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Caching Carbon

Scientists Explore an Ocean of Possibilities

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From the Editor

This year, our ocean issue recognizes the United Nations Ocean Decade with a close look at the carbon cycle in the deep blue sea. In "Our Evolving Understanding of Biological Carbon Export" (p. 20) researchers analyze the processes and organisms that make up the biological carbon pump. Authors of the opinion "The Science We Need to Assess Marine Carbon Dioxide Removal" (p. 16) encourage scientists to develop standards for judging the effectiveness of carbon dioxide removal methods. Finally, with research presented at AGU23, we examine when and how carbonate corals made a new island in the Philippines (p. 2). Dive in!

On the Cover

Seagrass stretches toward the sunlight at Lassing Park in St. Petersburg, Fla. Credit: Joe Walen, Unsplash

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A Philippine Island Detective Story

Sometime in the past 50 years, a small island appeared about 100 meters off the coast of Lumaniag Village in the Philippines, 77 kilometers southwest of Manila. The island consists of large coral boulders and mangroves sitting atop a gravel bar and helps shield the village from punishing waves and storms.

But accounts of when and how the island appeared remained fuzzy. So a team of researchers set out to uncover when and how the island came to be. They collected field measurements, archival data, and interviews from village elders to reveal the island's stormy history.

A new island off the coast of Lumaniag Village, Philippines, is about 100 meters from the coast at low tide. Credit: DOST-PCAARRD Tsunami Project, via Adonis Gallentes

Collecting Clues

The island is 100 meters at its widest and runs parallel to the mainland coastline for about half a kilometer. Mangroves cover its landward side, and gravel and coral boulders litter the seaward side.

The base of the island is a gravel bar, which Lumaniag villagers agreed built up slowly, said Adonis Gallentes, lead researcher on the project and a marine science graduate student at the University of the Philippines Diliman. For a while it remained submerged, even at low tide, until "powerful waves brought large boulders to the area and made the island visible overnight," Gallentes said the villagers reported.

But were those powerful waves from a tsunami or a storm? Were they the result of one event or many?

During several visits to the island, the researchers cataloged 108 coral boulders that were at least 1 meter on their longest side and measured each boulder's position, size, orientation, and density. They snorkeled to survey the surrounding reef, mapped the coastal profile, and collected bathymetry data of the seafloor. These measurements helped show that the boulders came from the reef southwest to northwest of the island. To move them, waves at least 1.8 meters high would have been needed.

Next, the researchers determined when the coral boulders were deposited on the nascent gravel bar. They drilled core samples from the boulders, and uranium-thorium (U-Th) radioisotope ages from 22 of them revealed that the corals were ripped from the reef and died between the 1960s and the early 1970s.

To corroborate the U-Th ages, the researchers gathered historical records on earthquakes, tsunamis, and typhoons. Records showed no tsunamis taking place around the time the coral boulders died, but the team was able to identify 11 typhoons with timings, strengths, and tracks that could have moved them.

"Everything suggests that the island was formed by storm events, not tsunamis, and that the most crucial events happened during the 1960s to early 1970s," Gallentes said.

The new island is covered by large coral boulders on the seaward side and mangroves on the landward side. Credit: DOST-PCAARRD Tsunami Project, via Adonis Gallentes

Research assistant Michelle Manglicmot interviews an elder living in Lumaniag Village about historical storms and wave events. Credit: DOST-PCAARRD Tsunami Project, via Adonis Gallentes

"Powerful waves brought large boulders to the area and made the island visible overnight."

Finally, with a short list of typhoon candidates in hand, the team interviewed 11 Lumaniag villagers old enough to have lived through the storms. The villagers agreed that no tsunami-generating earthquakes took place during the time in question, but they recalled the destructive effects of Typhoons Dading (international name: Winnie) in 1964 and Welming (Emma) in 1967. In addition,

Researchers (clockwise from left) Mikko Garcia, Benjamin Ermita, and Fernando Siringan collect a core sample from a coral boulder for uranium-thorium analysis. Credit: DOST-PCAARRD Tsunami Project, via Adonis Gallentes

Adonis Gallentes stands near coral boulders that were transported by waves far larger than the transitional monsoonal waves visible here. Credit: DOST-PCAARRD Tsunami Project, via Adonis Gallentes

Adonis Gallentes stands next to one of the coral boulders on the new island near Lumaniag Village. Credit: DOST-PCAARRD Tsunami Project, via Adonis Gallentes

one resident specifically mentioned that boulders were brought in by a typhoon in 1971, when her sister was 15 days old. Most likely, that would have been Typhoon Barang (Elaine) or Krising-Dadang (Faye-Gloria) in October of that year.

The team looked at the wind speed and path of each storm and found that all four created waves strong enough to have transported the boulders. None of the storms was in the strongest category for typhoons, but they all had just the right track to help turn an unassuming gravel bar into a barrier island.

"This study demonstrates that a coast's geomorphology can be greatly altered by typhoons," and not only the strongest ones, the team wrote in a *Geomorphology* paper on the research (bit.ly/coral-boulder-transport). The researchers presented their work at AGU's Annual Meeting 2023 (bit.ly/AGU23-island).

A Village's Shield

"I find this research compelling and timely," said Talea Mayo, a coastal ocean modeler at Emory University in Atlanta. She complimented the researchers' "comprehensive" use of tools to unravel the island's history. "The use of U-Th to narrow and identify the likely timeline of associated events, and then a combined approach to further narrow likely causes, is novel, with fascinating results."

Studies like this one "may inform the development of nature-based approaches to the resilience of coastal communities," said Mayo, who was not involved with the research.

"At present, the nearby community is thankful for the existence of this new island," Gallentes said. Strong storms have become more frequent in recent decades, he added, but the island "acts like a shield" by dissipating waves before they reach the mainland.

"This study demonstrates that a coast's geomorphology can be greatly altered by typhoons."

Human intervention strengthened that shield. Villagers planted a patch of mangroves on the island's landward side in the 1990s, and more mangroves naturally colonized other areas of the island later. They have helped prevent subsequent large storms from sweeping the boulders away.

However, Lumaniag's shield could one day be overcome by a strong enough storm. "When that happens," Gallentes said, "the gravels and mangrove debris that will be carried by the waves can even be more destructive to the community."

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

Ocean Vessels May Trigger Lightning Strikes

Since ancient times, sailors have feared sudden lightning strikes, which could set ships alight and doom crews. Today that danger is minimal, but lightning itself could be even more common. Recent research indicates that oceangoing vessels might, in fact, make lightning more likely.

The mechanisms for this lightning enhancement are still debated. One theory holds that aerosols emitted in ships' exhaust alter how storms develop, leading to more lightning. Alternatively, the ships themselves—tall metal objects on a watery plain—could draw in strikes.

In a new study published in *Earth and Space Science* (bit.ly/ships-lightning) and a presentation at AGU's Annual Meeting 2023 (bit.ly/AGU23-ships-lightning), scientists take a fresh look at the phenomenon with the help of additional data pairing the locations of lightning strikes and the locations of ships.

Though the data don't show direct strikes to ships, they do show a distinct prevalence of lightning strikes very close to shipping lanes versus slightly farther away, said study author Michael Peterson, a scientist at Los Alamos National Laboratory. His takeaway: Ocean vessels attract lightning strikes and likely even cause them in some cases.

Electrifying Encounters

The idea that shipping traffic might increase the frequency of lightning strikes was first put forth in a 2017 paper that used data from a network of ground-based sensors called the World Wide Lightning Location Network (WWLLN; bit.ly/lightning-enhance). The authors found that lightning density was up to 2 times greater in some areas of the South China Sea and Indian Ocean near shipping lanes than in regions without ship traffic.

They suggested that aerosol particles from ship exhaust might change convection inside thunderstorms, increasing electrification and causing more lightning bolts to strike.

Peterson said he thinks there also may be another, simpler explanation: Ships are big metal poles.

He looked at the same WWLLN data the authors of the 2017 paper did and added in data on shipping emissions from the Emissions Database for Global Atmospheric Research (EDGAR), as well as transponder data that track the locations of ships around the world.

"Understanding the origin of lightning enhancement over ship tracks is important and unresolved," wrote Yakun Liu, a postdoctoral researcher at the Massachusetts Institute of Technology who studies lightning, in an email. "Lightning generation over ship tracks is an excellent natural experiment to infer the physics involved," said Liu, who wasn't involved in the new research.

By putting ship transponder data together with data from WWLLN recording the locations of individual lightning strikes, Peterson found that lightning was 15 times more likely to occur near a ship than 2 kilometers (1.2 miles) away and 66 times more likely than 25 kilometers (15.5 miles) away.

"You introduce a tall metal object like that in such an environment where you already have strong electric fields—that could potentially incite additional lightning flashes."

The magnitude of the increase in strikes was surprising, Peterson said. "That ended up being something that we didn't expect to find, to be honest," he said.

To Peterson, it's a clear sign that ships are precipitating lightning strikes. If strikes were being caused by aerosols from ship exhaust, they'd likely happen over a more dispersed area, he said, not just in the very near vicinity of the ships themselves.

Location Matters

Ship transponder data are expensive, so Peterson was able to look at data only from in and near U.S. coastal waters. With the EDGAR data, he was able to get a worldwide view of shipping lanes. Ship emission aerosols lead to the formation of low-lying clouds, much like airplane contrails, that appear behind ships as they move. They are therefore a proxy for shipping traffic, though they don't show individual ship locations.

That data set also showed that lightning strikes were more common very close to shipping lanes compared with areas nearby with less shipping traffic—but only in the Bay of Bengal and the South China Sea. In other regions, such as the Red Sea, Mediterranean,

Lightning strikes over the ocean may be made more likely by ships and the aerosols they emit in their exhaust. Credit: Zoltan Tasi/Unsplash and U.S. East Coast, there was no increase in lightning near shipping lanes.

Peterson said he thinks the Bay of Bengal and South China Sea might host clouds that are highly electrified but don't produce many lightning strikes. Ships could provide the extra push to tip these clouds into generating sizzling bolts of electricity.

"You introduce a tall metal object like that in such an environment where you already have strong electric fields—that could potentially incite additional lightning flashes," Peterson said.

Meanwhile, strikes in other places, such as near the U.S. East Coast, might also be precipitated by ships, but not frequently enough to reveal patterns in WWLLN data.

In all, 36% of the vessels with transponder data that Peterson looked at in his study had experienced a near or potentially direct lightning strike over the course of 3 years. Some ships, like those that sail through stormy waters in the Gulf of Mexico, had seen dozens or even hundreds of close strikes.

Though Peterson's work indicates that metal ships likely incite lightning strikes, he points out that aerosols probably play a role as well. It's likely that both aerosols from marine diesel and the presence of ships themselves are enhancing lightning near shipping lanes, though their relative contributions are still unclear.

"Clearly, there is not a simple or direct answer."

"Clearly, there is not a simple or direct answer to the question of how lightning discharges are invigorated over ship tracks," Liu said.

Better data on lightning activity near ships would help clear the matter up and, Liu said, would also be important to the shipping industry. Though ships are designed to channel lightning to the water without harming people, equipment for steering, navigation, and more might be damaged by strikes, he said. Knowing where a strike may be more likely and what, if anything, could be done to reduce the risk could help keep ships, and their human passengers, safe.

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

Affordable Robots Measure Soil Respiration

George Koech, Elizabeth Forbes, and John Naisikie Mantas install fluxbots at Mpala Research Centre in Kenya. Credit: Spencer Frey

When Elizabeth Forbes walked into an enormous spiderweb and its weaver at the Mpala Research Centre in the Kenyan savanna, she was most worried about the approximately $45,000 carbon dioxide flux chamber in her backpack.

"The first thing I did was carefully take the backpack off, put it on the ground, and then freak out and try to get the spider off me," she said.

Forbes was conducting research on how the loss of large herbivores affects carbon cycles in the savanna for her doctorate in ecology at the University of California, Santa Barbara. Lugging around an expensive, heavy instrument wasn't ideal for long field days (or spider encounters), so she set out to create a more affordable way to measure soil carbon flux.

Soil carbon flux, or the rate at which carbon dioxide (CO_2) is exchanged between the atmosphere and the soil, provides key information about an ecosystem's carbon budget. Massive amounts of carbon are stored in Earth's soils, but anything from respiring microbes to cracks in soil to anthropogenic activities such as deforestation can cause that carbon to move into the atmosphere.

"Measuring soil carbon flux…is central to understanding terrestrial ecosystem dynamics," wrote George Koech, an ecologist at Mpala, in an email. "Soil carbon serves as the primary energy source for microorganisms and exerts a fundamental influence on soil structure and ecosystem productivity."

"Soil carbon serves as the primary energy source for microorganisms and exerts a fundamental influence on soil structure and ecosystem productivity."

However, gathering detailed data on soil carbon flux is traditionally either time-consuming or expensive. And standard methods aren't continuous. Expensive autonomous instruments can't be left unattended overnight where they could be trampled by animals or flooded by rain. "You kind of need to babysit them," said Kathleen Savage, a biogeochemist at the Woodwell Climate Research

Center. This leaves many areas without data on nighttime and postrainfall fluxes.

"A lot of the field is looking at lower-cost options, where you kind of sacrifice a little bit of the resolution, or how sensitive your instrument is, but you gain something more affordable," said Savage, who researches greenhouse gas fluxes from natural systems. She has developed some of these low-cost options herself but was not involved in the new instrument design.

