EARTH, SEA, AND SKY:

Leaders In Discovery

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

70 YEAR ANNIVERSARY EDITION

"Aside from its natural beauty, the Lamont Campus serves as one of the premiere intellectual centers in the Earth sciences. It attracts excellent graduate students and the best postdoctoral fellows out there. Our cast of...PhD-level scientists allows us to teach an amazing breadth of courses and provide top-notch mentorship for students and postdocs. Most importantly, it's a friendly environment… and the extent of cooperation is unparalleled."

–Wallace Broecker ***1931-2019***

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CHANGING ICE, CHANGING COASTLINES

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REAL-TIME EARTH

Science on the Front Lines of Our Changing Planet
Lamont-Doherty Earth Observatory | Columbia University

__Cover:__ NASA Goddard Space Flight Center image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing). Data and technical support: Moderate Resolution Imaging Spectrometer (MODIS) Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group. Additional data: U.S. Geological Survey (USGS) Earth Resources Observation and Science Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights). February 2002.
__Opposite page:__ Maurice Ewing and Frank Press in front of Lamont Hall, early 1950s. Photo courtesy of Lamont-Doherty Earth Observatory.

Earth, Sea, and Sky:

Leaders In Discovery

Above: *Skaftafell Glacier, Iceland. Panorama photo by Jeremy Hinsdale.*

The Lamont-Doherty Earth Observatory is a rare enterprise. With strategic initiatives supporting inquiries that span the Earth, sea, and sky, our portfolio is broad, deeply ambitious, and inclusive of all aspects of the planet's dynamics. We are home to the greatest breadth of Earth science research and the largest concentration of Earth and climate scientists of any academic institution in the nation. Lamont's scientists seek to understand Earth's future by analyzing the history of climate change recorded in ice cores, tree rings, glaciers and their margins, corals, land and ocean sediments, and other natural archives. Lamont researchers are pioneers in the development of instruments to make observations from all types of platforms, including ships, underwater vehicles, aircraft, drones, and satellites. Lamont operates the *Marcus G. Langseth*, an oceanographic research vessel able to collect critical measurements, samples, and real-time data world-wide. This extraordinarily broad range and depth of scientific investigation set Columbia University's geoscientific research, particularly in the area of Earth's changing climate and its impacts, apart from that of peer institutions.

The year 2019—Lamont's 70th year—found our scientists adding important discoveries to the Observatory's robust body of research and continuing our tradition of exposing and illuminating distinctive aspects of our planet, how our world is changing, and how it is responding to global climate change. Characteristic of the Observatory, these explorations leveraged groundbreaking methods of observation, bringing to bear the full force of existing scientific knowledge as well as the innovative creativity that is and has always been the cornerstone of Lamont science. This year and throughout the past seven decades, Lamont scientists have pushed the edge of understanding to uncover new insights about our home planet and new predictions about life in the future.

Among the stories appearing in this year's report are accounts of research into the observable shift of the ocean conveyor belt and what its present slowdown foretells about future climate; a discovery about the influences of volcanic activity on hurricane production; findings that trace the diminishing protective powers from hurricanes of wind shear and what they mean for the U.S. East coast; evidence that melting at the so-called "third pole," the mountain glaciers of the Himalayas, has accelerated markedly since the start of the 21st century because of rising atmospheric temperatures; and how climate change is fueling rampant wildfires.

Today, with the growing body of information on the impact of climate change on myriad aspects of life on Earth, Lamont's contribution to creating new knowledge to inform global solutions has never been more crucial or more exciting. As we advance into our 71st year, and all of the discoveries that await, we proudly present this, our annual report for 2019.

> *"Steady changes to Earth's climate have spun off, with increasing regularity, new examples of extreme weather and growing hazards to ecosystem health and human sustainability. Our mission of inquiry and discovery has never been more necessary or urgent."*

Dear Friend,

2019 has been a milestone year for Lamont, for a number of reasons. As the academic year drew to a close at the end of June, our planet was on the threshold of what would be the warmest month on record. Steady changes to Earth's climate have spun off, with increasing regularity, new examples of extreme weather and growing hazards to ecosystem health and human sustainability. Our mission of inquiry and discovery has never been more necessary or urgent. The research chronicled in this report demonstrates the continuing ability of Lamont scientists and students to illuminate the impacts of climate change, sharpen our understanding of the underlying Earth system dynamics, and inform solutions and strategies for the challenges we face in the future.

During the past year, our friend and Lamont icon Wally Broecker passed away. His death has led all of us to reflect on his profoundly influential contributions across Earth science and on the seemingly boundless joy and energy for discovery he brought to this campus community for more than six decades. Thus, among the many stories about our scientific research and discoveries from the past year described in this report, we also include a piece by Columbia professor and Dean of Science Peter de Menocal on Wally's life and legacy.

2019 also marked Lamont's 70th anniversary. In 1949, Maurice "Doc" Ewing had the clarity of vision to accept an offer from Columbia University President Dwight Eisenhower to establish a new type of Earth science campus on a wooded bluff overlooking the Hudson River in Palisades, New York. Prior to that time, Ewing had worked in Schermerhorn Hall on the Morningside Heights campus, investigating the structure of Earth's crust with the new field of explosion seismology. Within a few years of Lamont's founding, Ewing had secured an oceanographic ship, the R/V *Vema*, and expanded the reach of the Observatory's scientists to the world's oceans. Following in Ewing's footsteps have been hundreds of intellectually curious, driven researchers who have continued building on his legacy, inventing novel ways to explore the workings of our planet, creating new scientific fields, and contributing broadly to Earth and environmental sciences.

