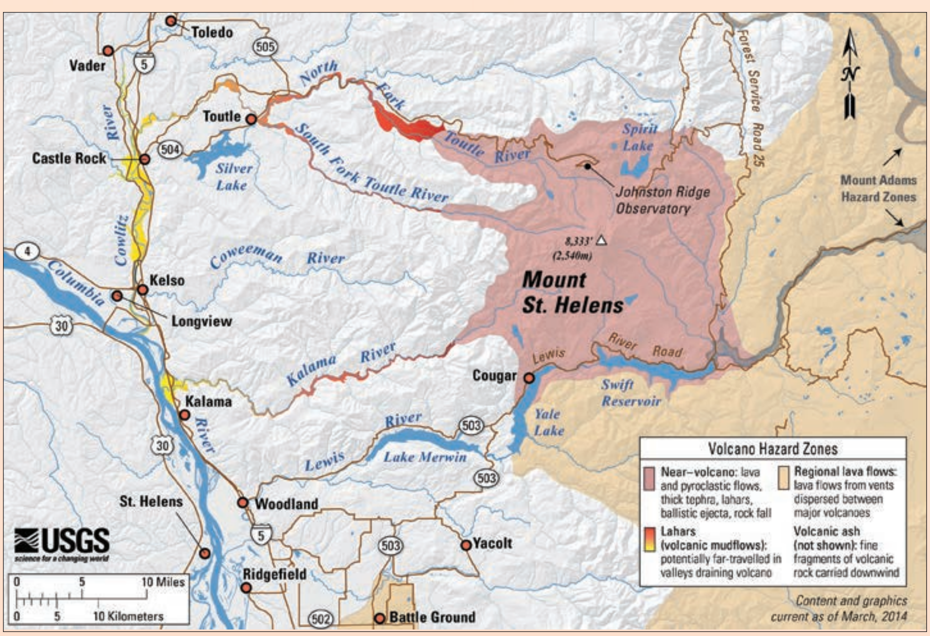

Volcanologists produce maps for regions surrounding specific volcanoes that delineate areas subject to different hazards. This simplified hazard map around Mount St. Helens in Washington highlights zones at risk for hazards such as pyroclastic flows and rockfalls as well as more distant mudflows. Credit: U.S. Geological Survey

Collaboration, Not Colonialism

A third similarity between the work of observatory volcanologists and city climate resilience programs is the need to work collaboratively with local experts and residents while avoiding scientific colonialism. Many of the world's most dangerous volcanoes are found in low- and middle-income nations. Officials and scientists in those countries often benefit from having colleagues from observatories in other countries help them assess and interpret their local volcanic risks. However, this assistance sometimes leads to resentment when researchers from abroad collect and publish critical data without properly acknowledging or including local observers.

Resentment toward scientific collaborators can also occur in efforts around urban resilience to climate change. Many of the communities most vulnerable to climate threats are in countries and cities that lack large scientific establishments or budgets to implement resilience measures. By contrast, the most visible and prevalent approaches to climate resilience have been developed by and for wealthier communities. The Thames Barrier, built decades ago to protect London from severe flooding, was an early example of this; Copenhagen's infrastructure to manage intense rainfall is a more recent one.

Wealthy institutions sometimes help secure resources to support managers and technical staff in lower-income areas, who can then better understand and engage with local populations and develop culturally appropriate responses. As the sustainability manager in the city of Portland's Bureau of Planning and Sustainability, one of us (M.A.) was frequently called upon to advise city officials in other countries. Similarly, the World Bank commonly brings in advisers from the European Union or North America to consult on projects in Africa and Asia. However, as with volcanologists, the goal of these urban resilience advisers must be to help local officials achieve scientific self-sufficiency rather than dependence.