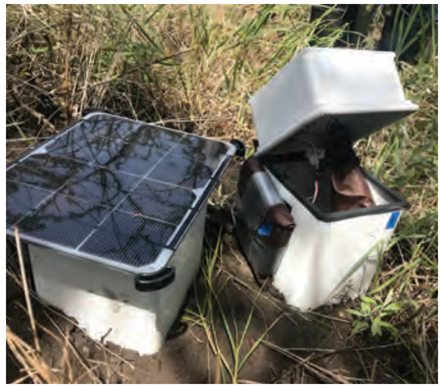
To manually gather soil carbon flux data, researchers insert a cylindrical collar a few centimeters into the ground. They then place a CO_2 sensor on top, trapping and measuring the CO_2 being emitted by the soil.

Forbes and her colleagues instead engineered a set of 18 lidded devices they call fluxbots. Each is a bit larger than a loaf of bread and costs about $367 to build.

"Instead of having to walk around with the little sensor version and plop it on top of these collars, the collar was the robot," said Forbes, now a postdoctoral research fellow at Yale School of the Environment. "The robot was just inserted into the soil, and the lid would open and close, sort of on a predetermined schedule."

The researchers installed the fluxbots in the Kenya Long-Term Exclosure Experiment at Mpala on plots with and without large herbivores. At both sites, they were distributed both beneath trees and in open areas.

The fluxbots collected hourly data for almost 2 months in 2019, resulting in more than 10,000 soil carbon flux measurements. The researchers published their findings in *Journal of Geophysical Research: Biogeosciences* (bit.ly/fluxbots) and presented them at AGU's Annual Meeting 2023 (bit.ly/AGU23-fluxbots).



The researchers' do-it-yourself approach, intended to make the fluxbots affordable, sometimes meant using tools such as duct tape, zip ties, and clear nail polish. Credit: Elizabeth Forbes

Moisture's Surprising Role

Carbon flux tends to correlate with heat: The warmer the soil temperature is, the more active microbes are, and the higher the carbon flux is. To their surprise, the scientists found that carbon flux at Mpala was higher at night. They suggested that in ecosystems with high heat and limited water, soil carbon flux is more tightly coupled to moisture than to temperature. They also found that flux levels were lower beneath tree canopies than in open areas and higher in areas with herbivores than without. They theorized that large animals such as elephants can disturb soil and cause higher flux.

Forbes noted that the fluxbots made it possible to gather data that otherwise would have been inaccessible. Nevertheless, the team recommended several improvements for future fluxbot iterations, one of which is already in the works. One change is an adapter collar that would allow researchers to validate a fluxbot's measurements on the same soil footprint as the fluxbot itself.

With the original instrument, researchers cross-checked the data by measuring a nearby soil patch. But because carbon flux can vary significantly over small areas, validating the results was complicated. Savage agreed with the suggested fluxbot upgrade, noting that her group does the same with devices they have developed.

The low-cost fluxbots could be particularly useful in the Global South, Savage said, because many countries there don't have sufficient data to do their carbon accounting. Some, such as the Democratic Republic of the Congo, even rely on measurements of other countries' carbon levels to estimate their own.

Instruments such as the fluxbots are "perfect" for these countries to make their own measurements in their own forests, Savage said. "It's a big leap, and it's relatively cost-effective."

By **Emily Dieckman** (@emfurd), Associate Editor

An Electrifying Approach to Carbon Capture

Scientists are developing technology to bring more alkaline water to the ocean surface. Credit: Matt Hardy/ Unsplash

As the race to reduce greenhouse gases in the atmosphere intensifies, a group of researchers at the University of Calgary is using electricity to enhance seawater's ability to store carbon.

The group is developing an instrument, dubbed PEACH (Practical Electrochemical Air Capture and Hydrogen), that uses an electrochemical cell, analogous to a lithium-ion battery, to capture alkaline sodium ions from salt water.

Although a prototype is still being designed, electrochemist Arthi Gopalakrishnan said the PEACH module will be a book-sized device made of nickel-plated steel that could be bolted onto others in an array.

These arrays could be lowered more than 500 meters into the ocean to gather ions, then raised to release them as sodium hydroxide at shallower depths, creating an "alkalinity pump" from deep water to the surface.

Alkaline surface waters draw carbon dioxide (CO_2) from the atmosphere, eventually converting it to bicarbonate, which can securely store carbon in the ocean for more than 10,000 years. A by-product of the ion exchange is hydrogen, which could be stored as a fuel. The group presented the research at AGU's Annual Meeting 2023 in San Francisco (bit.ly/AGU23-PEACH).

Building Blocks

Although PEACH technology has yet to advance beyond a laboratory setting, geochemist Steve Larter, who first developed the concept, said the scalability of the technology is part of what makes it so exciting.

"Think of it as a LEGO brick," Larter said. "One LEGO brick will do so much. You can stack hundreds together, and you'd have a bigger system."

> **"We don't have other technologies that could scale up at this level."**

This modularity is what attracted Gopalakrishnan to work on the project. "Our system is very flexible," she said. "We don't have other technologies that could scale up at this level."

PEACH technology, Larter said, could be deployed extensively in the ocean, perhaps on floating platforms. "You might imagine something that has wind turbines or solar panels on it to generate power, electrochemical cells, and then pumps and pipes to move the water around."

However, PEACH could also be used at a smaller scale on land, for example, in the reservoirs of brine produced by oil and gas drilling. PEACH cells, Larter said, could add carbon dioxide to the brine before it is reinjected underground.

Effects on Marine Ecosystems

The PEACH project is one of several ocean alkalinity enhancement (OAE) technologies being developed globally. Many of them involve seeding the ocean with mined minerals or industrial by-products. PEACH "just utilizes the ocean water. It's mimicking the natural process of [carbon] capture from the atmosphere," Gopalakrishnan said.

Mike Kelland, CEO of Canadian carbon sequestration company Planetary Technologies cautions that electrochemical OAE approaches such as PEACH are not entirely benign. Planetary Technologies uses magnesium hydroxide to lower ocean acidity. "It's true that they haven't added anything to seawater," Kelland said, "but the actual effect is a complete change of the ocean's chemistry, in exactly the same way as if you've added something."

Larter and Gopalakrishnan acknowledged that care would be needed in deploying the process at scale.

"You're adding slightly more basic water to the near-surface seawater; you don't want to add it in a very concentrated form so that you kill everything there," Larter said.

"We need to spread it across time," Gopalakrishnan said. "These are parameters that might be challenging when we deploy at scale."

Chemistry Is Key

Pumping sodium ions from depth should be relatively safe at modest scales, said Lennart Bach, a marine biogeochemist with the University of Tasmania who studies the ecological effects of OAE. However, "if you extract alkalinity from depth, what happens if that alkalinity-depleted [more acidic] deep water gets upwelled to the surface?" Bach is not involved in the PEACH project.

The Calgary team noted that judicious choice of deployment location would be important when rolling out these technologies.

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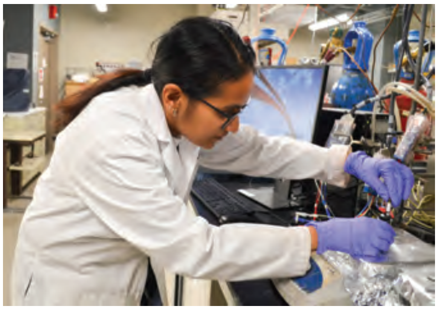


Technology that Arthi Gopalakrishnan (pictured here) and her colleagues are developing in a laboratory at the University of Calgary could one day be used to draw gigatons of carbon dioxide from the atmosphere. Credit: Nadine Sander-Green

Deep bottom water, Bach said, should eventually return to a more alkaline state through natural processes.

Other so-called blue carbon ocean sequestration techniques—such as farming kelp or using iron fertilization to stimulate phytoplankton blooms—rely on manipulating plant growth to drive carbon capture. Bach said he favors techniques such as PEACH, which avoid biological drivers. "Don't rely on biology to do the job," he said, "because biology is another level of complexity, and using it for CO_2 removal appears to be much harder."

"Geoengineering is not, in principle, a dangerous thing, but it is something we might have to do."

PEACH technology might one day be part of a suite of techniques used in a "colossal industry" to remove carbon from the atmosphere, Larter said. And though the public is rightly concerned about technology that manipulates natural processes, "we're already geoengineering," he said. "Most of the CO_2 we emit goes into the ocean anyway, acidifying it."

"Geoengineering is not, in principle, a dangerous thing, but it is something we might have to do, and we need to do it safely," Larter said. "So we need to research it."

By **Bill Morris,** Science Writer

A Not-So-Hoppy Future for Beer?

Europe is home to prime areas for growing aromatic hops, a flower used in brewing beer. But, as conditions have gotten hotter and drier, yields have declined in the continent's hops-growing heartland, according to a study recently published in *Nature Communications* (bit.ly/hops-decline). Soaring temperatures are also reducing hops' alpha acid content, the source of beer's bitter flavor.

Though the findings seem to spell an uncertain future for hoppy beer, some experts have cautioned that changing tastes and an adapting industry are likely contributing to the trends.

Hoppy Conditions

According to the World Meteorological Organization, Europe is the world's fastest warming continent, with average temperatures currently more than 2°C higher than during the preindustrial period. Droughts have increased in strength and frequency since the 1800s (bit.ly/Europe-drought).

Focusing on the Czech Republic, Germany, and Slovenia, researchers paired industry data on hops yields and alpha acid content over two 24-year periods, 1971–1994 and 1995–2018, with regional weather data and long-term climate records from European meteorological agencies. Comparing the two time periods, the researchers found that dry conditions caused hops yields to fall by almost 20% in some regions, while alpha acid content dropped by as much as 34%.

Hops sprout from rootstock in early spring, flower at the start of summer, and develop flavor-filled "cones" as days shorten after the summer solstice. The data showed that the start of the hops growing season has shifted forward by about 13 days since 1970, and the cones are developing up to 31 days earlier. That means the hops are ripening under longer, hotter days.

"If the hops are grown in hotter temperatures, that is going to force the plant to use more water," said Colorado State University plant scientist William Bauerle, who was not involved in the study. "It's going to degrade the alpha acids and the aroma profile, the volatiles, and the essential oils. Those aromas can literally just volatilize away—they evaporate into the air and are lost."

Adapting to the changes will be difficult, said study coauthor Miroslav Trnka, a climate scientist at the Czech Academy of Sciences. Though the lack of water availability can be addressed to some extent through irrigation, "defending the field against high temperatures is very difficult," he explained.

Many other food crops, such as barley, can be sown and harvested earlier in the year to avoid the extremes of midsummer, Trnka said, but hops are tied to the shortening days, meaning that "you cannot actually avoid the summer heat."

Farming, he said, "has always been seen as something [for which climate] adaptation is fairly easy and straightforward." But these findings show that "we should not overestimate our adaptation [capabilities] because there are some obstacles that are hard to play with."

The researchers' models predict that in a continuously warming climate, European hops yields will fall by 4%–18% by 2050, and alpha acid content could drop by as much as 30%. They warned that the European hops industry will need to expand by 20% to keep ahead of climate change.

"Those aromas can literally just volatilize away—they evaporate into the air and are lost."

Some experts, however, thought the study's findings could be taken out of context.

Adrian Forster, a coauthor of *Hops: Their Cultivation, Composition and Usage,* who has been studying the effects of climate change on hops since the 1990s, said that changing tastes in the beer market might have contributed to the observed changes. He noted that the study's authors equate alpha acid content with "quality," but the so-called "aroma hops" favored by craft brewers are naturally low in alpha acids. "The constantly changing range of varieties is not discussed," he said of the study. "This does have an impact on the yield and alpha acid content."

Hops breeder Kerry Templeton of New Zealand's Plant and Food Research also noted that the reported decline in alpha acid content coincided with the rise in popularity of craft beer brewing. Alpha acid, he said, is no longer the main indicator of hops quality for many brewers.

"Alpha acids are not the thing I'd be worried about causing a drop in hop quality," Templeton said. "Alpha's still important, but it's not the be-all and end-all of everything." Templeton was not involved in the study.

Caught on the Hop?

The industry has been aware of the impact of climate change on alpha acid production and crop yield for decades, and adaptation is well underway, Forster said. According to his

"I don't see our beer disappearing in a hurry."

recent research, different hops varieties react differently to heat and water stress: Older "landrace" varieties, which are closely adapted to local conditions, fare worse, whereas some newer breeds withstand a hot, dry season far better (bit.ly/hops-climate). That knowledge, he said, should allow breeders and brewers to shift their focus to more climate-resistant varieties, although he acknowledged it may take time.

"It's not so easy to convince brewers they have to change their recipes—they are quite conservative," Forster said.

Adaptation to climate change through selective breeding could mean revisiting the ancient varieties from which today's commercial hops varieties were originally cloned, Bauerle said. "We can breed, knowing those genetic histories, to adapt the hop to whatever climate we'd like to grow it in."

Hops yields are on the decline in some parts of Europe. Credit: Markus Spiske, Unsplash

"The trade-off will be giving up potential aroma and flavor profiles," Bauerle said. "You might be able to successfully breed for a warmer climate, but what kind of genetics do you give up in order to do that?"

Hops, Templeton said, might also be grown in other parts of the world. He pointed out that though hops are traditionally thought to grow only in a narrow band around the midlatitudes, commercial crops have been successfully trialed in Florida and Brazil using artificial outdoor lighting to control the photoperiod, or "day" length (bit.ly/supplemental-lighting).

"Worldwide there's a lot of areas that could be growing hops that aren't," he said. "I don't see our beer disappearing in a hurry."

By **Bill Morris,** Science Writer

Local Fishers Help Uncover Coral Clinging to Underwater Cliffs

Around 5 years ago, Joey Angnatok, an Inuit fisher, researcher, and boat captain, lowered fishing nets from his vessel, FV *What's Happening,* into the Labrador Sea near Makkovik, a town in Newfoundland and Labrador, Canada. Seafloor data suggested that the ocean should be 700 meters deep. But when he let out that much net, he still had several hundred meters of slack floating on the surface, indicating that the nets had hit bottom earlier than expected. As he tried to reel the nets back in, they got snagged.