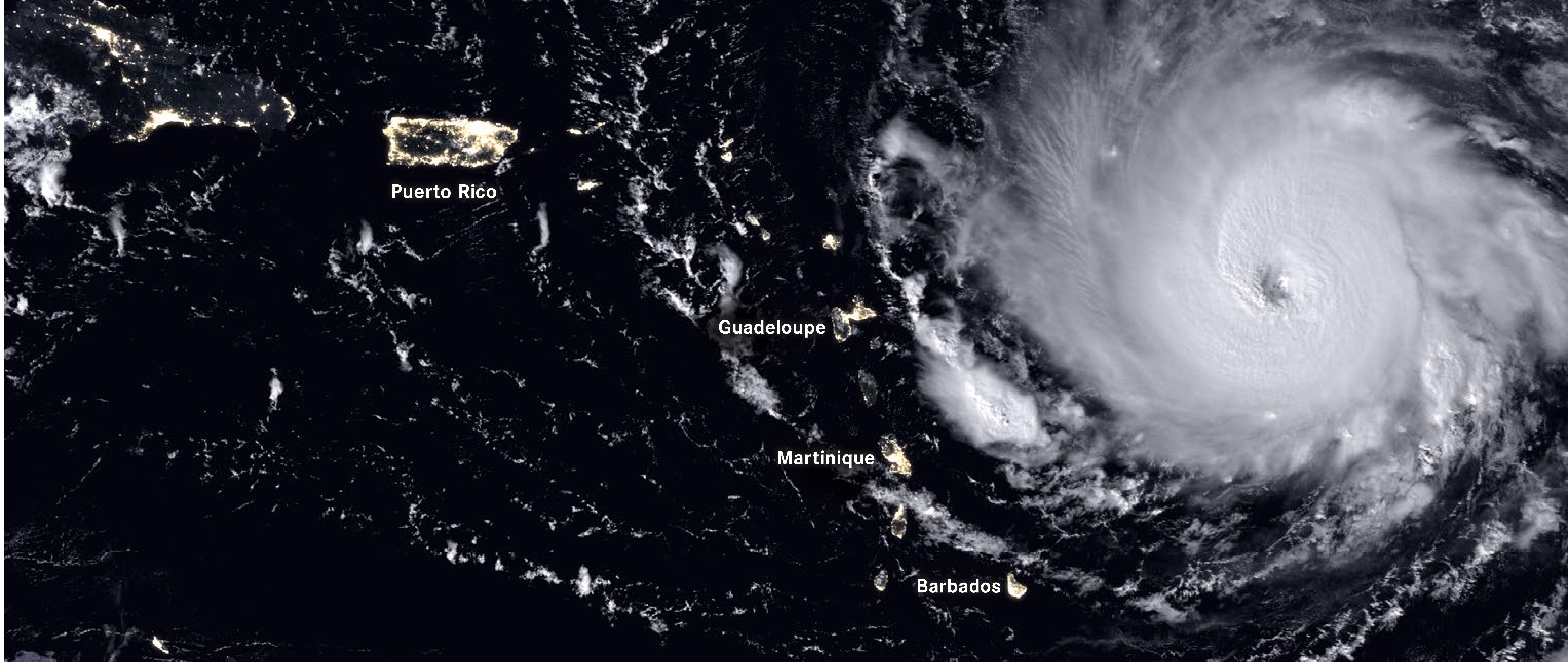
Your donations every year fuel this work directly, by helping Lamont scientists improve our understanding of our planet's past and present, and by enhancing our ability to address the major environmental challenges ahead for all of us. We deeply appreciate the generosity of our donors and the scientific progress their gifts make possible.

For another year, thank you for your support.

With best wishes,

Sean C. Solomon
Director

70 YEAR ANNIVERSARY EDITION



Large Volcanic Eruptions Can Alter Hurricane Strength and Frequency

By Nicole deRoberts

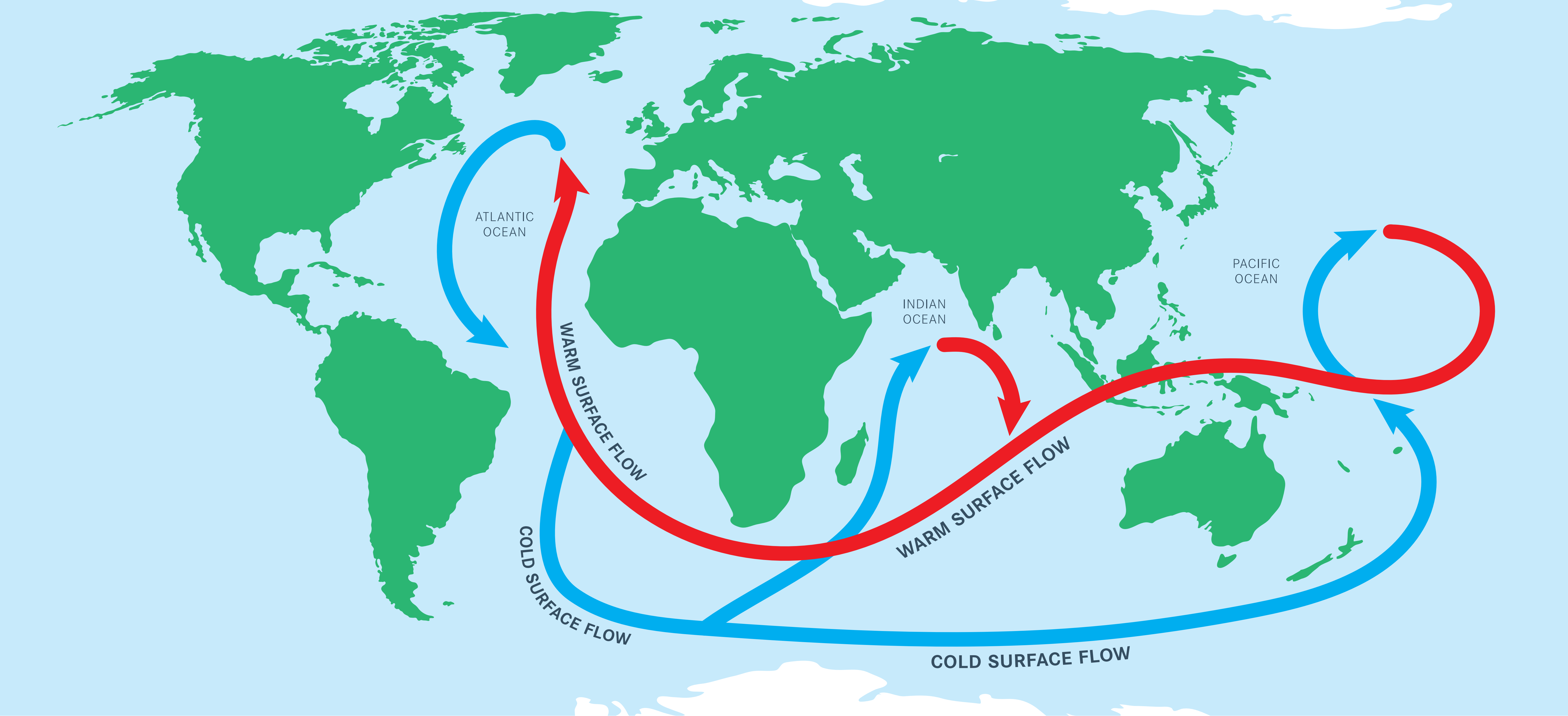
Above: *Hurricane Irma forming over the Atlantic Ocean in September 2017. NASA Earth Observatory image by Joshua Stevens and Jesse Allen, created from day-night band data from the Visible Infrared Imaging Radiometer Suite on the Suomi National Polar-orbiting Partnership satellite.*