Damage downstream of Mount Pinatubo in the Philippines, including to a bridge over a river channel, is seen in this photo from June 1991 following the volcano's massive eruption that month. Prior to this event, Pinatubo had not erupted for centuries. Credit: U.S. Geological Survey

As most cities share a common set of responsibilities—including public safety, water management, emergency response, and maintenance of infrastructure—they also share common challenges in dealing with climate change (even if their specific mix of risks varies). Peer-to-peer learning efforts have thus tried to fill pronounced gaps in climate knowledge at the city scale. Nongovernmental organizations like the C40 Cities Climate Leadership Group, MetroLab Network, ICLEI–Local Governments for Sustainability, and the Resilient Cities Network (launched from the Rockefeller Foundation's 100 Resilient Cities initiative) have all helped grow awareness of the increasing threats cities face, as well as best practices for responses. Federal agencies in the United States, including the Federal Emergency Management Agency, the Department of Housing and Urban Development, and NOAA, also offer guidelines to local governments.

But local officials have at times criticized the approaches of such broadly focused programs and agencies for being too prescriptive or top-down. Even the idea that there is a single model of a "resilient city" that "ordinary cities" should aspire to has received considerable pushback [*Naef*, 2022]. What is often missing is the input of local experts, including Indigenous voices, who have the knowledge and breadth of practical experience needed to advise their cities about the challenges they face and about appropriate, feasible, and tailored solutions.

As most cities share a common set of responsibilities, they also share common challenges in dealing with climate change.

Here, too, government volcanologists can offer useful lessons. National agencies like the U.S. Geological Survey (with its Volcano Disaster Assistance Program), the Japan Meteorological Agency, Italy's Istituto Nazionale di Geofisica e Vulcanologia, France's Institut de Physique du Globe de Paris, and New Zealand's GNS Science all have teams of well-resourced volcanologists that they can deploy to emerging crises. Rather than acting unilaterally to collect data or direct responses, these teams assist in assessing immediate dangers while supporting local scientists and officials, with whom they have often already established relationships, to take over response efforts as quickly as is practical [*Lowenstern et al.*, 2022].

Organizations focusing on urban climate resilience could follow the model of these programs to create similar arrangements that partner with city governments and offer rapid assistance during emergencies coupled with long-term human resource development. Such partnerships need not be prescriptive or viewed as purely altruistic. Less developed countries can offer key lessons to their richer counterparts that may

Participants at a workshop in Garut, West Java, Indonesia—including scientists from the U.S. Geological Survey's Volcano Disaster Assistance Program and local partners—discuss the uses of volcano hazard maps. Credit: U.S. Geological Survey

only now be starting to cope with the kinds of large-scale climate-driven disruptions that have affected emerging economies for many decades. *Anguelovski et al.* [2014], for example, noted resilience lessons from Durban (South Africa), Quito (Ecuador), and Surat (India) that are relevant for cities in the Global North facing new challenges.

Furthermore, as volcano observatories and international exchange programs are critical for training future generations of eruption experts, new programs focused on helping vulnerable cities prepare for climate disasters could similarly include education and training of future resilience experts as part of their charters.

Sharing Needed Knowledge

Transferring lessons from volcano science into the realm of urban resilience starts with initiating conversations between volcanologists, especially those from observatories, and city resilience officers. A primary motivation for this article is the recognition that these groups rarely have opportunities to interact. (Indeed, it is unclear where an article like this one is most likely to be seen by both groups.) The International Association of Volcanology and Chemistry of the Earth's Interior has organized 12 Cities on Volcanoes (CoV) conferences since 1998 in cities (like Portland) that either have been or could be affected by eruptions from nearby volcanoes. Yet these meetings have almost exclusively covered volcanic hazards; representatives from nonvolcanic cities and resilience officers focused on climate threats rarely attend.

The kinds of conversations that are needed could be organized as part of a future CoV-like conference if resilience officers were invited. AGU would make

Transferring lessons from volcano science into the realm of urban resilience starts with initiating conversations between volcanologists, especially those from observatories, and city resilience officers.

sense as a sponsor for such a conference. Likewise, the World Bank (which has long promoted global information exchange related to urban sustainability), the MetroLab Network (a U.S.-based organization pairing cities and universities that are studying and implementing urban resilience strategies), or foundations that support city climate action could serve as hosts. NOAA's Climate Adaptation Partnerships, which provide high-quality regional climate research and are building durable relationships with local policymakers, could be a valuable collaborator in these discussions.