"We ruined, I think, six or seven nets," Angnatok said.

Wanting to protect his gear in the future, Angnatok remembered writing "Don't ever come back here again" in his notebook.

Not long afterward, however, Angnatok's colleague David Cote, an ecologist at Fisheries and Oceans Canada who was searching for unknown areas of marine biodiversity, asked him whether he'd come across anything interesting recently. Angnatok is often consulted on research projects, because as a lifelong fisher who has been collecting climate data with researchers and fellow Inuit for more than 30 years, he has a strong knowledge of the sea bottom. "Over the years, you have a little dictionary in your head of what certain places look like," he said. Angnatok told Cote what happened with his nets, and the pair suspected that coral might have been the culprit.

After refining seafloor maps, researchers searched for coral gardens with a remotely operated vehicle. Credit: Dave Cote, Fisheries and Oceans Canada

Joey Angnatok's local ecological knowledge led to the discovery of unknown coral biodiversity in the Labrador Sea. Credit: Dave Cote, Fisheries and Oceans Canada

Angnatok's experience, combined with other local ecological knowledge, spurred the discovery of an unknown trove of coral biodiversity and helped improve seafloor maps of the Labrador Sea, according to a new study published in *Ecology and Society* (bit.ly/biodiversity-Labrador). "The benefits of working together are really illustrated in this project," Cote said.

Clues from the Deep

Cold-water corals are sensitive creatures, slow to recover from damage caused by deep-sea trawlers, oil and gas exploration, and climate change stressors such as rising water temperatures. They are also a priority for conservation because they provide vital habitats for many species.

To protect coral ecosystems in Labrador, researchers first needed to find them.

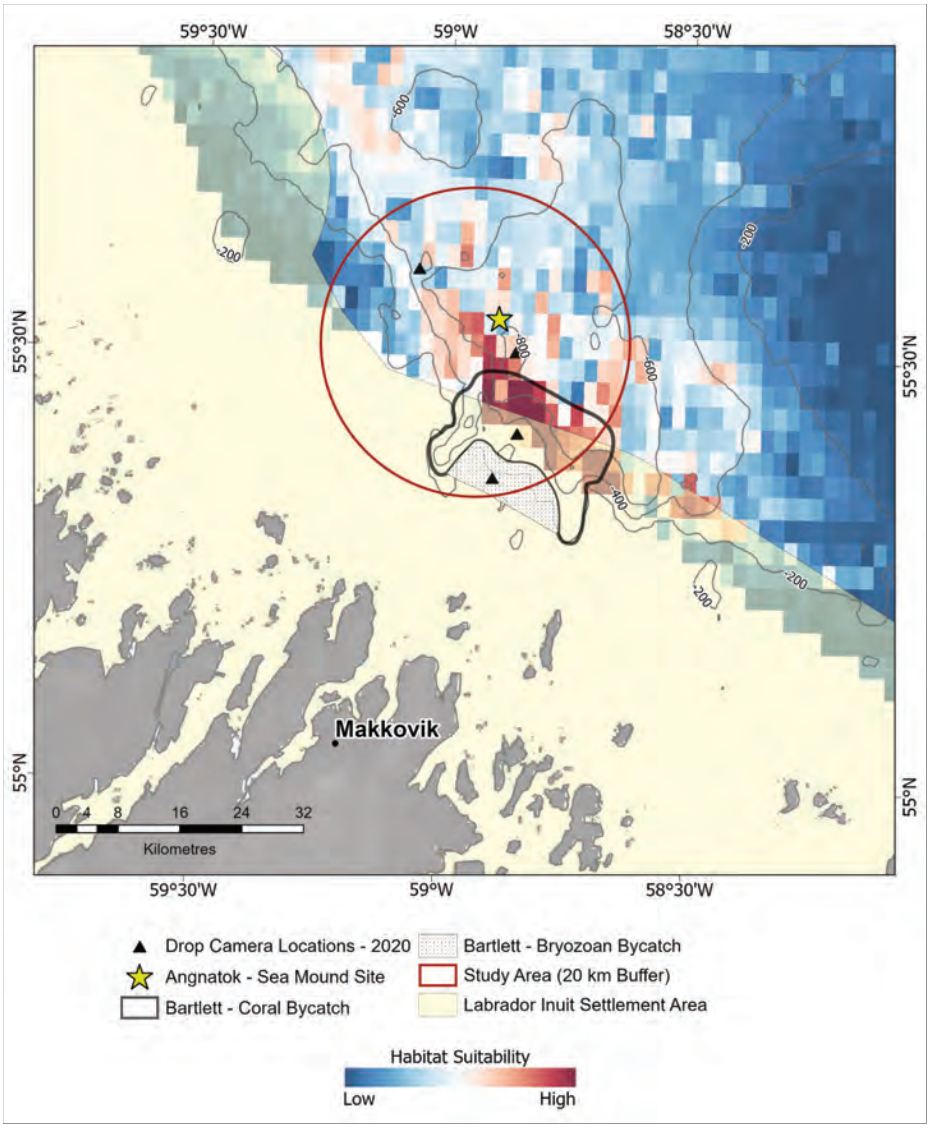
Many coral species thrive on underwater rocky slopes rather than in mud. But researchers had one big problem: The seafloor maps of the Labrador Sea are notoriously inaccurate, meaning that they couldn't be used to identify patches of steep seafloor to start the search.

The rise on the seafloor that Angnatok found was a clue to where coral might be, because seamounts often slope off steeply on all sides. Another local fishing captain, Wilfred Bartlett, had discovered coral in his fishing nets a few kilometers away from Angnatok's seamount.

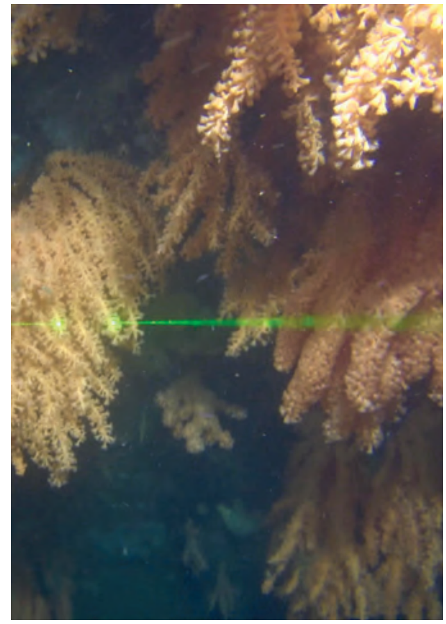
"What helped is that local people pinpointed where things were," said Vincent Lecours, a geographer at Université du Québec à Chicoutimi who wasn't involved in the study. "They identified the haystack to look in instead of having a barn full of hay and looking for the needle."

> **"Local people identified the haystack to look in instead of having a barn full of hay and looking for the needle."**

Computer models that predict the locations of coral habitats using fishing and envi-



Cameras surveyed parts of the Labrador Sea based on several knowledge sources, including the seamount detected by Joey Angnatok, coral regions identified by Wilfred Bartlett, and existing bathymetric data. Credit: Resilience Alliance, CC BY 4.0 (bit.ly/ccby4-0)



The researchers discovered an area of hidden coral biodiversity, called the Makkovik Hanging Gardens, by searching for underwater slopes and cliffs. Credit: Dave Cote, Fisheries and Oceans Canada

ronmental data also pointed to locations close to Bartlett's and Angnatok's points of interest. Using these data, the team triangulated an area to search for coral.

Improving Seafloor Maps to Refine the Hunt

Aboard CCGS *Amundsen* in 2020 and 2021, the researchers surveyed the target region with a multibeam sonar to improve the existing seafloor maps.

Within the maps, they could pick out an area of sloping bedrock—a good candidate for coral growth. To get a better view, the researchers piloted a remotely operated vehicle into the depths and faced the cliffs. "That's when these beautiful corals appeared on the control room screen," Cote said. "Everybody was pretty excited."

From the video, they could see a host of coral species anchored to the cliffs, with the types of species changing at different depths. They had discovered an area of high biodiversity in the black box that is the Labrador Sea. They named the area the Makkovik Hanging Gardens.

In addition to identifying biodiversity hot spots, discoveries like this one can help local fishers avoid areas of the ocean that can damage fishing gear. "I try to share information with other fishermen and say, 'If you want to keep your nets fishable, avoid this spot,'" Angnatok said.

"These beautiful corals appeared on the control room screen. Everybody was pretty excited."

By improving the maps of this part of the Labrador Sea, the researchers have also identified new cliffs to explore. "It's an area that we probably wouldn't have surveyed for a long time had we not learned from this particular exercise," Cote said.

They already think they're onto something and are hoping to explore another garden their camera spotted.

By **Andrew Chapman** (@andrew7chapman), Science Writer

Even Treated Sewage Harms Freshwater Ecosystems

Rivers are awash with excess nutrients, chemicals, and other pollutants, including sewage. Globally, roughly 50% of wastewater is treated at facilities before being released into nearby bodies of water (bit.ly/wastewater-estimates). But new research shows that even advanced treatment might not be enough to safeguard the health of freshwater ecosystems.

Researchers released diluted, treated wastewater into an unpolluted stream in northern Spain and made a before and after comparison of energy flows through the ecosystem.

"We found subtle yet fundamental shifts in ecosystem function after adding wastewater," said Ioar de Guzman, a freshwater ecologist at the University of the Basque Country in Spain and lead author of the study. By manipulating a pristine ecosystem, she and her colleagues could isolate the effects of wastewater, which can be masked in streams that contain other types of water pollution.

Agricultural runoff, containing nitrogen-rich fertilizer, is a familiar blight, causing lurid green algal blooms that choke aquatic life.

"Wastewater is probably a bigger stressor to river functioning than agriculture," said Mario Brauns, a freshwater ecologist from the Helmholtz Centre for Environmental Research in Germany who works on food web analysis with de Guzman but was not involved with the new study.

"We found subtle yet fundamental shifts in ecosystem function."

Besides nitrogen and other nutrients, sewage is laced with an insidious cocktail of toxic contaminants derived from cleaning and beauty products, pharmaceuticals, and more.

Decades of investment to reduce wastewater pollution, driven by legislation such as the European Water Framework Directive and the U.S. Clean Water Act, show that treatment can significantly improve water quality. But, de Guzman said, "even after advanced treatment, toxic compounds and nutrients still remain."

Researchers found "fundamental shifts in ecosystem function" after the introduction of wastewater to a stream in northern Spain.Credit: Arturo Elosegi

In their experiment, de Guzman and colleagues used wastewater from a large treatment facility near Elgoibar, in northern Spain, that uses physical and biological processing, involving separation tanks and microbial digestion, for example, and advanced screening to remove extra nutrients and metals.

Aftereffects

Ecological impact assessments are often conducted after a wastewater treatment plant has been established, using sites upstream to gauge conditions without the effects of the facility. But these control points might not accurately reveal what wastewater does to a stream because the water can already be degraded, Brauns explained. Isolating the effects of each pollution source would be nearly impossible.

To look at the role of wastewater, de Guzman and colleagues first studied an unpolluted stream in good ecological condition. They split the stream into two sections and, over the course of a year, inventoried the entire ecosystem in each.

Starting at the base of the food web, they recorded the amount of leaf litter and biofilm—a mix of algae, organic material, and fungi that coats a streambed. They then counted and measured the invertebrates that fed on those resources and, finally, the fish at the top of the food web. During the following year, they surveyed each stream section again, after channeling wastewater into only the downstream reach.

Biodiversity counts such as these are the cornerstone of ecological impact assessments, but the researchers also wanted to define ecosystem health. They did this by quantifying how much energy was produced and consumed at different tiers of the feeding network.

The team calculated the amount of energy supplied as leaf litter and biofilm and how much of each was eaten depending on the biomass, body mass, and metabolic rate of

Researchers surveyed the ecosystem—from algal communities to invertebrates and fish—to figure out how wastewater pollution disrupted energy flows through the food web. Credit: Arturo Elosegi each species. By comparing the path of energy flowing from each resource before and after diverting wastewater, the researchers could attribute any changes to wastewater pollution.

"This energy flow is the beating pulse of our ecosystems. Measuring that energy gives us a valuable metric of ecosystem health."

The team scraped biofilm off bricks placed on the streambed. Credit: Ioar de Guzman

"This energy flow is the beating pulse of our ecosystems," said Amy Rosemond, an aquatic ecosystem ecologist at the University of Georgia who was not involved in the study. "Measuring that energy gives us a valuable metric of ecosystem health," she said.

The increase in nutrients should stimulate biofilm growth, priming higher levels of the food web with extra energy, de Guzman said. As expected, the amount of biofilm increased after the wastewater was introduced. In turn, invertebrates ate more biofilm and less leaf litter.

The surprise, de Guzman said, was that the amount of energy flowing to the fish did not increase. She said she thinks changes to the invertebrate community (with pollution-resistant species becoming more dominant) could be responsible. But she would need more data on the fishes' diets and energy demands before saying for certain. These results were published in the *Journal of Environmental Management* (bit.ly/wastewater-impact).

"This is an interesting ecological surprise," Rosemond said. "We know that nutrient pollution can decouple the predator-prey relationship." Having extra food of a certain type benefits some species, she explained, but those organisms aren't necessarily the most palatable food for predators, so that extra energy can remain untapped.

Researchers counted and measured invertebrates. Credit: Ioar de Guzman

Cumulative Effects

"This is a clever way to disentangle wastewater impacts from other pollution sources," said Sujay Kaushal, a hydrochemist at the University of Maryland who was not involved in the study. The results show that after much investment in advanced wastewater treatment, there is still room for improvement, he added.