Lamont climate dynamicist Suzana Camargo and Université du Québec à Montréal's Francesco Pausata produced a study this year that provides deeper insight into how large volcanic eruptions affect hurricane activity. Previous studies could not clearly determine the effects of volcanic eruptions on hurricanes, because the few large volcanic eruptions in the last century coincided with El Niño-Southern Oscillation events, which also influence hurricane activity. In their study, which appeared in the *Proceedings of the National Academy of Sciences*, Camargo and Pausata approached this relationship by simulating very large volcanic eruptions in the tropics multiple times. Their modeling told a more complex story than previous work had indicated.

"This is the first study to explain the mechanism of how large volcanic eruptions influence hurricanes globally," said Camargo.

According to their findings, large tropical volcanic eruptions can affect hurricanes by shifting the Intertropical Convergence Zone (ITCZ), a region that encircles the Earth near the equator and greatly influences rainfall and hurricane activity. As the ITCZ moves after a large volcanic eruption, it affects both the intensity and frequency of hurricanes, causing some regions to experience an increase in activity and other regions to experience a decrease. For example, a large eruption in the tropical regions of the northern hemisphere leads to a southward shift of the ITCZ. This results in an increase in hurricane activity between the equator and the 10°N parallel, and a decrease farther north. The zone's southward shift has further effects in the southern hemisphere, causing a decrease in activity on the coasts of Australia, Indonesia, and Tanzania, while Madagascar and Mozambique experience an increase. These changes can last for up to four years following the eruption.

Camargo and Pausata were able to separate the effects of volcanic eruptions and El Niño-Southern Oscillation on hurricane activity and show the different impacts that the two factors have on hurricanes globally. Their findings are important in helping scientists better understand regional hurricane risk.



Changes in Ocean 'Conveyor Belt' Foretold Abrupt Climate Changes by Four Centuries

Same Atlantic Current Is Weakening Today

By Sarah Fecht

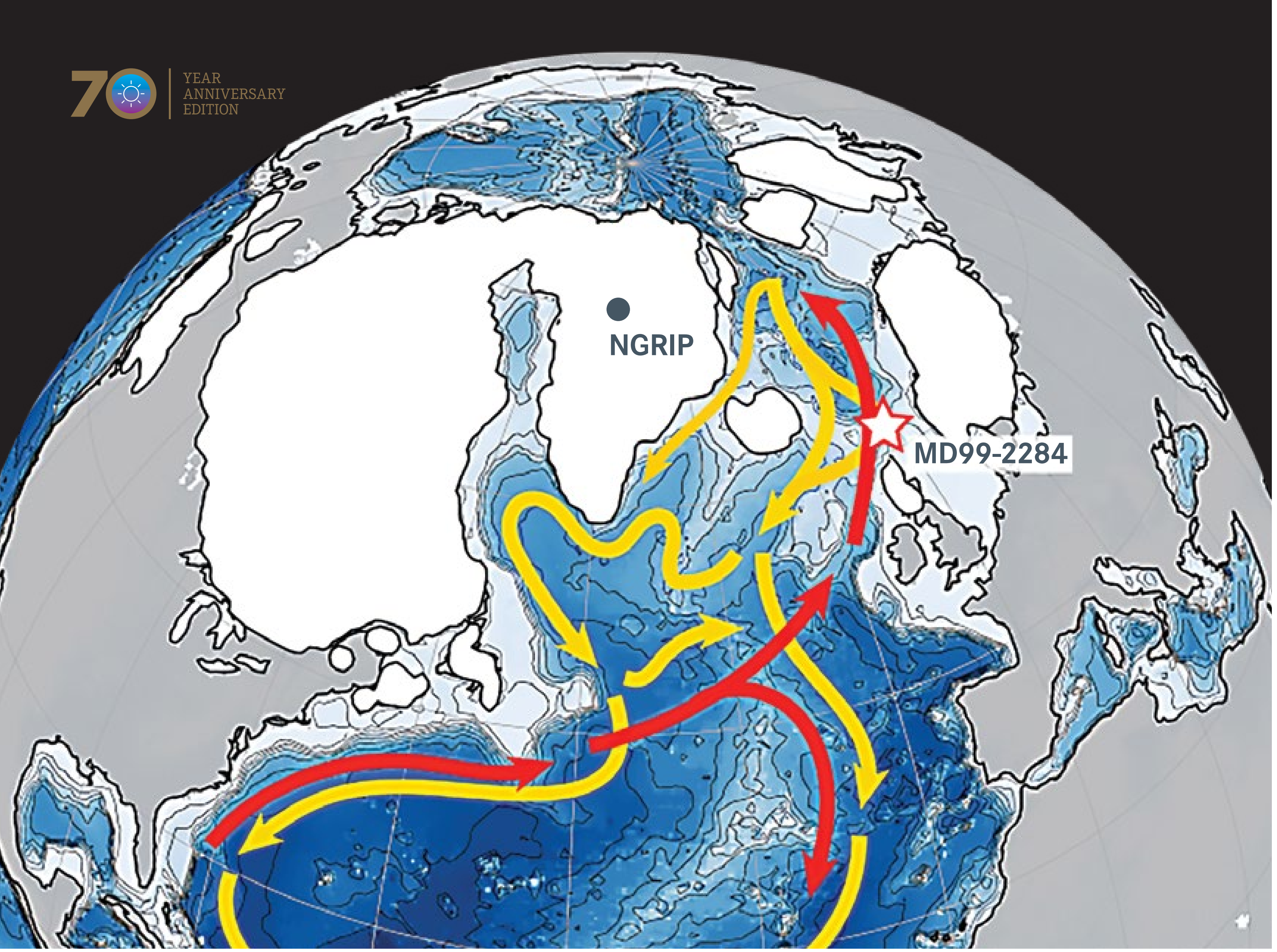
Above: *the ocean's "conveyor belt" circulation pattern is an important player in global climate, regulating weather in the Arctic, Europe, and around the world. Image from Muschitiello et al., 2019.*

In the Atlantic Ocean, a giant "conveyor belt" carries warm waters from the tropics into the North Atlantic, where they cool and sink and then return southwards in the deep ocean. This circulation pattern is an important player in the global climate, regulating weather patterns in the Arctic, Europe, and around the world. Evidence increasingly suggests that this system is slowing down, and some scientists fear that further slowing could have major effects, such as causing temperatures to dive in Europe and warming the waters off the east coast of the United States, potentially harming fisheries and exacerbating hurricanes.