In such a setting, volcano scientists could share with urban resilience officials how they filter and focus knowledge of a global phenomenon to the distinct conditions of an individual volcano, as well as how they communicate with local populations to meet their specific needs for safety and security. These discussions could reveal insights that better prepare urban governments and their residents for the increasingly dangerous climate perils to come.

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New research finds that ice melt in Antarctica could lead to more subglacial eruptions, affecting volcanoes such as Mount Erebus, seen here. Credit: Josh Landis, U.S. Arctic Program, Public Domain

Antarctic Ice Melt May Fuel Eruptions of Hidden Volcanoes

A slow climate feedback may be bubbling beneath Antarctica's vast ice sheet. The continent, divided east to west by the Transantarctic Mountains, includes volcanic giants such as Mount Erebus and its iconic lava lake. But at least 100 less conspicuous volcanoes dot Antarctica, with many clustered along its western coast. Some of those volcanoes peak above the surface, but others sit several kilometers beneath the Antarctic Ice Sheet.

Climate change is causing the ice sheet to melt, raising global sea levels. The melting is also removing weight from the rocks below, with more local consequences. Ice sheet melt has been shown to increase volcanic activity in subglacial volcanoes elsewhere on the globe.

Coonin et al. ran 4,000 computer simulations to study how ice sheet loss affects Antarctica's buried volcanoes, and they found that gradual melt could increase the number and size of subglacial eruptions.

This unloading of ice sheets reduces pressure on magma chambers below the surface, causing the compressed magma to expand. This expansion increases pressure on magma chamber walls and can lead to eruptions.

Some magma chambers also hold copious amounts of volatile gases, which are normally dissolved into the magma. As the magma cools and when overburden pressure reduces, those gases rush out of solution like carbonation out of a newly opened bottle of soda, increasing the pressure in the magma chamber. This pressure means that melting ice can expedite the onset of an eruption from a subglacial volcano.

Eruptions of subglacial volcanoes may not be visible on the surface, but they can have consequences for the ice sheet. Heat from these eruptions can increase ice melting deep below the surface and weaken the overlying ice—potentially leading to a reduced pressure from the surface and further volcanic eruptions.

The authors stress that this process is slow, taking place over hundreds of years. But that means the theorized feedback could continue even if the world curtails anthropogenic warming. Antarctica's ice sheet was much thicker during the last ice age, and it is possible that the same process of unloading and expansion of magma and gas may have contributed to past eruptions. (*Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2024GC011743, 2024) **—Madeline Reinsel,** *Science Writer*

Aerosols Could Be Weakening Summertime Circulation

Over the past several decades, summer jet streams (or west to east wind flow) and weather systems in the Northern Hemisphere have weakened. Projections suggest the trend will continue, which could make extreme heat events more likely and affect air quality.

Some studies have hypothesized that the weakening is related to Arctic amplification, or the way the Arctic is warming more quickly than the rest of the planet, because this phenomenon reduces the temperature difference between the equator and the North Pole. But others have suggested that anthropogenic emissions of aerosols, which lead to a similarly weakened gradient, may be more directly to blame.

Using Detection and Attribution Model Intercomparison Project (DAMIP) data, *Kang et al.* studied how anthropogenic factors may have influenced summertime circulation patterns between 1980 and 2020. They found that aerosols play just as big a role as greenhouse gases do in the slowdown of wind patterns and atmospheric flow during the summer months. Changes in aerosol emissions can influence the strength of the weather systems by altering the flow of energy between land and ocean.

A reduction in aerosol emissions in North America and Europe during this period meant more sunlight reaching Earth's surface, causing a greater energy contrast between these land surfaces and the ocean. This caused energy export to the air over the ocean. As a result, the energy converged over the higher-latitude ocean (40°N–70°N), weakening the gradient between the poles and the equator, as well as the weather systems. This effect is about twice as pronounced over the Pacific because aerosol emissions were reduced more in Eurasia than in North America.

Increased aerosol pollution from South and East Asia had the same weather-weakening effect, but through the opposite process: The increased pollution decreased the amount of solar energy that reached the surface and reduced the energy transport between land and the lower-latitude (25°N–40°N) Pacific Ocean. Ultimately, less energy converged over the lower-latitude Pacific, further weakening the energy gradient and the weather systems.