There is no single solution to wastewater pollution, Brauns said, although the best place to start is by limiting what gets into our waterways in the first place. Aside from wastewater pollution, our rivers face a barrage of human threats as they flow past cities and agricultural areas.

Point source wastewater pollution can be regulated, but diffuse inputs such as runoff from agricultural land and roads can be harder to trace and attribute. These pollution sources can merge—amplifying the overall effect on water quality. "Now we need to find out how these combined stressors impact ecosystem function," Brauns said.

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

Thunderquakes Map the Subsurface

Thunderstorms rumble, clap, and roll across the sky, shaking windows and scaring pets. As the acoustic waves travel from the air to the ground, they create seismic waves. Researchers have now shown that these "thunderquakes" can be detected by buried fiber-optic cables and used to image the upper few meters of the subsurface. The method could help scientists identify unseen, shallow hazards such as sinkholes, especially in urban areas where seismometers might not be available.

Distributed acoustic sensing (DAS) methodology monitors vibrations and takes advantage of fiber-optic cables installed underground. Within a cable are long glass tubes that carry pulses of laser light, transmitting data across cities and oceans. Some of the strands are used for communications, but some fibers are considered "dead" and not in use. These strands can be used for DAS systems.

As a laser pulses signals down the cable, the light reflects off imperfections, air bubbles, and dust within the glass. "Our computer, what we call the interrogator device, listens for all these little, tiny reflections off of imperfections in the fiber, and it learns the normal state [of the cable]," said Nolan Roth, a geophysicist doctoral student at Pennsylvania State University and lead author of the paper. The result is a sort of map of imperfections.

Any seismic wave that shakes the ground will also affect buried fiber-optic cables. As a wave hits the cables, the system stretches and compresses, changing the position of the imperfections. The interrogator can see those changes, and the new study shows that with some calculations, scientists can figure out the characteristics of a passing seismic wave.

Roth and his colleagues divided the more than 4,200 meters of fiber-optic cables in a DAS array beneath Pennsylvania State University into segments and measured imperfections every few meters. They looked at how hundreds of thunderquake waves hit different parts of the cable.

Underground Imaging

Seismometers measure three directions of motion: two horizontal and one vertical. DAS arrays record seismic waves as compression and stretching of the cable in only one direction, said Roth, "which makes it very difficult to figure out what kind of waves you're looking at."

Tapping into fiber-optic cables to measure how seismic waves stretch and compress them is a way to detect what sort of wave energy is moving through the ground. Researchers can use this information to map the surrounding geology. Credit: Christoph Scholz/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

To tease out more information about the waves, Roth and colleagues tracked how different angles between the cable length and the orientation of the incoming wave produced different signal amplitudes in the cables. They modeled how such an acoustic wave made by a thunderquake would enter the ground and turn into a seismic wave and how it would intercept the DAS array.

Their modeling revealed how the cable imperfections moved and the type of seismic wave that was produced. The researchers published their results in the *Bulletin of the Seismological Society of America* (bit.ly/wavefield-modeling).

Understanding what type of wave is rumbling through the ground allows researchers to image the subsurface structure. Thunderquake waves behave like regular seismic waves—they bounce when they reach a boundary, such as one between rock and an empty space in a sinkhole or basement or the top of the water table. Scientists can map out where these bounces occur below the surface to determine where boundaries lie.

The abundance and coverage of fiber-optic cables within an urban setting mean there are lots of opportunities to use DAS to reveal underground features, what Roth calls "urban seismology."

With DAS, one cable can act like tens of thousands of seismic sensors, an array that is unmatched with conventional seismometers, said Verónica Rodríguez Tribaldos, a geophysicist at the German Research Center in Potsdam who was not involved in the study.

At the moment, DAS data from thunderquake waves can help researchers see about 10 meters deep, depending on the subsurface conditions, Roth said. The team had success mapping a few hundred meters laterally from the cables, he added, but more work is being done to understand how to get the best resolution.

The study is "a good example of how this novel sensing technique (DAS) can provide new insights into the physics of seismic phenomena and even the interaction between atmospheric processes and the underground," Rodríguez Tribaldos noted.

The study is "a good example of how this novel sensing technique (DAS) can provide new insights into the physics of seismic phenomena and even the interaction between atmospheric processes and the underground."

"A big bonus of having this fiber-optic cable is we can use it to do urban seismology and detect the sinkholes that could really cause some damage to roads and sidewalks," Roth said.

Rodríguez Tribaldos agreed and added that it could also be used for continuous monitoring of processes that could cause changes in seismic velocities in an area, such as groundwater fluctuations.

By **Sarah Derouin** (@Sarah_Derouin), Science Writer

Microbe Goo Could Help Guide the Search for Life on Mars

Sticky substances secreted by microbes may help create landforms on Earth. And new research shows that these substances are more preserved in iron-rich sediment. Mars is decidedly iron-rich (it's the Red Planet, after all), so the new study adds to evidence that microbe goo could help researchers explain landform creation there.

"I think this is going to open up a new direction for astrobiology," said Alicia Rutledge, a researcher on the project and a geologist at Northern Arizona University.

Microbes secrete extracellular polymeric substances, or EPSs, which have high cohesive strength. These substances serve mainly as a protective layer for microbes and a way to dispose of metabolic waste. "If you think of a slug leaving behind a trail of mucus, little microbial organisms will do that too," said Natalie Jones, a doctoral student at Northern Arizona University leading the research. Those sticky microbes exist within virtually all sediment types on Earth.

And that stickiness may be important in landform creation. Meandering rivers, for example, have strong banks. Scientists have generally thought that plant roots make these riverbanks stronger, but recent research has shown that the banks of some meandering rivers don't have vegetation (bit.ly/river-plants). EPSs could be one of the materials that stabilizes the sediment, Jones said.

EPSs are known to influence the formation of landforms on the scale of millimeters to meters, said Jaco Baas, a process sedimentologist at Bangor University in the United Kingdom who was not involved in the research. For example, Baas's experiments indicate that EPSs change the dimensions of how ripples form in riverbeds (bit.ly/cohesion-bedform).

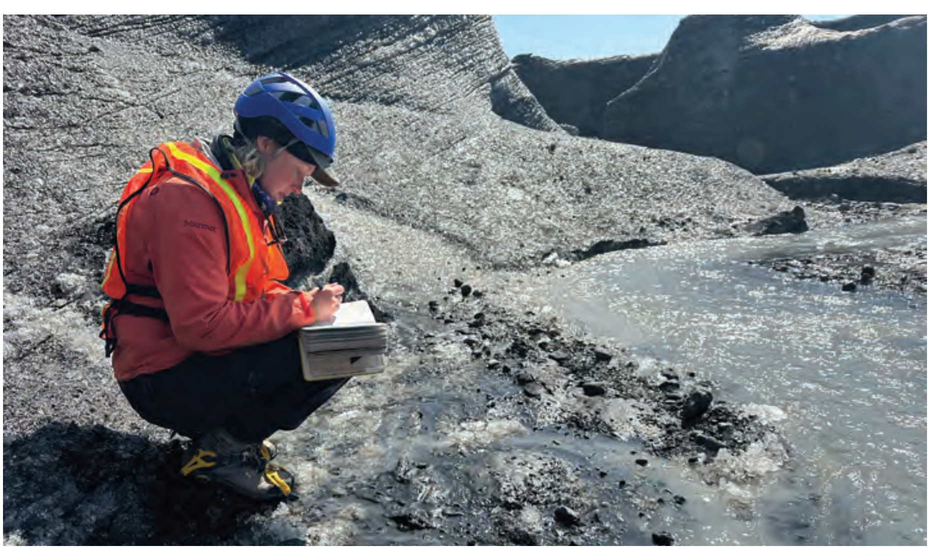
Jones and her colleagues are working to understand how EPSs may influence larger landforms on the scale of hundreds of meters to kilometers, such as meandering rivers, dunes, and shores or floors of lakes and oceans. Their studies in Iceland, New Mexico's White Sands National Park, and other locations have identified correlations between the presence of EPSs, erosion, mineralogy, and other factors.

Preliminary results show that landforms with mafic mineralogy (those rich in iron oxides) contain more EPSs. Jones and her team presented their results at AGU's Annual Meeting 2023 in San Francisco (bit.ly/AGU23-microbes).

Stickiness in Space

The findings suggest that the presence of EPSs could be particularly relevant for understanding landform development on Mars—a planet covered in red, iron-rich minerals.

Further research into EPSs could also aid in the search for life on the Red Planet. With better knowledge of how EPSs influence landform development, scientists could use images of ancient landforms on the surface of Mars to estimate the chances that EPSs existed in Martian sediment when those landforms were created. Those estimates could then help determine where a rover could look for other evidence of life, Jones said.



Natalie Jones collected water quality measurements and sediment sample data next to a supraglacial stream on the surface of the Breiðamerkurjökull glacier in Vatnajökull National Park in Iceland. Credit: Alicia Rutledge

"I think this is going to open up a new direction for astrobiology."

"We've got sand dunes on Mars, and people have been trying to figure out for a while why so many seem frozen," said Rutledge. "Are they frozen because there's ice? Are they cemented with salts? There's lots of theories out there and lots of hypotheses actively being tested. We're going to throw another one in there: How could microbial communities have stabilized these dunes in the past?"

Before it's possible to answer that question, scientists need "a lot more" evidence about where EPSs are present on Earth, what factors influence the presence of EPSs, and what sediment conditions must exist for EPSs to influence sediment transport, Jones said.

Because of Mars's reduced gravity, the cohesive strength of EPSs relative to the weight of sediment particles would be greater than on Earth, meaning that even small amounts of EPSs could be a significant factor in Martian landform creation, Jones said. "It's entirely possible that even if we see no effect on landscapes here on Earth, that we could potentially see an effect on Mars," she said.

EPSs could also offer direct evidence of past life on Mars, but current remote sensing tools aren't sensitive enough to detect EPSs in Martian sediment. "There is quite a big gap between doing this type of research on Earth and trying to do it remotely on another planet," Baas said. "But it's exciting nonetheless."

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

The Science We Need to Assess Marine Carbon Dioxide Removal

The window to limit global warming to Paris Agreement targets by reducing greenhouse gas emissions alone is rapidly closing. According to the Intergovernmental Panel on Climate Change [*Pörtner et al.*, 2022], to have a 50% chance of keeping warming below 1.5°C, the whole of society will need to limit all future carbon dioxide (CO_2) emissions to less than a few hundred billion tons. With global emissions of CO_2 in 2021 totaling 36 billion tons [*Friedlingstein et al.*, 2022], this limit implies a need to halve emissions within a decade, on our way to eliminating nearly all emissions by midcentury.

This formidable challenge becomes harder to overcome with each passing month. Therefore, many scientists, policymakers, entrepreneurs, and others have begun grappling with the reality that staving off intergenerational harms of climate change—from increasingly intense heat waves to more severe droughts and floods to rising risks from wildfire and tropical cyclones—will also require carbon dioxide removal (CDR) of legacy CO_2 from the atmosphere.

Several carbon removal methods are now being deployed on land, such as producing energy with biological material and capturing and storing the CO_2 produced (i.e., bioenergy with carbon capture and storage), planting more forests, or drawing massive amounts of air through absorbent filters. Because the ocean covers 71% of Earth's surface and, apart from the atmosphere, already serves as the largest net sink for anthropogenic CO_2 emissions [*Friedlingstein et al.*, 2022], various marine CDR, or mCDR, strategies are being proposed (Figure 1).

Three categories of mCDR approaches—ocean iron fertilization, artificial upwelling, and seaweed cultivation—aim to stimulate primary productivity at the ocean's surface with the expectation that some of the additional biomass produced will sink into and remain in the deep ocean.

In contrast, ocean alkalinity enhancement (OAE) involves dispersing alkaline materials such as lime on the ocean's surface to shift the chemical equilibrium of the seawater carbon system and thereby increase uptake of atmospheric CO_2. Still another approach proposes to remove CO_2 directly from seawater through electrochemical reactions and then store it underground.

Commercial, philanthropic, and government resources are increasingly being directed toward the development of these mCDR strategies, with several pilot deployments planned. But how effective might these pathways be at increasing ocean carbon uptake? Key to any CDR method is that it must durably store billions of tons of CO_2 in places where it cannot easily return to the atmosphere. Quantifying the effectiveness and durability of these processes in the ocean requires robust science for monitoring, reporting, and verification (MRV).

> **Quantifying the effectiveness and durability of marine carbon dioxide removal processes requires robust science for monitoring, reporting, and verification.**

Need for Standards and Transparency

Monitoring, reporting, and verification refers to a multistep process: The amount of greenhouse gas removed by a CDR activity over a period of time is monitored and reported to a third party that then verifies and certifies the results. MRV is often pursued so that companies can seek payment for removal activities in rapidly growing voluntary carbon credit markets or in smaller, regulated compliance markets.

Terrestrial CDR has given rise to many certifications, along with more than 2 dozen standards-developing organizations, yet this abundance has not consistently translated to high-quality CDR [*Arcusa and Sprenkle-Hyppolite*, 2022]. Here, "high-quality" refers to carbon removal that is both *additional*, meaning it would not have occurred without the intervention, and *durable*, meaning it is removed from the atmosphere for centuries to millennia.

Perhaps the most attention-grabbing example of attempted terrestrial CDR has been afforestation, especially since the World Economic Forum began promoting its 1-trillion-tree project in 2020. Despite the attention, MRV protocols for afforestation efforts lack standardization and can fail when tested with independent verification methods [*Marino et al.*, 2019].

Forest MRV protocols often rely on satellite monitoring supplemented by field-based tree inventory assessments to estimate changes in forest biomass. Simple models are then used to convert biomass changes into carbon storage inventories.