A Lamont-led study published in March provided fresh insight into how quickly these changes could take effect if the system continues weakening. The research was a collaborative effort with the Norwegian Research Centre and is the first to determine precisely the time lags between past changes to the ocean conveyor belt and major climate changes.

The team studied a key section of the ocean current pattern, known as the Atlantic Meridional Overturning Circulation (AMOC). They zeroed in on a section where water sinks from the surface to the bottom of the North Atlantic. They confirmed that the AMOC started weakening about 400 years before a major cold snap 13,000 years ago, and began strengthening again about 400 years before an abrupt warming 11,000 years ago.

"Our reconstructions indicate that there are clear climate precursors provided by the ocean state – like warning signs, so to speak," says lead author Francesco Muschitiello, who completed the work as a postdoc at Lamont and now works at the University of Cambridge.



__Above:__ a simplified diagram of the Atlantic Meridional Overturning Circulation (AMOC). Image from Muschitiello et al., 2019.
__Opposite page:__ changes in AMOC strength (blue line) began hundreds of years before the abrupt temperature changes over Greenland (red line) that marked the beginning and end of the hemispheric cold snap known as the Younger Dryas period (shown here by the gray column). Image from Muschitiello et al., 2019.

Core Truths

Until now, it has been difficult to resolve whether past changes in the ocean conveyor belt occurred before or after the abrupt climate shifts that punctuated the last deglaciation in the northern hemisphere. To overcome the usual challenges, the team pieced together data from a sediment core drilled from the bottom of the Norwegian Sea, a lake sediment core from southern Scandinavia, and ice cores from Greenland.

Scientists typically rely on radioactive carbon (carbon 14) dating to determine the ages of sediments; measuring how much carbon 14 remains in a fossil reveals how long ago the organism died, and thus how old the surrounding sediment is. This relationship is tricky in ocean sediments, though, because carbon 14 is created in the atmosphere, and it takes time for the carbon to make its way through the ocean. By the time it reaches the organisms at the bottom of the water column, the carbon 14 could already be hundreds or thousands of years old. So the team needed a different way to date the sediment layers in the marine core.

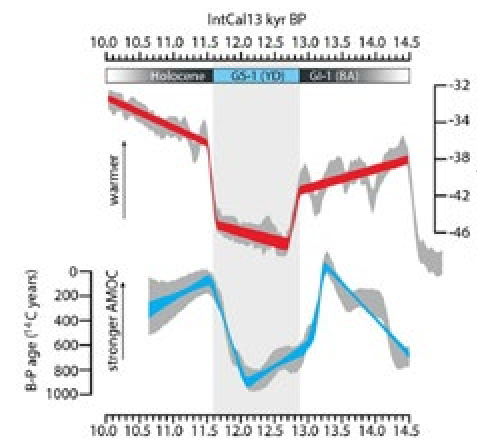
That's why they measured carbon 14 content in a nearby lake sediment core. The ancient layers of the lake contain decaying plants that pulled carbon 14 directly out of the atmosphere, so the scientists could learn the age of each lake sediment layer. Then they used a few techniques to match the lake sediment core layers to the marine core layers. Ash layers from two past volcanic eruptions in Iceland helped to line things up. This process gave the team the precise age of each layer in the marine core.

Next, they compared the real age of the marine sediments to the age they were reading from the deep-ocean carbon 14 measurements; the differences between these two gave them an estimate of how long it took for the atmospheric carbon 14 to reach the seafloor. In other words, it revealed how quickly water was sinking in this area, in a process called deep water formation that's essential to keeping the AMOC circulating. Now they had a record of ocean circulation patterns in this region over time.

The final piece of the puzzle was to analyze ice cores from Greenland, to study changes in temperature and climate over the same time period. Measurements of beryllium-10 in the ice cores helped the authors precisely link the ice cores to the carbon 14 records, putting both sets of data on the same timeline. Now they could finally compare the order of events between ocean circulation changes and climatic shifts.

Leads and Lags

Comparing the data from the three cores revealed that the AMOC weakened in the time leading up to the planet's last major cold snap, called the Younger Dryas, around 13,000 years ago. The ocean circulation began slowing down about 400 years before the cold snap, but once the climate started changing, temperatures over Greenland plunged quickly by about 6 °C.



A similar pattern emerged near the end of that cold snap; the current started strengthening roughly 400 years before the atmosphere began to heat up markedly, transitioning out of the ice age. Once the deglaciation started, Greenland warmed up rapidly – its average temperature climbed by about 8 °C over just a few decades, causing glaciers to melt and sea ice to drop off considerably in the North Atlantic.

"Those [400-year] lags are probably on the long side of what many would have expected," says Anders Svensson, who studies the paleoclimate at the University of Copenhagen, but who was not involved with the current study. "Many previous studies have suggested time lags of various lengths, but few have had the necessary tools to determine the phasing with sufficient accuracy."

Lamont paleoclimatologist and study co-author William D'Andrea was surprised by what they found – he says the lag times are two to three times greater than he would have expected.

Future AMOC

For now it's not fully clear why there was such a long delay between the AMOC changes and climatic changes over the North Atlantic.

It's also difficult to pinpoint what these patterns from the past could signify for Earth's future. Recent evidence suggests that the AMOC began weakening again 150 years ago. However, current conditions are quite different from the last time around, says Muschitiello; the global thermostat was much lower back then, winter sea ice stretched farther south than New York Harbor, and the ocean structure would have been much different. In addition, the past weakening of the AMOC was much more marked than today's trend so far.