Because aerosols have shaped summertime circulation patterns over the past 40 years, it will be important to continue research on how they may shape future summer climate trends, the researchers write. (*AGU Advances*, https://doi.org/10.1029/2024AV001318, 2024) **—Rebecca Owen,** *Science Writer*

New Insight into Inland Water Carbon Dioxide Emissions

Rivers, lakes, and reservoirs emit significant amounts of carbon dioxide (CO_2) into the atmosphere. But just how much they contribute to the global carbon cycle is uncertain.

To estimate inland water CO_2 fluxes, researchers measure CO_2 levels and emissions at various points along a waterway or body of water, then use those data to develop an estimate for the whole system based on statistical upscaling methods. But CO_2 concentrations can vary greatly over short distances, leading to uncertain estimates. In addition, these methods don't allow researchers to precisely determine the sources of the CO_2 being emitted.

Saccardi et al. present a new, process-based model that simulates the movement of CO_2 and gauges inland waters' contributions to overall CO_2 emission fluxes with more accuracy and detail than previous modeling techniques have done. The new model captures carbon fluxes for the approximately 22 million interconnected rivers, lakes, and reservoirs in the contiguous United States at mean annual flow between 1970 and 2000, calibrated to observations.

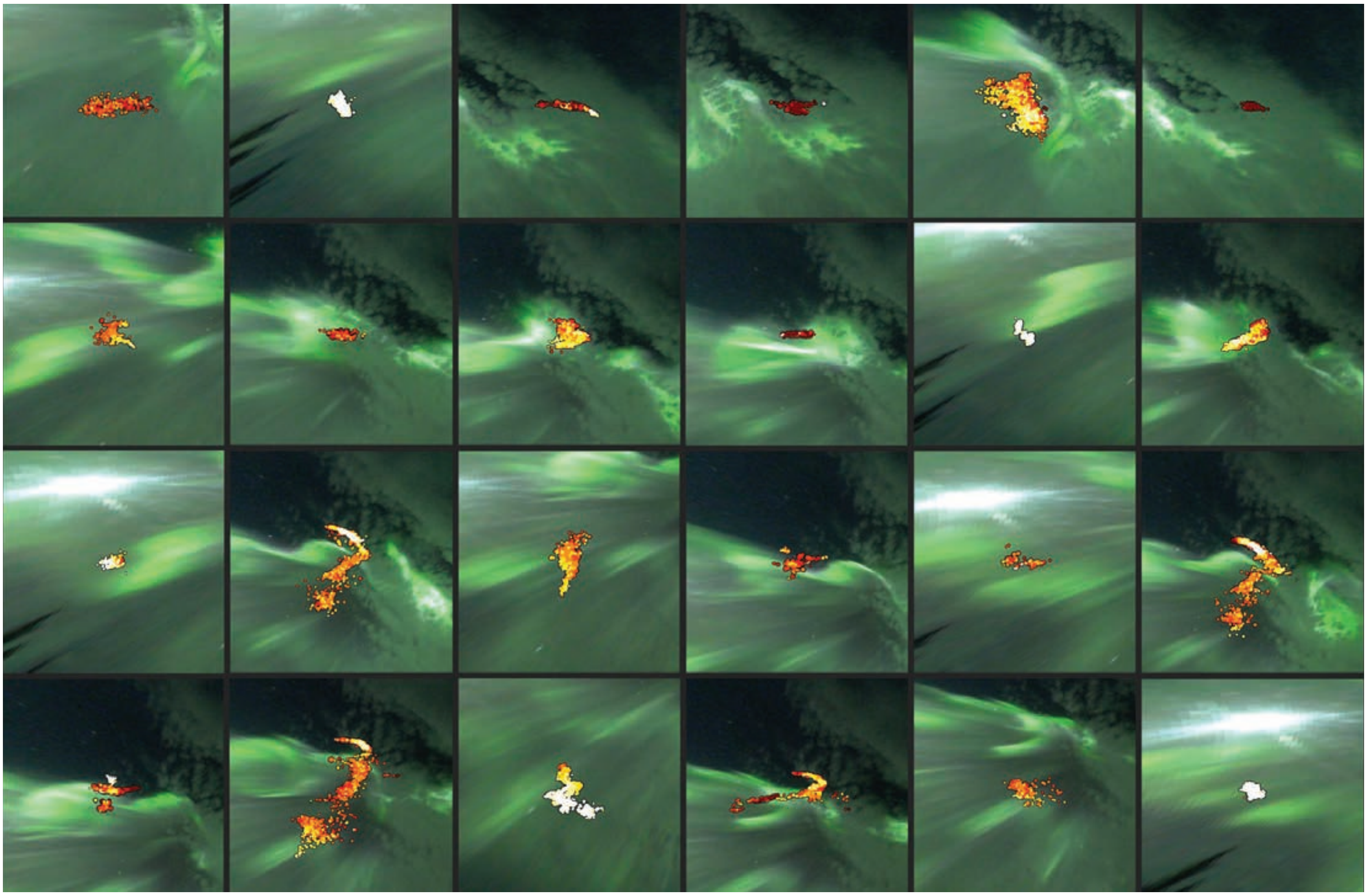
The researchers compared two models—their new CO_2 process-based transport model and an existing statistical upscaling model—that pulled from the same CO_2 dataset of samples from around the world. For their model, the team used data from 6,324 sites across the contiguous United States. The new model estimated CO_2 emission levels 25% lower than what the upscaling model suggested. It also suggested differences on a regional level, such as slightly lower fluxes in East Coast and Midwest waterways and slightly higher fluxes in the mountainous West.