To evaluate additionality, this carbon storage is compared to a hypothetical baseline representing the assumed trajectory of the system in the absence of intervention. But uptake of CO_2 by an afforested region is not typically measured. In the few instances in which uptake has been measured directly, quantitative inconsistencies were revealed [*Marino et al.*, 2019].

Assessing durability is complicated by the difficulty of predicting wildfires and plant diseases, which can rapidly release sequestered carbon to the atmosphere [*Joppa et al.*, 2021].

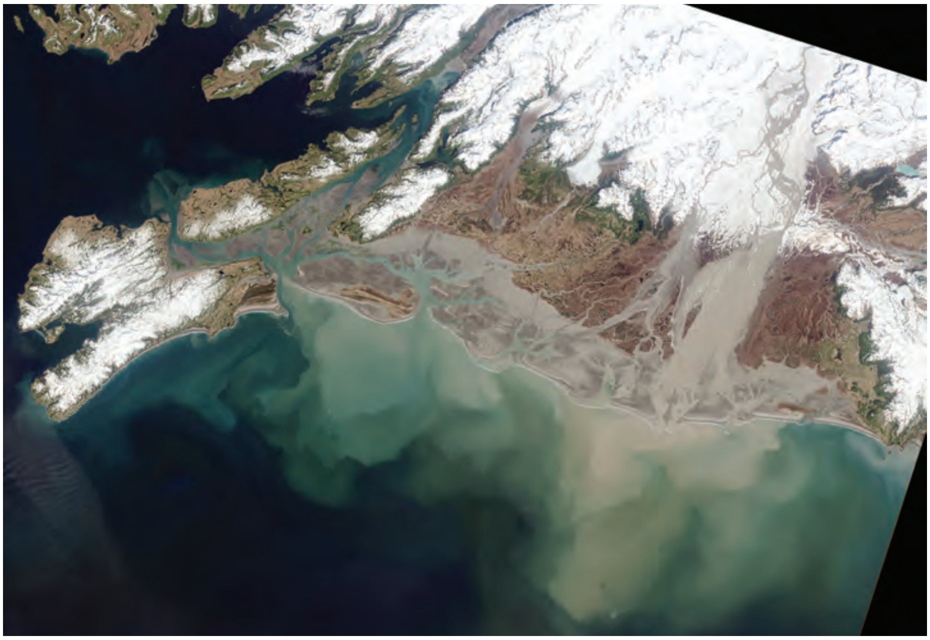
With all the different approaches and organizations involved, the terrestrial CDR landscape has grown into a tangled web of competing protocols that lack standardization and transparency.

In contrast, almost no MRV standards for mCDR exist. At least half a dozen companies involved in mCDR, and more that are rapidly entering the space, are starting to market their services to potential buyers interested in purchasing credits to offset carbon emissions. To support verification of these services, methods that rigorously quantify net carbon removal rates and storage durability of different mCDR approaches are urgently needed.

We argue that this vacuum opens an opportunity for oceanographic researchers to build these needed frameworks for MRV practices with high integrity, applying lessons from both successful and problematic protocols developed in the terrestrial CDR environment [*Bach et al.*, 2023].

Inventing Applied Ocean Biogeochemistry

Many oceanographers have been reluctant to do mCDR research. They cite various reasons, including a fear that doing so will shift public



The natural addition of glacial silt colors coastal waters, seen here in the Gulf of Alaska near the mouth of the Copper River. This process is a potential analogue for ocean alkalinity enhancement, one proposed method for marine carbon dioxide removal. Alpine glacier melt streams react with carbonate bedrock, increasing the alkalinity delivered to the marine environment. Credit: Robert Simmon and Jesse Allen/NASA Earth Observatory

and private investment away from critical emissions reductions and push ocean scientists away from basic research. If scientists stay on the sidelines as mCDR companies begin to sell carbon credits in largely unregulated marketplaces, however, the industry will move forward without their much-needed expertise.

For mCDR strategies either to grow into viable and quantifiable climate mitigation tools or to be dispensed with because research reveals they are ineffective, ocean scientists must step up to collaborate and codevelop MRV frameworks. In so doing, there is still room to pursue new, fundamental science and train the next generation of scientists in the emerging field of applied ocean biogeochemistry.

Evidence that some scientists are starting to take on more active roles was abundant at a September 2022 workshop on mCDR that was sponsored by the U.S. Ocean Carbon & Biogeochemistry Project Office with support from the U.S. National Science Foundation (NSF) and NASA and held at the University of Rhode Island.

More than 150 ocean scientists gathered—in person and virtually—with industry, nonprofit, and government agency stakeholders to explore key requirements and challenges of establishing MRV frameworks for several widely considered mCDR methods [*National Academies of Sciences, Engineering, and Medicine*, 2022].

One point of agreement was that the details of any MRV framework depend on which mCDR strategy is being tested.

The details of any MRV framework depend on which mCDR strategy is being tested.

MRV for methods intended to increase primary productivity would require assessments of the additional biomass created by the intervention, the fraction of that biomass exported to the deep ocean, and the length of time its carbon would stay in the ocean interior without being mixed back to the surface, where it could be released to the atmosphere.

Moreover, it would be imperative to assess whether the consumption of nutrients (e.g., nitrate, phosphate) to stimulate additional productivity would cause decreased productivity elsewhere. Another key question is whether additional oxygen consumed in the ocean interior through the respiration of the added carbon would lead to additional production of other greenhouse gases, such as nitrous oxide or methane, due to enhanced anaerobic respiration. Decreased productivity in other locations and/or increased production of other greenhouse gases could partially or fully negate the benefits of these mCDR approaches.

MRV for OAE would need to ensure that an intervention does in fact elevate seawater alkalinity and that the alkalinity-enhanced waters remain at the surface long enough to absorb additional atmospheric CO_2. Unlike the biologically mediated mCDR methods that rely on organic carbon remaining for centuries in the deep ocean, OAE increases the ocean's buffering capacity, similar to the natural process of rock weathering, and the associated CO_2 uptake is likely to be durable on millennial timescales [*Hartmann et al.*, 2023].

It's Time to Engage

The most emphatic point of agreement among workshop participants is that we now are within a fleeting window of opportunity to fill the MRV void for mCDR. Acting now could prevent inadequate or opaque protocols from becoming accepted defaults. Equally important, the nascent mCDR industry needs guidelines and baselines to verify whether their methods can work and therefore have value in the marketplace. Lacking such groundwork, the industry could fail to launch, eliminating or delaying promising carbon removal pathways. Or resources could be wasted through prolonged investments in techniques with little likelihood of working at scale.

Oceanography blends knowledge from physics, biology, geology, and chemistry, and oceanographers use observations, laboratory analyses, and numerical models to create holistic understanding. Now is the time for these scientists to apply their expertise to establish best practices for the quickly growing mCDR community.

Academic research into mCDR must accelerate and be transdisciplinary, while maintaining rigor and fulfilling commitments to equity and transparency. A positive sign for the needed acceleration is that funding agencies, such as the National Oceanographic Partnership Program and the U.S. Department of Energy, are developing programs for mCDR and MRV, and new sources

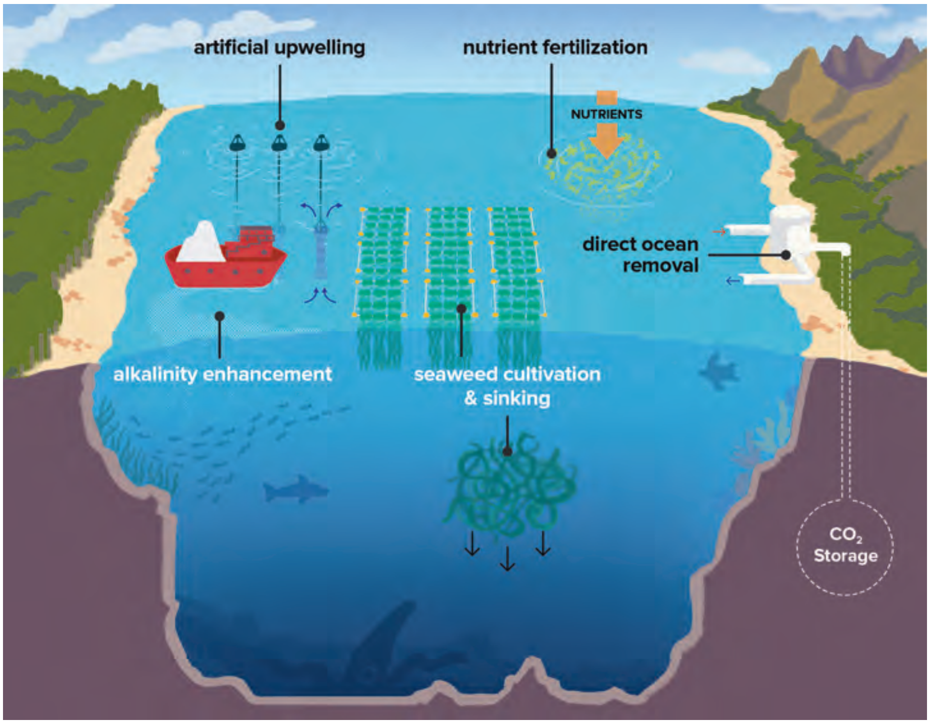


Fig. 1. Various strategies for removing carbon dioxide from seawater and sequestering it for long periods of time have been proposed, each with its own considerations and complications. Credit: Mary Heinrichs/AGU

of funding from philanthropy, venture capital firms, and private industry are also growing swiftly.

Participants at the recent workshop rallied around several recommendations. One is that field trials following detailed protocols are needed to prove the efficacy and safety of mCDR methods. These protocols should be codesigned by expert teams, including private-company engineers along with impartial scientists, with regulatory bodies taking responsibility as knowledge matures.

It's possible that coastal and island communities could be affected by mCDR—for example, via the build-out of macroalgal farms and associated ship traffic. So as part of the codesign effort, scientists should also partner with these communities to develop tools of MRV to prevent environmental degradation and fraud, and to ensure that the communities share in the benefits of mCDR actions.

Another recommendation, to further promote equity and transparency, is that data associated with MRV should be publicly available, accessible, and quality-assured. Ideally, a centralized registry of MRV protocols and outcomes from field trials should be created and indexed for easy reference, which may require surmounting issues related to intellectual property.

Ocean models will be critical tools in MRV, because many mCDR approaches will create changes that are hard, if not impossible, to observe directly in the vast, variable, and turbulent ocean. However, ocean models historically have not been built for this purpose. Adapting model simulations and related analysis tools to provide probabilistic quantifications of carbon removal with robust uncertainty budgets requires focused development aligned with that goal.

There is clearly a lot of work to be done to evaluate mCDR approaches and bring needed, internationally recognized MRV protocols to fruition. Considering the stakes, there is also a palpable urgency to do so. We urge the ocean sciences community to engage deeply in this work, whether by collecting and sharing relevant experimental or modeling data; teaching about mCDR approaches; providing expert reviews to journals, funding agencies, or private enterprises; contributing to best practices documents; or other means. With a sustained community effort, we can ensure that robust frameworks for verifying the effectiveness and safety of mCDR are developed in ways that advance the fundamental goal of helping mitigate the harms of a warming climate.

Acknowledgments

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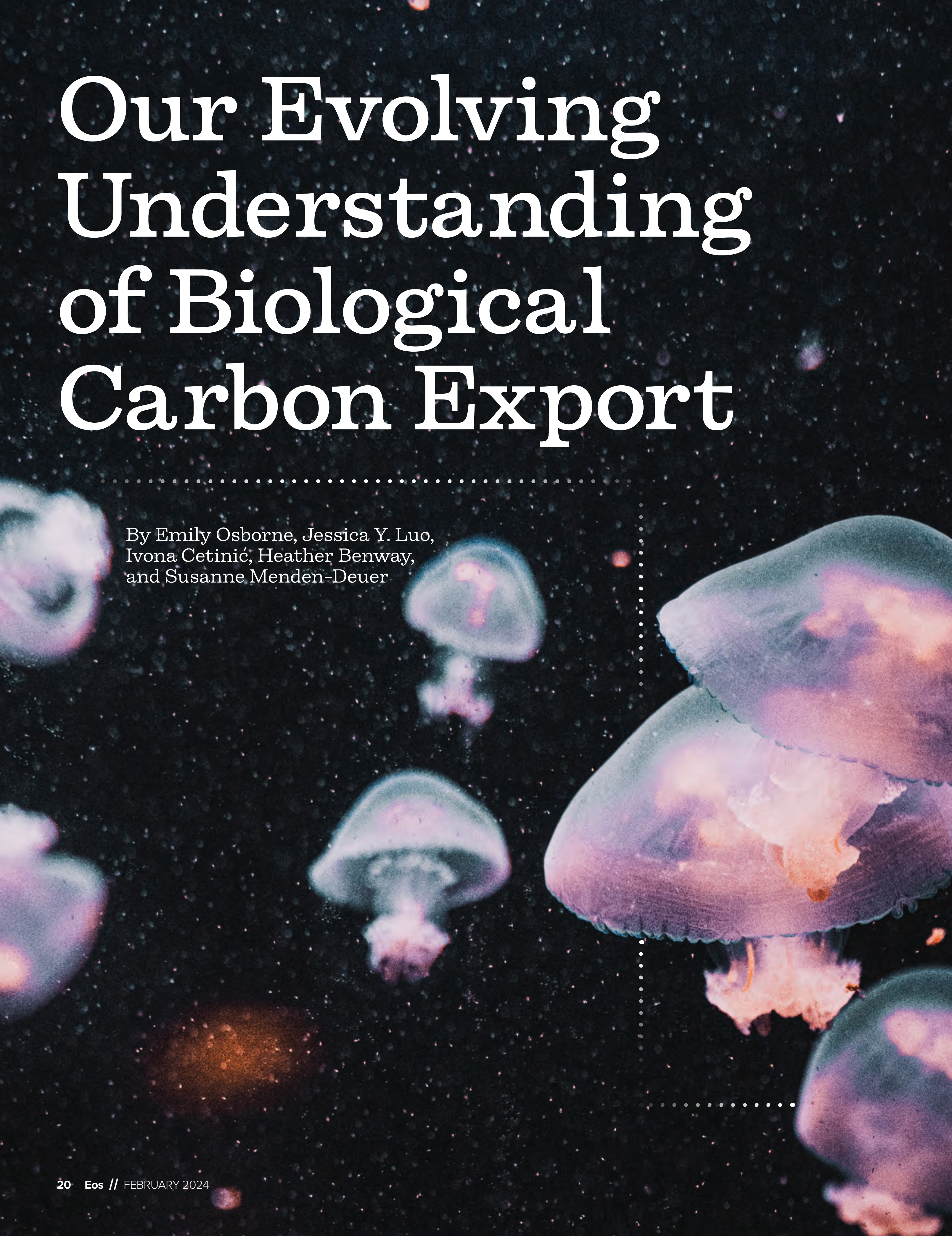


Our Evolving Understanding of Biological Carbon Export

By Emily Osborne, Jessica Y. Luo, Ivona Cetinić, Heather Benway, and Susanne Menden-Deuer

"Marine snow," ubiquitous across the open ocean, comprises tiny (approximately millimeter-long) bits of organic detritus that accumulate and break down as they descend through the water column. This photo shows marine snow in the water surrounding jellies. Credit: Florian Olivo, Unsplash

The array of processes and organisms that make up the biological carbon pump has immense influence on Earth's carbon cycle and climate. But we still have much to learn about how the pump works.