Nevertheless, D'Andrea says that "if the AMOC were to weaken to the degree it did back then, it could take hundreds of years for major climate changes to actually manifest."

Muschitiello adds, "It is clear that there are some precursors in the ocean, so we should be watching the ocean. The mere fact that AMOC has been slowing down, that should be a concern based on what we have found."

The study should also help to improve the physics behind climate models, which generally are based on the assumption that the climate responds abruptly at the same time as AMOC intensity changes. The model refinements, in turn, could make climate predictions more accurate. As Svensson puts it: "As long as we do not understand the climate of the past, it is very difficult to constrain the climate models needed to make realistic future scenarios."

Scientists Track Deep History of Planets' Motions, and Effects on Earth's Climate

Newly Forming Map of Chaos in the Solar System

By Kevin Krajick

Above: *Lamont geologist Paul Olsen in Arizona's Petrified Forest National Park, December 2013. At this site 200-million-year-old rocks are helping to reveal the past motions of other planets. Photo by Kevin Krajick.*

Scientists have long posited that periodic swings in Earth's climate are driven by cyclic changes in the distribution of sunlight reaching our surface. This is due to cyclic changes in how our planet spins on its axis, the eccentricity of its orbit, and its orientation toward the Sun – overlapping cycles caused by subtle gravitational interplays with other planets, as the bodies whirl around the Sun and by each other like gyrating hula-hoops.

But planetary paths change over time, and that can change the cycle lengths. This has made it challenging for scientists to untangle what drove many ancient climate shifts. And the problem gets ever more difficult the farther back in time you go; tiny changes in one planet's motion may knock other planetary motions askew – at first slightly, but as eons pass, these changes resonate against each other, and the system morphs in ways impossible to predict using even the most advanced math. In other words, it's chaos out there. Up to now, researchers are able to calculate the relative motions of the planets and their possible effects on our climate with reasonable reliability back only about 60 million years – a relative eyeblink in the 4.6-billion-year life of Earth.

However, in a paper published this year in the *Proceedings of the National Academy of Sciences*, a team of researchers demonstrated how they pushed the record farther back, identifying key aspects of the planets' motions from a period around 200 million years ago. The team is led by Lamont geologist and paleontologist Paul Olsen. Last year, by comparing periodic changes in ancient sediments drilled from Arizona and New Jersey, Olsen and colleagues identified a 405,000-year cycle in Earth's orbit that apparently has not changed at all over at least the last 200 million years – a kind of metronome against which all other cycles can be measured. Using those same sediments in the new paper, they now have identified a cycle that started out with a period of 1.75 million years, but is now operating every 2.4 million years. This, they say, allows them to extrapolate long-term changes in the paths of Jupiter and the inner planets (Mercury, Venus and Mars), the bodies most likely to affect Earth's orbit.

***Below:** view looking east toward the United States, on 7 October 2015, when the three planets most influential to Earth's orbit lined up with the Moon. Painting by Paul Olsen, inspired by a photo taken by U.S. astronaut Scott Kelly (acrylic on clay board, digitally modified).*

Olsen's ultimate aim: to use Earth's rocks to create what he calls a "Geological Orrery" – a record of climatic changes on Earth that can be extrapolated back into a larger map of solar system motions over hundreds of millions of years. He says it would open a window not just onto our own climate, but the evolution of the solar system itself, including the possible existence of past planets, and its possible interactions with invisible dark matter.

We spoke with Olsen about the Geological Orrery, his work, and the new paper.

Most people have probably never even heard the word "orrery." What is it, and how does it fit with our evolving understanding of celestial mechanics?

In the early 1800s, mathematician Pierre-Simon de Laplace took Newton's laws of gravitation and planetary motion and published his idea that it should be possible to develop a single great equation that would allow all the universe to be modeled. With only knowledge of the present, all the past and future could be known. This idea is embodied in the orrery, a mechanical model of the solar system. Clockwork mechanisms like this for predicting eclipses and the like go back to the ancient Greeks, but it's now clear the problem is far more complicated, and interesting.

We've since discovered that the solar system is not a clockwork. It is in fact chaotic over long time scales, so Laplace's grand equation was a mirage. This means you cannot unpack its history from calculations or models, no matter how precise, because the motions of the real solar system are incredibly sensitive. Varying any factor even a tiniest bit results in a different outcome after millions of years – even what the major asteroids, or minor planets, such as Ceres and Vesta, are doing. One of my coauthors, Jacques Laskar, has shown that computations can project forward or backward only 60 million years. After that, the predictions become utterly unreliable. Since Earth is about 4.6 billion years old, this means that only about 1.6 percent of its past or future orbit can be predicted. Over billions of years, the best calculations reveal many possible terrific events, such as one of the inner planets falling into the Sun or being ejected from the solar system. Maybe even that Earth and Venus could collide one day. We can't tell if any of these actually happened, or might happen in the future. So we need some other method to limit the possibilities.

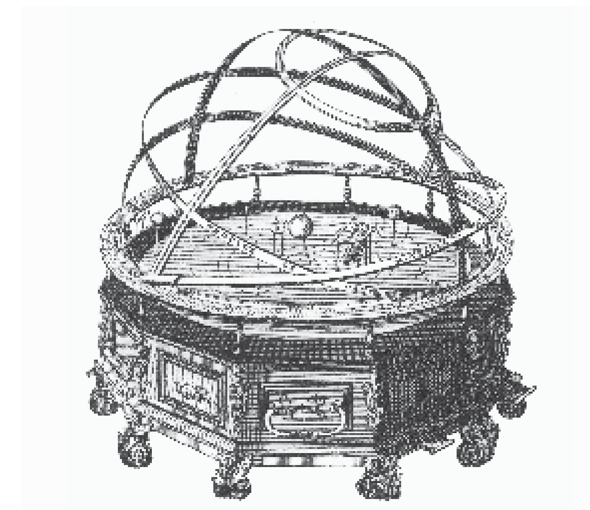
So, what is the "Geological Orrery?" Are you trying again to boil everything down to one equation, or is this something different?

The Geological Orrery is the opposite of an equation or model. It's designed to provide a precise and accurate history of the solar system. We get that history right here on Earth, from the history of our climates, which is recorded in the geological record, especially in large, long-lived lakes.