A new model captures carbon fluxes for rivers, lakes, and reservoirs in the contiguous United States, including the Columbia River, seen here. Credit: SMcD22/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

The results from the new model suggest that rivers, rather than lakes or reservoirs, are the main driver of CO_2 emissions among inland water sources in the contiguous United States. Stream corridors—the land and complex ecosystems surrounding waterways—may account for 84% of these CO_2 emissions, especially in the West and around larger rivers. Groundwater sources account for the remaining 16%.

Improvements in modeling capabilities could help further quantify the role that inland water sources play in contributing to CO_2 levels in the atmosphere, the researchers say, especially on a global scale. (*AGU Advances,* https://doi.org/10.1029/2024AV001294, 2024) **—Rebecca Owen,** *Science Writer*

Radar Reveals Electrical Activity in the Ionosphere



Researchers collected images of radar echo locations, or structures containing plasma turbulence in the thin, ionospheric plasma about 110 kilometers above Earth's surface. Each image was taken straight up toward the sky, and the bright white light seen toward the top of some frames is from the Moon. Credit: Magnus Ivarsen/TREx RGB

At night, charged particles from the Sun caught by Earth's magnetosphere rain down into the atmosphere. The impacting particles rip electrons from atoms, creating both beauty and chaos. These high-energy interactions cause the northern and southern lights, but they also scatter radio signals, wreaking havoc on ground-based and satellite communications.

Scientists would like to track electrical activity in the ionosphere by measuring the distribution of plasma, the form matter takes when positive ions are separated from their electrons, to help better predict how communications will be affected by electromagnetic energy.