The ocean was cycling carbon long before humans began fundamentally changing Earth systems. Since industrialization started in the 18th century, however, the ocean's carbon cycle has absorbed at least one quarter of anthropogenic carbon dioxide (CO_2) emissions, helping mitigate the impacts of climate change.

The ocean's pattern of absorbing and releasing carbon includes its movement from the water's surface to the seafloor. The dominant conduit for transporting carbon from the ocean surface to depth is the biological carbon pump (BCP). This flow of carbon creates a vertical gradient in carbon concentration in the water column, which enhances the ocean's capacity to absorb additional atmospheric CO_2. Consequently, the BCP is one of the most important determinants of oceanic absorption of atmospheric CO_2 over geologic timescales and, accordingly, an important determinant of global temperatures. Estimates have suggested that the present-day atmospheric CO_2 concentration would be 50% higher in the absence of the BCP.

The effects of accumulating anthropogenic CO_2 on Earth's climate make the BCP a foundational target of oceanographic research. Changes in the functioning of the BCP have direct implications for climate feedbacks, amplifying or mitigating global warming. Goals to implement or accelerate nature-based solutions and marine carbon dioxide removal (mCDR) interventions, some of which propose to stimulate the BCP to draw more carbon from the atmosphere, add urgency to better understand the BCP.

During a session at the 2022 Ocean Carbon and Biogeochemistry (OCB) summer workshop, participants identified critical elements of a future BCP research agenda, which we outline here.

The Complexities of Observing Small Things

The BCP removes about 10 petagrams (10 trillion kilograms) of carbon from the sunlit, or epipelagic, zone (0- to 200-meter depth) of the ocean each year [*Nowicki et al.*, 2022]. Coincidentally, this amount is roughly equal to the total annual average emission of anthropogenic carbon during the present decade. A large fraction of carbon absorbed by the surface ocean ultimately returns to the atmosphere through respiration, whereas only a small fraction (sometimes <1%) of those 10 petagrams makes its way to the deep ocean for long-term sequestration. At intermediate, or mesopelagic, ocean depth (200–1,000 meters), the BCP feeds essential carbon (and other nutrients) to mesopelagic food webs that not only modulate the amount of carbon exported to the deep ocean but also support important commercial fisheries.

The BCP's effects on Earth's ecosystems and climate are global in scale. The BCP is a composite of numerous interacting biogeochemical and physical processes—some poorly known—that operate over a range of spatial and temporal scales. Three main mechanisms transport biological carbon through the ocean: passive gravitational sinking of particles, active vertical migration of zooplankton and fish, and physical advection and diffusion of particulate or dissolved carbon (Figure 1) [*Siegel et al.*, 2023].

Decades of research have yielded major advances in our knowledge of the BCP.

However, observing processes that simultaneously occur on a range of spatial and temporal scales presents major challenges for research. Limitations, such as

The effects of accumulating anthropogenic CO_2 on Earth's climate make the BCP a foundational target of oceanographic research.

the difficulty of observing microscopic processes across a global scale and the continued discovery of diverse organisms with previously unknown ecological and physiological capacities, constrain our understanding of even the dominant processes that drive the BCP, causing significant uncertainties in estimates of the rates of carbon flux.

These uncertainties propagate into models that, depending on how they're parameterized, variably project either enhanced or decreased strength of the BCP under

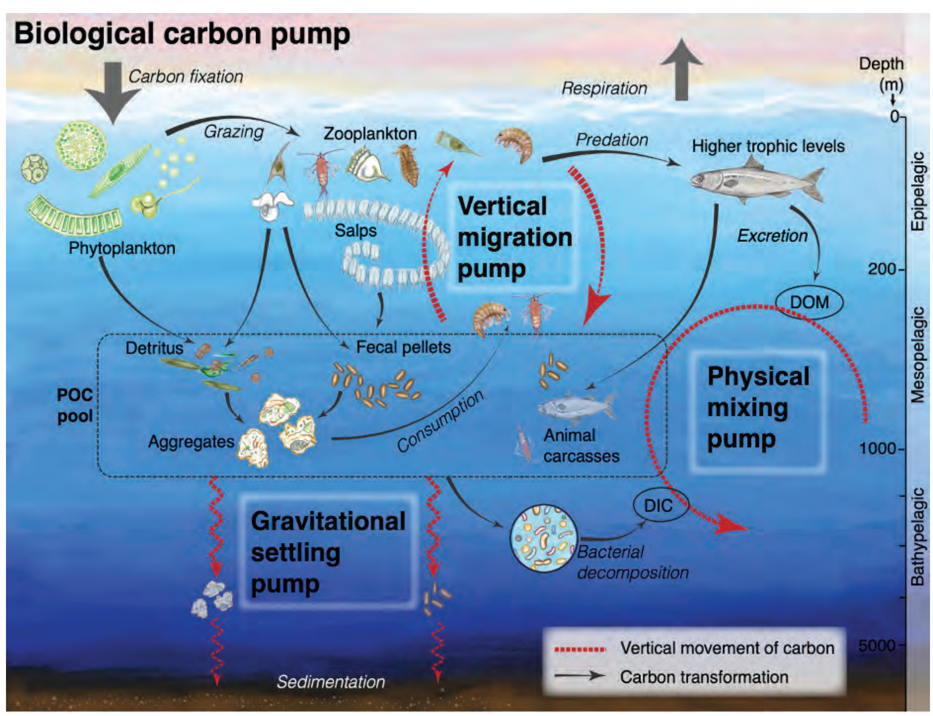
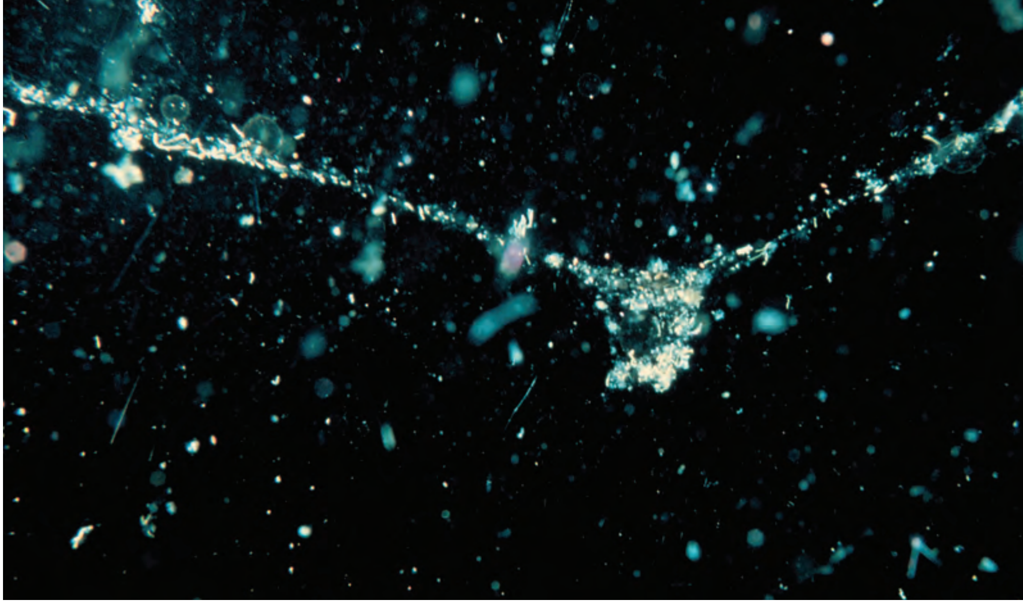


Fig. 1. The biological carbon pump involves many components, from microscopic plankton to large fish, as well as physical processes that transform carbon into different forms and transport it through the water column. POC = particulate organic carbon; DOM = dissolved organic matter; DIC = dissolved inorganic carbon. Credit: Kristen Krumhardt

future climate change scenarios. Such discrepancy in even the directionality—the enhancement or reduction of flux processes—has obvious ramifications for our ability to predict the effects of future CO_2 emissions on global climate.

A further hindrance is that the mechanistic relationships between climate drivers and the biological, physical, and chemical components of the BCP are too poorly understood to predict the effects of ocean warming, stratification, and acidification; expansion of oxygen minimum zones; or limitations of nutrient delivery on these components. By extension, climate-related changes in the efficiency and magnitude of carbon export to the deep ocean are unclear.



Marine snow floats within the photic, or epipelagic, zone, 55 meters below the sea surface in Monterey Bay, California. Credit: © Woods Hole Oceanographic Institution, S. Honjo

New Knowledge Means Advances—And New Uncertainties

Speakers at the 2022 OCB workshop laid the groundwork for group discussions by describing recent advances in BCP research and understanding. Their presentations highlighted substantial contributions to carbon export from organisms previously overlooked, such as pelagic (open-water) fishes [*Saba et al.*, 2021] and single-celled herbivores [*Larsson et al.*, 2022; *McNair et al.*, 2021], as well as nuanced advances in our understanding of how known carbon conduits, such as zooplankton and salp fecal pellets and carcasses, contribute to the BCP [*Steinberg et al.*, 2023]. Together these biological actors and processes that remineralize or redistribute carbon vertically are critical but uncertain contributors to long-term carbon sequestration.

Presenters also described the important lines of evidence that the paleoceanographic record provides on how the BCP has functioned over time, particularly because ocean temperature can affect the supply of organic carbon to the seafloor [*Boscolo-Galazzo et al.*, 2021]. And emergent environmental DNA tools were discussed, because they offer new approaches to identifying sources of carbon to the BCP from the epipelagic layer [*Durkin et al.*, 2022] down to the seabed [*Cordier et al.*, 2022].

Our understanding of carbon sequestration timescales is still in its infancy.

Ultimately, these observed processes and carbon sources must all be integrated into models to simulate the behaviors and responses of the BCP across the ocean system skillfully. Several studies featured during workshop discussions emphasized potential missing components from model representations of the BCP, including characterizations of various organism groups, how these groups stimulate the BCP [*Laufkötter et al.*, 2016; *Luo et al.*, 2022], and the ways in which these organisms affect and are affected by climate change [*Henson et al.*, 2022].

Known Unknowns: A Road Map for New Research

Rates of particulate sinking and carbon remineralization, as well as the residence times of BCP-exported carbon in the deep ocean—on regional to global scales—remain significant unknowns. Our understanding of carbon sequestration timescales is still in its infancy, and studies that design observing systems capable of tracking the fate of carbon and that can quantify the BCP carbon residence time are needed. In this vein, a better grasp of BCP processes is critical to determine the rates and magnitudes of carbon fluxes required to quantify and validate the effectiveness of different mCDR initiatives as these mitigation approaches advance. The downstream effects of mCDR on ocean ecosystem function, organisms that contribute to the BCP, and the resulting export efficiency represent additional major unknowns.

The sensitivities of organic carbon generation, particle size, and remineralization in the BCP to climate-associated changes, such as ocean warming, have not been studied in situ and are therefore not parameterized within models. Other challenges to improving models include better constraining key transfer processes of carbon, including respiration, production, and consumption; extrapolating species- or site-specific experiments to the global domain; and growing data sets that can be used to improve validation. The role of regional variability in global models, including in region-specific rates, is also largely unconstrained.

Moreover, investigations connecting domains, such as through coastal-to-open-ocean transport measurements, are needed to quantify how coastal processes contribute to global carbon export and sequestration. Intercomparisons between models and observations must identify whether a single modeling framework adequately represents the BCP or whether unique processes require individual representation. Such intercomparisons will be foundational to assessing and improving model performance and directing observational efforts.

Meaningful connections between process-level, mechanistically focused studies and larger-scale observational programs will be central to establishing statistical relationships and large-scale mass balances to connect disparate observational approaches. New global observational capabilities—including from the autonomous Biogeochemical-Argo (BGC-Argo) float network and NASA's Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE) mission—can feed data-assimilative mod-

> Pairing results from emerging tools with new global-scale observing systems may pave the way toward an operational system for monitoring the BCP.

els global-scale information on features such as phytoplankton community composition as well as unparalleled observations of in situ ocean biogeochemistry from the surface to 2,000-meter depth.