Earth's orbit and axis orientation are constantly changing because they are being deformed by the gravitational attractions of other bodies. These changes affect the distribution of sunlight hitting our surface, which in turn affects climate, and the kinds of sediments that are deposited. That gives us the geological record of solar system behavior.

***Above:** a mechanical orrery presented in 1713 by English inventor John Rowley to Charles Boyle, the Fourth Earl of Orrery – the source of the name for similar devices. Engraving from the Universal Magazine, 1749.*

Many scientists have used sediments to determine the effects of orbital deformations. That's how we know that the ice ages of the last few million years were paced by them. Some researchers have tried to go back much further in time. What is new here is the systematic approach of taking rock cores spanning tens of millions of years, looking at the cyclical sedimentary record of climate and accurately dating those changes over multiple sites. That allows us to capture the full range of solar-system-driven deformations of our orbit and axis over long time periods.



What are the rocks telling you about how such cyclic changes affect our climate?

With two major coring experiments to date, we've learned that changes in tropical climates from wet to dry during the time of early dinosaurs, from about 252 to 199 million years ago, were paced by orbital cycles lasting about 20,000, 100,000 and 400,000 years. On top of that is a much longer cycle of about 1.75 million years. The shorter cycles are about the same today, but the 1.75-million-year cycle is way off – it's 2.4 million years today. We think the difference is caused by a gravitational dance between Earth and Mars. This difference is the fingerprint of solar system chaos. No existing set of models or calculations precisely duplicates these data.

Opposite page: *digital elevation image of sedimentary strata formed on a lake bottom about 220 million years ago, near modern Flemington, N.J. LIDAR image from the U.S. Geological Survey; digital colorization by Paul Olsen.*

How far do you think we're going to get with this problem during your lifetime?

The next step is to combine our two finished coring experiments with cores taken at high latitudes. While our core data do a really good job of mapping some aspects of planetary orbits, they tell us nothing about others. For those, we need a core from an ancient lake above the paleo-Arctic or Antarctic circles. Such deposits exist in what are now China and Australia. We also would like to include deposits that extend the record up 20 million years or so towards the present, and another low-latitude core that we can precisely date. With those, we would be able to determine what if any changes have taken place in that Mars-Earth gravitational dance. That would be a full proof of concept of the Geological Orrery. I plan to certainly be around for that.

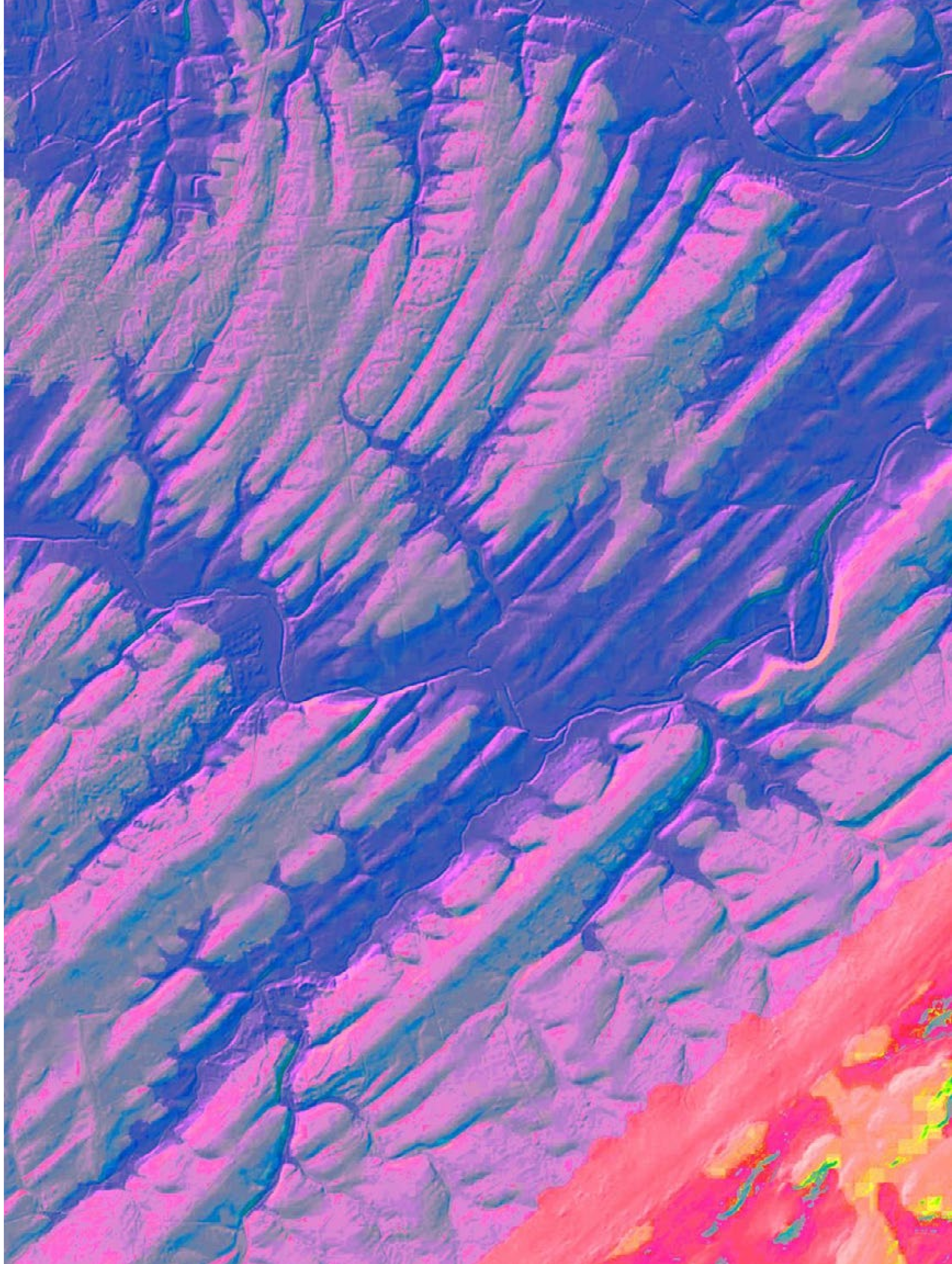
Your paper mentions that this work might offer insights into the evolution of the solar system – maybe even the wider universe.