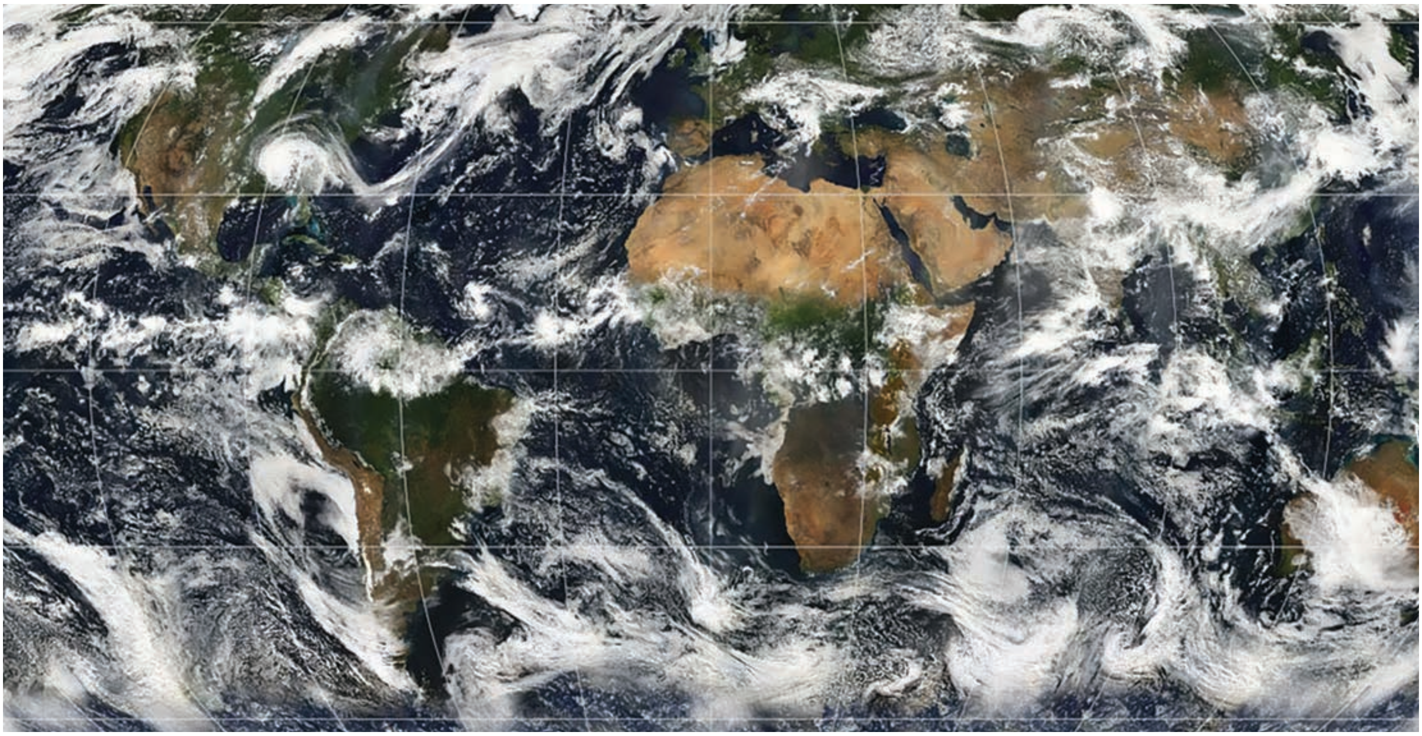
But analyzing plasma in the ionosphere is a challenge because its distribution changes quickly and is often unpredictable. In addition, collisional physics makes detecting true motion in the lower ionosphere exceedingly difficult.

Using a dataset from a radar system called ICEBEAR (Ionospheric Continuous-wave *E* region Bistatic Experimental Auroral Radar), *Ivarsen et al.* applied a new algorithm that can detect clusters of radar echoes indicating plasma structures as small as a meter across and track their movement in the ionosphere. From the movement of these structures, researchers can infer the properties of the electric field causing their motion.

The researchers tested their system using data from days during which ionospheric activity was difficult to parse using conventional methods. The results were consistent with those from simultaneous low-Earth-orbit satellite measurements, which currently offer one of the few ways of understanding these high-energy interactions.

Combining the high-resolution data from ICEBEAR with the new algorithm makes it possible to track the motion of electric field bursts, the researchers conclude. However, they note that some of these bursts may be too quick or localized for the algorithm to handle, so further improving the technique to identify patterns with greater nuance is a natural next step. The findings may help scientists predict when and how communications will be disrupted. Coupled with computer vision techniques, they could also help scientists design communication methods that are resilient in the face of electromagnetic activity in space. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2024JA033060, 2024)

—Saima May Sidik, *Science Writer*



This map shows global cloud cover on 11 July 2005 based largely on observations by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on NASA's Terra satellite. The cloud cover patterns reveal large-scale atmospheric circulation. Credit: NASA

Bringing to Light Climate Change's Effects on Atmospheric Circulation

The effects of climate change in thermodynamic signals, such as atmospheric temperatures, is relatively well understood. Its effects on atmospheric circulation, however, are more complex because the atmosphere is noisy and chaotic and because thermodynamic changes can generate effects that make circulation changes difficult to decipher.