Emerging approaches for characterizing the composition of biological particles via environmental DNA sequencing offer new ways to investigate major players associated with particulate carbon export. Pairing results from emerging tools with new global-scale observing systems such as PACE and BGC-Argo may pave the way toward an operational system for monitoring the BCP. Such an operational system will span vast temporal and spatial scales and overcome historical observational limitations on our capacity to quantify carbon export on a routine basis.

In addition, we now know that many processes contributing to the BCP are ephemeral, and determining those processes' contributions (both their frequency and magnitude) to carbon export is particularly challenging. For example, the influences of episodic and ephemeral biological events like jelly-falls and salp blooms on BCP function are poorly quantified, although some studies have demonstrated their importance [e.g., *Steinberg et al.*, 2023]. Partnering with the global BGC-Argo array to modify the timescales over which some floats profile the water column (normally 10 days) to capture ephemeral BGC processes (~1-day timescales) can help fill this observational gap and feed data-assimilative models.

Data management will lay the groundwork for developing an operational system capable of routinely and effectively ingesting data. Synthesizing, consolidating, and cross-validating data are essential for observation-model intercomparisons, which require accessible, well-managed data and data products created in consultation with the modeling community.

Another key factor in improving BCP understanding involves supporting and investing in the next generation of BCP researchers, who reflect diverse perspectives and backgrounds and who bring distinct skill sets and experiences to the table, from at-sea observational work to molecular work to working with large, complex data sets. To take a step in this direction, invited speakers at the OCB workshop reflected gender balance and representation of both senior scientists who have spent their careers advancing BCP frontiers and early-career researchers who are pushing the research agenda forward with new perspectives and approaches.

Collectively Envisioning a Complex Future

Community discussions at the OCB workshop highlighted the complexity of the BCP. Ongoing studies of mechanistic relationships are bringing to light existing strengths and opportunities of both models and empirical studies, as well as needed research targets and infrastructure. The importance of the BCP in the global carbon cycle makes it essential that we capitalize on opportunities to discover thus far unknown processes and better quantify known ones.

Our knowledge of the BCP fundamentally dictates our capacity to understand and estimate carbon fluxes globally and to predict how these fluxes will affect climate, and vice versa. As potential implementations of mCDR advance, the oceanographic and climate science communities also face an urgent need to better understand these approaches to minimize their environmental harm, maximize their effectiveness, and ultimately contribute to enhancing climate change resilience.

Acknowledgments

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Seawater Dynamics in an Underexplored Antarctic Fjord

In a new study, researchers analyzed the basic oceanography of Marian Cove, a narrow fjord north of the Antarctic Peninsula. Credit: Cristian Coman/Imaggeo, CC BY-ND 3.0 (bit.ly/ccbynd3-0)

About 150 kilometers north of the Antarctic Peninsula lie the South Shetland Islands, a cluster of more than a dozen islands that harbor glaciers, volcanoes, and a tundra ecosystem with penguins and seals. On the southwestern side of King George Island, glacial meltwater meets salty seawater in a narrow, little-explored fjord known as Marian Cove.

The flow of seawater into and out of fjords like Marian Cove plays a critical role in sustaining healthy Antarctic coastal ecosystems. However, climate change can alter seawater dynamics, and the Antarctic Peninsula region has been warming up much faster than the rest of the world.

Now, *Kim et al.* have conducted the first in-depth analysis of Marian Cove's basic oceanography, which could aid predictions about the regional effects of climate change.

Between 2011 and 2021, the researchers visited Marian Cove multiple times aboard a ship, from which they took measurements of temperature, salinity, and current speed at various locations and water depths. They also mounted instruments at the entrance to the fjord that continuously collected data from 2018 to 2021. The northeastern end of Marian Cove is closed, and its southwestern end opens into a larger bay.

Their data analysis revealed that wind has the greatest influence in determining the direction of the fjord's surface current, whereas deeper currents flow in the opposite direction. Easterly winds, blowing from within the fjord out into the bay, play the biggest role in increasing the fjord's salinity because they move fresh surface water out of Marian Cove and cause salty water to flow in beneath the surface.

On average, the analysis showed, water stays in Marian Cove for about 9 days before it flows out into the bay. However, when easterly winds are particularly strong, water may stick around for less than 2 days, which could limit the growth of phytoplankton.

Prior research has already suggested that climate change will shift the ecology of bottom-dwelling organisms in Marian Cove. These new findings set the foundation for further insights into the future of this fjord—and others like it. (*Journal of Geophysical Research: Oceans,* https://doi.org/10.1029/2023JC020111, 2023) **—Sarah Stanley,** *Science Writer*

AI Meets Its Match: The Butterfly Effect

A 2003 low pressure system swirls in the North Atlantic. In the atmosphere, tiny fluctuations can grow in unpredictable ways. AI fails to capture this so-called butterfly effect. Credit: NASA, Public Domain

Weather forecasting historically has depended on the time-consuming and energy-intensive method of using supercomputers to crunch complex sets of mathematical equations. An up-and-coming alternative involves training artificial intelligence (AI) to predict how current atmospheric conditions will evolve. However, *Selz and Craig* report that models based on AI fail to account for a process that fundamentally limits weather predictability: the butterfly effect.

The butterfly effect describes how the consequences of tiny perturbations can very quickly grow to have a major impact on a system's final outcome, as in the metaphorical example of a flap of a butterfly's wings in Brazil ultimately influencing the development of a tornado in Texas.

In weather science, these fast growing uncertainties are most often related to convection and precipitation. But this initial variation grows much more slowly in AI systems than in reality, potentially making AI weather predictions unreliable.

This doesn't mean that AI is useless when it comes to weather forecasting. Currently, the butterfly effect is not the limiting factor in weather prediction, because atmospheric measurement errors are still large enough that the butterfly effect is comparatively negligible.

AI does model weather in midlatitude conditions well with the current level of measurement error, though Selz and Craig note that accuracy may vary in exceptional meteorological conditions. Scientists may also be able to improve AI algorithms, for example, by artificially generating additional training data to teach these algorithms the power of the butterfly effect. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL105747, 2023) **—Saima May Sidik,** *Science Writer*

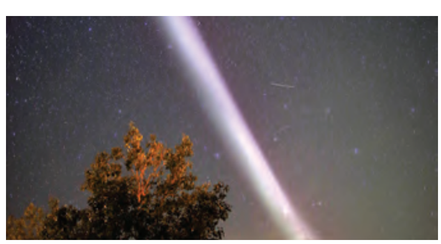
Probing Rare Hot Plasma Flows in the Upper Atmosphere

Near Earth's poles, observers of the night sky often behold aurorae, colorful light shows in the upper atmosphere caused by interactions between the solar wind and our planet's magnetosphere. A little closer to the equator, a different upper atmosphere phenomenon sometimes occurs: subauroral ion drift (SAID).

SAID events typically involve narrow, rapid, westward flows of extremely hot plasma—a mixture of charged particles—through the ionosphere. In recent years, scientists have linked SAID events with visible structures in the sky known as SAR (stable auroral red) arcs and STEVE (strong thermal emission velocity enhancement).

SAID events usually occur between dusk and midnight but have occasionally been detected in the predawn hours. In a new study, *Horvath and Lovell* take a closer look at the characteristics and formation of rare, postmidnight SAID events.

The researchers focused on 15 events detected near South America in 2013. To better understand them, they analyzed data from the Defense Meteorological Satellite Program, the Van Allen Probes, the Geostationary Operational Environmental Satellites, and various measures of auroral activity.



Upper atmosphere phenomena known as subauroral ion drifts sometimes produce visible ribbons of light in the sky, like this one seen in Canada in 2015. Credit: Elfiehall/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

They found that much like premidnight SAID events, the 15 postmidnight events appear to have arisen from the complex interplay of ionospheric conditions and geomagnetic dynamics, including electric field formation and wave-particle interactions that serve as localized heat sources.

These findings provide new insights into upper atmosphere plasma dynamics and could help deepen understanding of the potential for SAID events to disrupt radar signals for satellite tracking and other critical applications. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2023JA031677, 2023) **—Sarah Stanley,** *Science Writer*

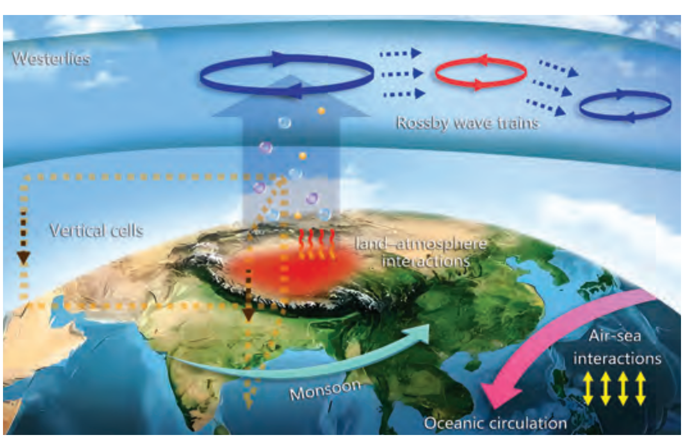
Earth's "Third Pole" and Its Role in Global Climate

Lake Ximencuo, a glacial moraine lake, sits among peaks of the Nianbaoyeze Mountains on the Tibetan Plateau. Credit: Tenace10/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Located at the intersection of South, Central, and East Asia, the massive Tibetan Plateau is often considered to be Earth's "Third Pole."

A land of large glaciers, permafrost, and heavy snow, the plateau feeds a vast network of rivers, including major waterways like the Ganges, Indus, Mekong, Yangtze, and Yellow. These rivers together make up Asia's "water tower," providing water to nearly 40% of the world's population.

The Tibetan Plateau also plays a substantial role in the global climate system by affecting atmospheric circulation and driving weather patterns, such as the Asian summer monsoon, around the planet. And in turn, climate crucially influences the plateau. A projected warmer and wetter climate will affect the region's glaciers, snow cover, permafrost, runoff, and vegetation, affecting ecosystems locally and globally.



This schematic illustrates ways in which the Tibetan Plateau affects the global climate system. Credit: Jianping Huang

Huang et al. review the latest research investigating the Tibetan Plateau's role in and susceptibility to the changing climate. Although inquiry into the plateau's influence on climate dates to the 1880s, recent advances in observational data and numerical modeling offer new insights.

The researchers divide their review into six thematic sections, covering observations of land-atmosphere interactions, climate system changes over the Tibetan Plateau, the plateau's effects on atmospheric species transport, thermal and dynamical forcing of the plateau, its modulation of the global climate, and potential future changes in the plateau's climate and forcings. For example, they discuss research demonstrating how the plateau drives surface pollutants into the upper troposphere during the Asian summer monsoon.

They also outline how the plateau couples with the monsoon to influence global climate patterns in the summer, whereas in the winter, it drives the climate through its effects on planetary Rossby waves.

In addition, the authors identify a suite of needs for future research, such as the following:

- improving data collection to quantitatively understand the effect of climate on diabatic heating over the plateau
- improving the temporal resolution of observations (e.g., hourly to daily) to model atmospheric processes like clouds and precipitation more accurately
- improving regional and global climate model systems to reduce biases in their representation of the plateau
- crafting a complete physical image of the Tibetan Plateau's climate dynamics and thermal effects on the global climate

Focusing on these improvements will help scientists gain a more complete and systematic understanding of the plateau and its place in the current and future climate, the authors say. (*Reviews of Geophysics*, https://doi.org/10.1029/2022RG000771, 2022) **—Aaron Sidder,** *Science Writer*

Humans Have Boosted Atmospheric Mercury Concentrations Sevenfold

Mercury is a naturally occurring element that under some conditions can become methylated and highly toxic. It is therefore important to understand the sources and transport of mercury to estimate its potential risks.

Volcanic activity is the primary source of natural mercury on Earth. But because volcanic activity is so volatile, the concentration and distribution of volcano-sourced atmospheric mercury haven't been well quantified previously.

Geyman et al. estimated total volcanic emissions by using satellite measurements of atmospheric sulfur dioxide. The researchers then used previous measurements of the ratio of mercury to sulfur dioxide to calculate how much mercury would be contained in those emissions. They also modeled atmospheric transport of volcanic mercury to track where the heavy metal drifts.

Volcanoes emit about 230 megagrams of mercury per year, supporting a preanthropogenic atmospheric reservoir of about 580 megagrams of mercury, the study found. But in 2015, the total estimated atmospheric mercury reservoir was measured at about 4,000 megagrams—nearly 7 times larger than volcanoes' natural contributions. Human emissions of mercury, primarily from coal combustion, mining, and industry sources such as metal and cement production, have dwarfed natural emissions.

Volcanic gases, as well as lava, erupt from vents at Hawai'i's Kīlauea volcano in September 2023. Kīlauea is among Earth's largest volcanic mercury sources, but present human emissions are much greater than all volcanic sources combined, a study in Geophysical Research Letters *found. Credit: L. Gallant/U.S. Geological Survey, Public Domain*

The tropics and the extratropical Northern Hemisphere receive the most volcanic mercury emissions. But the geographic distribution of these natural emissions, which can be highly variable, could obscure regional trends in anthropogenic mercury emissions. According to the authors, that should be considered in assessments for the efficacy of the 2013 Minamata Convention on Mercury, which aims to reduce global mercury emissions. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL104667, 2023) **—Rebecca Dzombak,** *Science Writer*

Gently Down the Stream: Carbon's Journey from Land to Sea and Beyond

Rivers, streams, lakes, and reservoirs occupy just 1% of Earth's surface but route large amounts of terrestrial carbon to the ocean. Along the journey, carbon dioxide is also released into the atmosphere in a process known as evasion. But much about the land-to-ocean carbon cycle is not yet understood.