If all this works out, we could plan the grand mission to use the Geological Orrery for at least the rest of the time between 60 and 190 million years ago. This mission would be expensive by geology standards, because rock coring is expensive. But the results would have far-reaching implications. For sure we would have data to produce high-quality climate models for ancient eras on Earth. And there is no doubt we would have the parameters for past climates on Mars or other rocky planets. But more excitingly and more speculative is the possibility of exploring how we might need to tweak gravity theory, or test some controversial theories, such as the possible existence of a plane of dark matter in our galaxy that our solar system passes through periodically.

We're talking deep time here. Does this have any application to questions about modern-day climate change?

It does have relevance to the present. in addition to the way climate is tuned to our orbit, it's also affected by the amount of carbon dioxide in the air. Now we're heading into a time when CO_2 levels may be as high as they were 200 million years ago, early dinosaur times. This gives us a potential way to see how all the factors interact. It also has resonance with our search for life on Mars, or for habitable exoplanets.

The paper is coauthored by Jacques Laskar, Observatoire de Paris; Dennis Kent and Sean Kinney, Lamont-Doherty Earth Observatory; David Reynolds, ExxonMobil Exploration; Jingeng Sha, Nanjing Institute of Geology and Paleontology; and Jessica Whiteside, University of Southampton.



What's Really Feeding Long Island's Destructive Brown Tides?

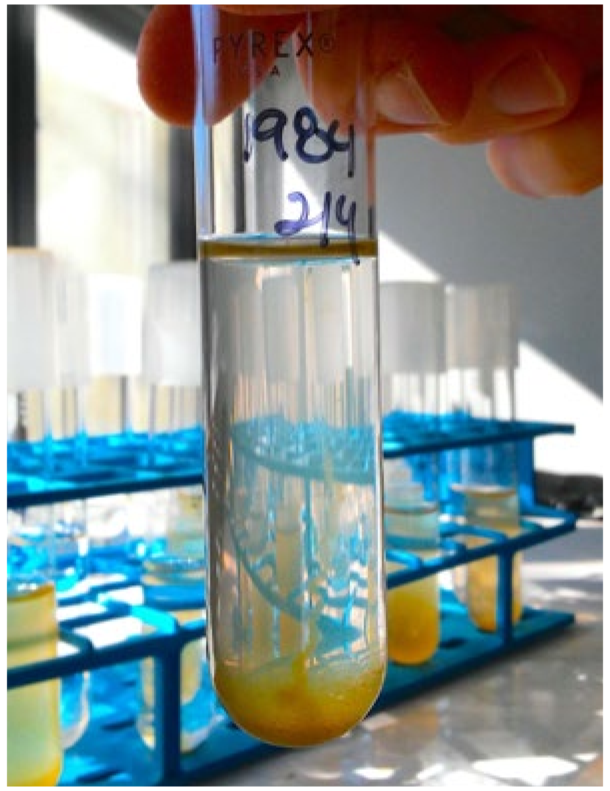
By Marie DeNoia Aronsohn

Above: *harmful algae blooms known as brown tides can crowd out native seagrasses and poison shellfish. Photo by Florida Fish and Wildlife.*

The algae species *Aureococcus anophagefferens* surfaced off Long Island in 1985, turning estuaries the color of mud, crowding out native seagrass, and poisoning shellfish. The algae flourished, choking a once thriving shellfish industry and detracting from the region's all-important tourism trade. At high densities the algae can result in devastating brown tides, which continue to plague Long Island's Great South Bay and other mid-Atlantic waters. By leveraging a genomic approach called metranscriptomics, Lamont microbiologists have developed a new understanding about this species, which points to a new, more effective strategy to limit its growth. The researchers determined that phosphorus management may be important to controlling brown tides.

"The algae flourished, choking a once thriving shellfish industry and detracting from the region's all-important tourism trade"

Right: *Aureococcus growing in a test tube in the Dyhrman laboratory at Lamont. Photo by Sheean Haley.*



Scientists wanted to know how *Aureococcus anophagefferens* managed to grow so well along coastlines that are heavily impacted by human activities. A 2011 study provided a critical starting point by sequencing this alga's genome–identifying that it had capabilities which allowed it to thrive in anthropogenically modified ecosystems high in organic matter. In a 2014 study, follow-up research uncovered the phytoplankton's survival secret, which lies in its DNA; *Aureococcus* can make enzymes that break down organic nitrogen and phosphorus when inorganic nutrients run low, allowing it to beat out competing organisms and flourish. The nitrogen and phosphorus *Aureococcus* need to bloom often come from storm water run-off and other land-based sources.

Based on the DNA and other research, scientists learned how the genes encoded in the genome turned on and off in response to the supply of nutrients such as nitrogen and phosphorus, developing a metatranscriptomic approach to identify the activities of *Aureococcus* in a mixed community of other algae. Traditionally, researchers track the blooms by counting the cells in the water and measuring water chemistry to see if the algae are limited for nitrogen or phosphorus.

"You monitor water chemistry and how many cells are there, and that can tell you whether the algal community is getting enough nitrogen or enough phosphorus, and that influences management and mitigation decision making," said Lamont microbial oceanographer and senior author Sonya Dyhrman. This has typically meant focusing efforts on reducing nitrogen inputs into the estuaries that host brown tides.

However, in the study, which was published in *Frontiers in Microbiology* in February 2019, Dyhrman and her colleagues took a different, more direct approach to assess what is feeding these cells, bringing their inquiry to the cells in the waters off the Hamptons. Dyhrman compares the traditional way of gauging the *Aureococcus* activities to going into a refrigerator and deciding whether a person is healthy on the basis of what is in that refrigerator.

"It's this idea that we are making inferences about the health or activity of the algae based on what's in the water rather than looking at the cells themselves. A much better way than looking in the refrigerator would be to test you to see if you are healthy or not. What we set about to do with this study was to ask the algae themselves if they are getting enough nitrogen or enough phosphorus," explained Dyhrman.

In effect, they asked which genes are turned on and off, knowing–from previous findings–that distinct, specific genes are activated by nitrogen and others by phosphorus availability. What they found was surprising.

"The chemistry of the water (the refrigerator approach) was telling us they're not getting enough nitrogen. But when we looked at the cells, they were turning on all of their genes that indicated they were not getting enough phosphorus. Not what we expected," said Dyhrman.