Models offer many robust predictions of changes in atmospheric circulation resulting from climate change, but these predictions have proven difficult to verify. That's beginning to change as researchers accumulate a longer observational record of atmospheric circulation and as they develop new tools.

Shaw et al. review known effects of climate change on circulation, summarize the current understanding of their mechanisms, and point to knowledge gaps and opportunities for future research. They forecast a coming "golden age" in the study of circulation dynamics that may resolve discrepancies between models and observations and improve our understanding of how climate change will affect Earth's climate system.

Already-detected signals of climate change affecting circulation include a poleward shift of jet streams in the lower troposphere and a weakening of the Northern Hemisphere jet stream and storm track. The dynamics of some signals are understood and have been attributed to human activities. For example, efforts to improve air quality have led to a decrease in aerosols over land. Because aerosols reflect sunlight, this decrease has led to increased surface radiation and surface temperatures, which has weakened the summertime Eurasian jet over the past 40 years.

The precise mechanisms behind other signals, such as the shift of the Hadley cell edge, which represents the edge of the dry subtropics where deserts are predominantly located, remain debated. Several other signals have been proposed or modeled but have not yet been seen in observations.

In some cases, glaring discrepancies exist between modeled predictions and observations. They show opposite trends in how the tropical Pacific's sea surface temperature pattern is changing, for instance, which leads to discrepancies in regional storm track trends. Another challenge lies in distinguishing climate change–related responses from noise.

These and other issues may soon be resolved, the authors say, through the use of better data and new tools such as artificial intelligence that offer improved analytical capabilities. Studies that track signals across seasons and regions or that focus on extreme events could be particularly useful, they write.

Such advances could help elucidate the mechanisms behind complex circulation dynamics and improve how they are represented in climate models, enhancing our understanding of global atmospheric patterns and improving forecasts of climate change. (*AGU Advances*, https://doi.org/10.1029/2024AV001297, 2024) **—Nathaniel Scharping,** *Science Writer*

Warm Seawater Encroaches on Major Antarctic Ice Shelf

The vast Antarctic Ice Sheet holds more than half of Earth's fresh water. In several places around the continent, the ice extends over the ocean, where it forms large floating shelves. Observations suggest that many of these ice shelves are thinning as they melt from below, with implications for ocean dynamics, global sea level, and Earth's climate.

For now, the Filchner-Ronne Ice Shelf—one of Antarctica's biggest, extending over the Weddell Sea—appears to be relatively stable, thanks to near-freezing currents circulating over the continental shelf beneath it. However, climate models predict that shifting ocean currents may bring warmer water to the continental shelf in the future.

Scientists are keeping a keen eye on Antarctica's ice shelves, including the Filchner-Ronne Ice Shelf, pictured here, because of their predicted future influence on sea levels and climate. Credit: Observational data courtesy of Landsat 8 satellite (Bands: 2, 3, 4, 8) & USGS. Data processed by Paul Quast. O.V.E.R.V.I.E.W./Flickr, CC BY 2.0 (bit.ly/ccby2-0)

To gain a clearer picture of the Filchner-Ronne Ice Shelf's future, *Steiger et al.* analyzed water temperature and velocity data from 2017 to 2021. The data were captured by sensors attached to bottom moorings along the seafloor and subsurface floats near the ice shelf.

Prior research had already shown that during summer, relatively warm seawater rises from middle depths in the nearby ocean up to the continental shelf, then along the undersea Filchner Trough toward the edge of the ice shelf. However, most of these observations have been limited to single-site or single-year data.

In this study, researchers found that the summertime flow of warm water occurs not just along the Filchner Trough but also along a second, smaller trough to the east and that the relative importance of each path varies from year to year. During warmer-than-average years, the warm water flows more rapidly across the continental shelf.

In addition, the analysis highlights two summers, 2017 and 2018, when both anomalously warm inflows and anomalously low amounts of floating sea ice occurred. The researchers suggest that scant ice cover alters ocean dynamics, causing warm water to rise and more readily surge onto the continental shelf.