Knowing how much carbon is transported from land to ocean and how much is lost to the atmosphere and elsewhere on the journey—and how factors like human activity and ecosystem type influence these processes—could help scientists gain a more complete picture of the global carbon cycle.

Tian et al. present a global quantification of carbon export and carbon dioxide (CO_2) evasion from before the industrial era to the present. Their research indicates that inland waters move nearly half of the carbon absorbed by the land to the atmosphere and oceans. It also reveals significant anthropogenic perturbations to this land-to-ocean carbon cycle. Their work is the first global quantitative assessment of this process, addressing a knowledge gap identified in the Intergovernmental Panel on Climate Change's Sixth Assessment Report.

Using the Terrestrial/Aquatic Continuum module of the Dynamic Land Ecosystem Model, the researchers conducted simulations moving from a preindustrial baseline forward in time. This allowed them to observe the effects of different variables on the land-to-ocean carbon cycle, including increased atmospheric carbon, land use change, and increasing nitrogen inputs to rivers.

Their model shows a 25% increase in global carbon entering the water from 1800 to 2019. Of that extra carbon, 23% was exported to the oceans by rivers, whereas 59% was evaded to the atmosphere. Per year, inland waters today transport 869 teragrams of carbon to the ocean and 1,113 teragrams of carbon to the atmosphere.

Some notable knowledge gaps remain, including the extent to which anthropogenic influences are affecting the transport of carbon from land to ocean. In addition, better observations are needed in headwater zones and arctic regions. (*Global Biogeochemical Cycles*, https://doi.org/10.1029/2023GB007776, 2023) **—Nathaniel Scharping,** *Science Writer*

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The National Center for Integrated Coastal Research (UCF Coastal) at the University of Central Florida (UCF) seeks a dynamic and innovative leader to serve as its **director**. This is a full-time, 12-month, tenured associate professor or professor position, anticipated to begin **Fall 2024**.

MINIMUM QUALIFICATIONS:

A Ph.D., terminal degree, or foreign degree equivalent from an accredited institution in an area appropriate to UCF Coastal. The selected candidate must also have a demonstrated record of high impact research related to coastal systems demonstrated by a strong scholarly and funding record that is commensurate with rank in a department/school related to the candidate's area of expertise.

View job online for more information.

To apply: **https://findajob.agu.org/job/8023312/associate-professor-or-professor-and-director-national-center-for-integrated-coastal-research/**.

In addition to the online application, candidates should upload a cover letter, a current curriculum vitae, a statement of research and leadership experience, a vision statement for the Center, three (3) research publications from the last five (5) years most aligned with this position, and a list with contact information for three (3) professional references.

ETH zürich

PROFESSOR OF HYDROLOGY AND WATER RESOURCES MANAGEMENT

The Department of Civil, Environmental and Geomatic Engineering (D-BAUG, **www.baug.ethz.ch**) at ETH Zurich invites applications for the above-mentioned position.

The new professor is expected to develop a strong international research programme within two topical areas:

(a) ecohydrological processes at the soil-plant-atmosphere interface, their numerical modelling, and engineering applications and impact studies at urban and catchment scales;

(b) planning and management in the water-energy-food-ecosystem nexus, developing hydrosystem models, and stakeholder interaction and resource optimization tools.

The successful candidate is expected to be an established leader in one of these two areas and ready to grow the group in the second area. Successful candidates hold a PhD degree in environmental engineering or geosciences, with an outstanding research portfolio that combines strengths in numerical modelling, environmental sensing, and data analysis. A strong commitment to teaching at Bachelor and Master level courses in the environmental engineering curriculum is expected. In general, at ETH Zurich undergraduate level courses are taught in German or English and graduate level courses are taught in English. Academic achievements should be complemented by a demonstrated ability to lead a research group and generate external funding. The position will be filled at full professor level.

The professorship is embedded at the Institute of Environmental Engineering IfU at D-BAUG. IfU consists of seven complementary chairs covering fields in environmental engineering from urban water, microfluidics, ecological system design, to air quality and earth observation. Zurich is an outstanding hub for water research, with excellent collaboration opportunities within ETH and with proximity to the Swiss Federal Institutions EAWAG and WSL.

ETH Zurich is an equal opportunity and family-friendly employer, values diversity, and is responsive to the needs of dual-career couples.

Please apply online: **www.facultyaffairs.ethz.ch**

Applications should include a curriculum vitae, a list of publications, a statement of future research and teaching interests, a description of the leadership philosophy, a description of the three most important achievements, and a certificate of the highest degree. The letter of application should be addressed **to the President of ETH Zurich, Prof. Dr. Joël Mesot. The closing date for applications is 15 February 2024.**

■	■	C	A	R	■	C	F	A	A	■	C	O	D	A
■	V	I	E	D	■	R	A	M	I	■	O	K	E	D
N	I	N	T	H	■	O	V	E	R	D	R	I	E	S
D	O	G	S	O	F	W	A	R	■	C	A	M	P	S
A	L	E	■	L	A	D	■	■	R	E	L	A	S	E
M	I	S	A	D	D	■	T	R	O	D	■	N	E	L
U	N	T	I	E	■	T	R	I	O	■	C	O	A	L
■	■	■	O	R	C	H	E	S	T	R	A	■	■	■
F	I	R	N	■	I	E	E	E	■	I	M	B	U	E
U	T	E	■	A	T	M	S	■	A	B	E	I	N	G
M	A	N	T	L	E	■	■	B	O	N	■	S	S	A
B	L	E	E	D	■	S	Q	U	E	L	C	H	E	D
L	I	G	N	A	L	O	E	S	■	I	R	O	N	S
E	A	U	S	■	S	I	R	E	■	K	E	P	T	■
S	N	E	E	■	U	L	E	S	■	E	E	S	■	■

PRINCETON UNIVERSITY

OPEN RANK FACULTY POSITION

The Department of Geosciences at Princeton University is seeking applications for an **open-rank (tenure track or tenured) faculty position in Climate Science**. We are seeking candidates with an outstanding research track record in the area of climate dynamics broadly interpreted, expertise in advanced theories and concepts of the atmospheric general circulation and geophysical fluid dynamics, and commitment to mentoring and advising the next generation of climate scientists. The appointee will be also a member of the Program in Atmospheric and Oceanic Sciences, a joint program between the Department of Geosciences and the NOAA Geophysical Fluid Dynamics Laboratory.

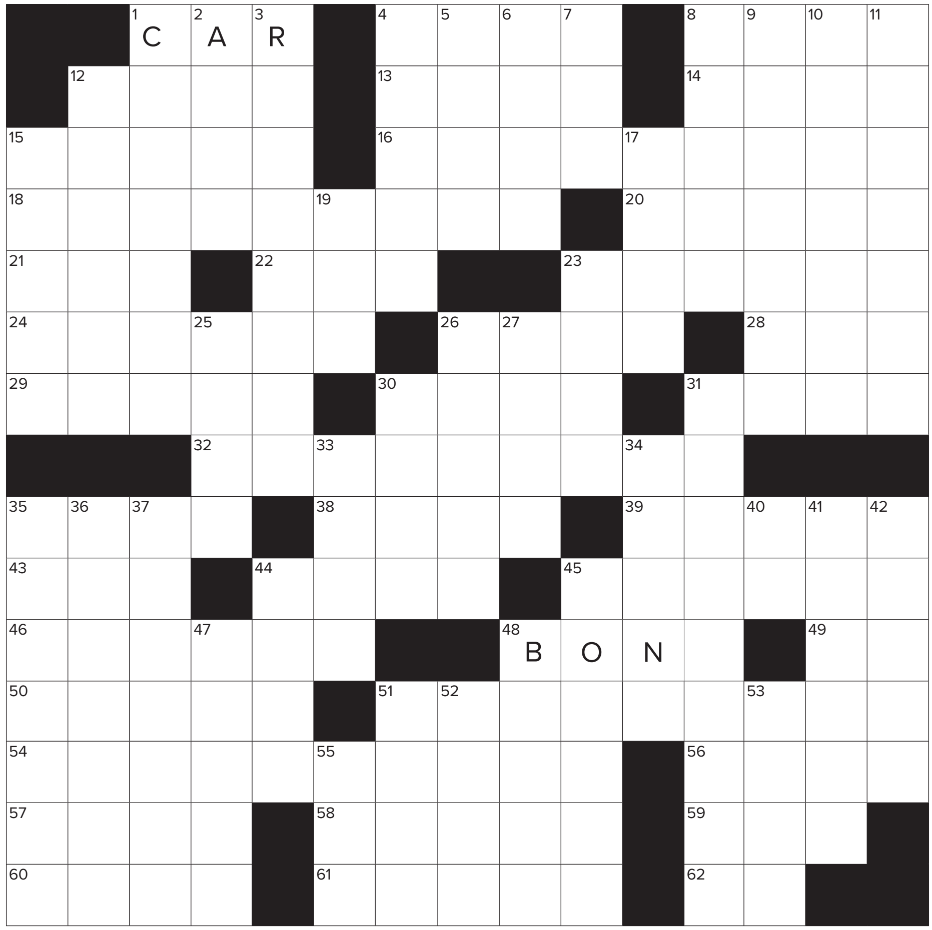
Applicants should submit a curriculum vitae, including a publication list, statements of research and teaching interests, and contact information for three references at: **https://puwebp.princeton.edu/AcadHire/position/32504**. Evaluation of applications will begin as they arrive; for fullest consideration, apply by **February 29, 2024**; but applications will be accepted until the position is filled.

Diversity and inclusion are central to Princeton University's educational mission and its desire to serve society. Members of the Geosciences department have a deep commitment to being inclusive. We believe that commitment to principles of fairness and respect for all is favorable to the free and open exchange of ideas, so we seek to reach out as widely as possible in order to attract outstanding individuals as students, faculty, and staff. As noted in the University's non-discrimination statement, we are committed to nondiscrimination on the basis of personal beliefs or characteristics: https://dof.princeton.edu/governance/policies/non-discrimination-statement.

This position is subject to the University's background check policy.

Follow the Carbon

By Russ Colson, Minnesota State University Moorhead



ACROSS

1 Automobile convoy?—and the first part of a theme triplet for this puzzle
4 1986 Act of Cong. addressing computer fraud/abuse
8 Ending section in music
12 Competed
13 Branches, or actor _____ Malek
14 Approved
15 Final push, as in "The project is in the _____ inning"
16 Dehydrates too much
18 They're set loose in armed conflict, symbols of uncontrollable chaos
20 Tent sites
21 Ending for b, d, g, h, k, m, p, r, s, t, v, w, and y
22 Boy
23 Eye procedure do-over?
24 Do math wrong, e.g.
26 Stepped (on)
28 First word in Dante's *Inferno*, "_____ mezzo del cammin di nostra vita," or an ending for fun, fen, and ken
29 Set loose, as in "_____ your wings and free your soul" (Rumi)
30 Nirvana, or Peter, Paul, and Mary
31 *Crustal rock, a reservoir that holds 86% of Earth's surface carbon, includes this high-C material
32 Made with strings, brass, woodwinds, and percussion
35 Preglacial granular snow
38 Professional org. in electrical engineering
39 Infuse pervasively
43 Indigenous person of Utah
44 Units of pressure, abbr.
45 One human or alien
46 *Reservoir holding 100 times Earth's surface carbon
48 Good French candy?—and the second part of a theme triplet for this puzzle
49 Org. providing retirement benefits
50 "I ain't got time to _____" (Jesse Ventura, former wrestler, governor, author, and actor)
51 Suppressed vehemently, or an onomatopoeia in "he _____ through the mud"
54 Woody plants that produce oil for perfumes and soaps. Hint: anagram for the football field boundaries beyond which a touchdown is scored
56 They're in the fire?
57 Parisian waters
58 King, or thoroughbred stallion
59 Retained
60 Knife, or snotty start for red or ring
61 Plural ending for amp, nod, and mod
62 Savings bond options

DOWN

1 Most nurturing?
2 Chevron-shaped characters in the upper center of keyboards
3 Wallet, or person with credit
4 Sometimes three's a _____, —a hint for the circled squares
5 Bean for Egyptian falafel
6 USA nickname abbr.
7 *Reservoir holding 0.001% of Earth's total surface carbon
8 *Carbon-rich material extracted from seawater by living things or living things that extract carbon from seawater
9 All right, then, I say nay
10 *Aqueous reservoir holding 0.05% of Earth's surface carbon
11 Marketing claim: ______ ______ products
12 Fiddle
15 142 perhaps, depending on the isotope, and don't forget the units, abbr.
17 Disconnected, in online lingo
19 Bell bottoms, Beanie Babies, or Pokémon Go
23 Cheer or dig
25 Greek god of eternal cycles, or "when computers reach singularity, don't turn the _____ _____"
26 *Terrestrial biomass, a reservoir that contains 0.001% of Earth's surface carbon, includes these
27 Hot air might do it
30 Classic 1950s sci-fi horror movie
31 Attended
33 Attribute or commend
34 Narrow and long
35 Football mistakes
36 Demonym for pizza, Leonardo, or Etna
37 Go back on a promise (alternate spelling)
40 A chess set has four
41 Still in the outbox
42 Great Scott!
44 Alan ____ of *M*A*S*H*
45 Grievance, as in "I have ____ ____ to pick"
47 Past, present, or future
48 Extras, like pay at Christmas
51 *Part of reservoir that holds 0.002% of Earth's surface carbon, including permafrost
52 Hebrew writing convention
53 First Nations people of Canada
55 Tiger school of the Southeastern Conf.

See page 31 for the answer key.

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