It is not clear whether the warmer flows of 2017 and 2018 actually reached the edge of the Filchner-Ronne Ice Shelf itself. However, researchers did observe warmer waters meeting the ice in summer 2013, and previous research suggested this warm water movement was associated with wind patterns.

Ongoing observation could help clarify the precise drivers of year-to-year differences in this warm water flow. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2023JC020700, 2024) **—Sarah Stanley,** *Science Writer*

Magmatic Fluids and Melts May Lie Beneath Dormant German Volcanoes

Central Europe may not come to mind when considering areas at risk of a volcanic eruption. However, as recently as 11,000 years ago, volcanoes erupted in the Eifel Mountains of what is now western Germany.

Today the Eifel volcanic field lies dormant, but multiple lines of evidence have hinted that new eruptions could one day occur. Now, *Eickhoff et al.* have applied advanced seismic imaging techniques to peer into the crust beneath the region in unprecedented detail, highlighting multiple subsurface structures that appear to be pockets of magma and magmatic fluids from the upper mantle.

The new analysis actually revisits data collected in the Eifel region 35 years ago by specialized trucks that direct seismic signals into Earth's crust and then detect reflected waves. Since then, techniques for processing this seismic reflection data have advanced considerably, enabling today's scientists to extract far more detailed images of subsurface features from existing datasets.

In addition to imaging previously detected subsurface structures at higher resolution, the team outlined features never seen before. These structures—detected at depths of 10–30 kilometers—are similar to sills, or flat sheets of igneous rock that form between existing crystalline host rock. The features' characteristics suggest that they may be pockets of magmatic melt, fluids, or supercritical gas that rose into the crust from the upper mantle.

The presence of these potential magmatic patches raises the possibility that future eruptions could occur in the Eifel region should the magma become buoyant enough to ascend to the surface. The researchers call for further study using state-of-the-art volcanic assessment techniques to better clarify the area's volcanic hazards. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL111425, 2024) **—Sarah Stanley,** *Science Writer*

Executive Director,
Roger F. Wicker Center for Ocean Enterprise

Job Summary: The Executive Director of the Roger F. Wicker Center for Ocean Enterprise will be responsible for overseeing a new research and development facility focused on blue technology innovation. Their duties will include managing the facility, supporting leasing and outreach efforts, and fostering a collaborative environment for economic development. The goal is to advance new technologies to market and meet the research and development needs of various partners, including federal, state, academic, and industry entities.

Primary Duties and Responsibilities: Financial Leadership and Strategic Growth: As the Executive Director, you will be responsible for the overall financial health and strategic direction of the Roger F. Wicker Center for Ocean Enterprise. This includes developing and implementing comprehensive business plans, managing fiscal resources, and driving sustainable growth through strategic initiatives.

Operations Management and Tenant Relations: You will oversee all operational aspects of the Center, including staff management, policy development, contract negotiations, and tenant relations. Your focus will be on ensuring a high level of tenant satisfaction by providing exceptional support and addressing their needs proactively.

Business Development and Fundraising: You will actively seek out new business opportunities and funding sources through strategic outreach, relationship building, and effective marketing. Your ability to connect with potential clients, government officials, and industry influencers will be crucial to the Center's success.

Development and Collaboration: You will play a key role in supporting USM's vibrant blue economy innovation ecosystem by collaborating with various stakeholders, including other USM units, government agencies, non-profit organizations, and economic development entities. Your ability to build strong partnerships and drive collaborative initiatives will be essential.

Talent Management and Development: You will be responsible for recruiting, supervising, and providing career development opportunities for the Center's staff. Your leadership will be instrumental in creating a positive and supportive work environment that attracts and retains top talent.

Other duties as assigned.

Minimum Qualifications: A Master's degree in a relevant field (e.g., marine, coastal and ocean science, ocean engineering, data science, marine policy, maritime logistics, robotics, etc) and 5 years of related experience. Ability to obtain a Transportation Worker Identification Credential (TWIC) and clear other research security and export control regulations.

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monitor
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