It was the first-time scientists were able to use the gene expression approach to specifically ask this harmful alga species what resources it's using in the field–something that hasn't been trackable until recently.

"The cells were telling us something different from the water chemistry," said Dyhrman. "Which means that we need to think about not just nitrogen but also phosphorus when we think about controlling or mitigating these blooms."

"We have shown with this method that the algal cells are rapidly responding to variables in their environment that we either cannot detect, or have not yet detected," said Louie Wurch, lead author and assistant professor at James Madison University. "We have a lot more to learn, and this has really opened the door for a lot of exciting future research!"

Above: *Louie Wurch, assistant professor at James Madison University and collaborator with Sonya Dyhrman's group at Lamont, prepares brown tide samples for metatranscriptome analyses. Photo by Sonya Dyhrman.*

> *"You monitor water chemistry and how many cells are there, and that can tell you whether the algal community is getting enough nitrogen or enough phosphorus, and that influences management and mitigation decision making"*

Melting of Himalayan Glaciers Has Doubled in Recent Years

By Kevin Krajick

Above: *Changri Nup glacier, with Mt. Everest in the background. Photo by Joshua Maurer.*

A newly comprehensive study shows that melting of Himalayan glaciers caused by rising temperatures has accelerated markedly since the start of the 21st century. The analysis, spanning 40 years of satellite observations across India, China, Nepal, and Bhutan, indicates that glaciers have been losing the equivalent of more than a vertical foot and half of ice each year since 2000 – double the amount of melting that took place from 1975 to 2000. The study is the latest and perhaps most convincing indication that climate change is eating the Himalayas' glaciers, potentially threatening water supplies for hundreds of millions of people downstream across much of Asia.

"This is the clearest picture yet of how fast Himalayan glaciers are melting over this time interval, and why," said lead author Joshua Maurer, a Ph.D. candidate at Lamont. While not specifically calculated, the glaciers may have lost as much as a quarter of their enormous mass over the last four decades, said Maurer.

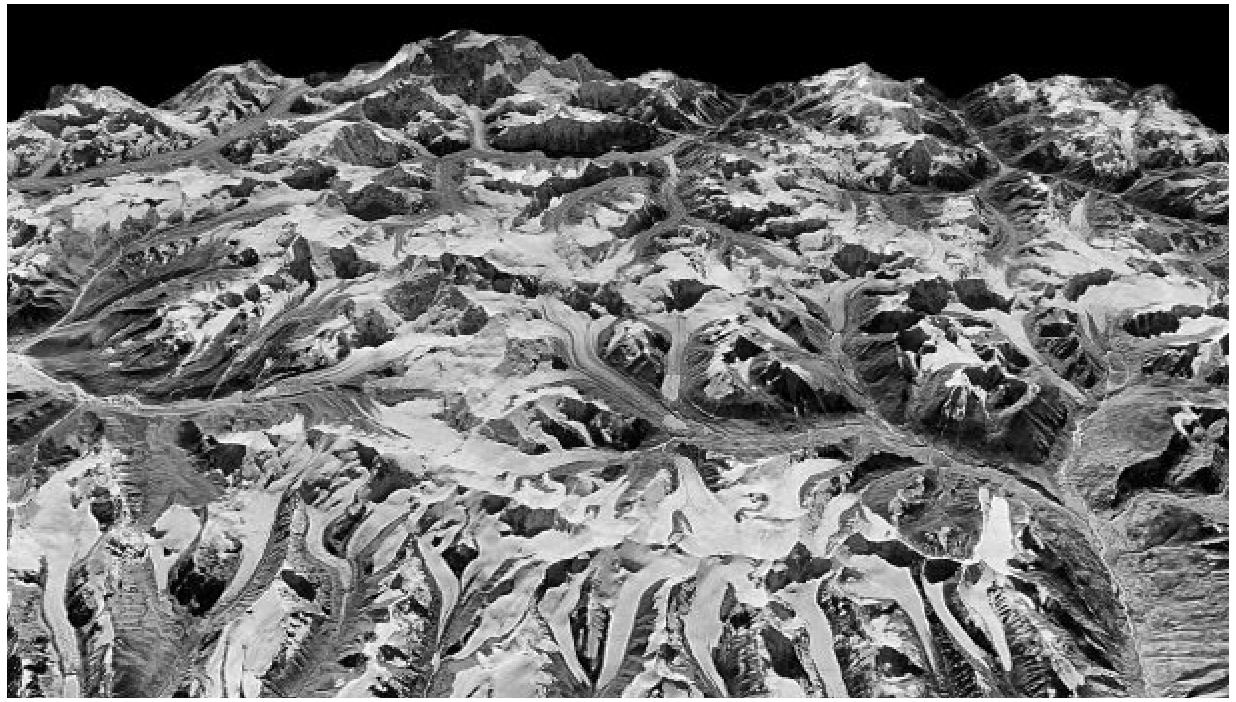
"This is the clearest picture yet of how fast Himalayan glaciers are melting over this time interval, and why."

Currently harboring some 600 billion tons of ice, the Himalayas are sometimes called Earth's "third pole." Many other recent studies have suggested that the glaciers are wasting, including one this year projecting that up to two-thirds of the current ice cover could be gone by 2100. But up to now, observations have been somewhat fragmented, zeroing in on shorter time periods, or only individual glaciers or certain regions. These studies have produced sometimes contradictory results, both regarding the degree of ice loss and the causes. This latest study synthesizes data from across the region, stretching from early satellite observations to the present. The synthesis indicates that the melting is consistent in time and space, and that rising temperatures are to blame. Temperatures vary from place to place, but from 2000 to 2016 they have averaged 1 °C (1.8 °F) higher than those from 1975 to 2000.

Maurer and his colleagues analyzed repeat satellite images of some 650 glaciers spanning 2,000 kilometers from west to east. Many of the 20th-century observations came from recently declassified photographic images taken by U.S. spy satellites. The researchers created an automated system to turn these into three-dimensional models that could show the changing elevations of glaciers over time. They then compared these images with post-2000 optical data from more sophisticated satellites, which more directly convey elevation changes.

They found that from 1975 to 2000, glaciers across the region lost an average of about 0.25 meters (10 inches) of ice each year in the face of slight warming. Following a more pronounced warming trend starting in the 1990s, in 2000 the loss accelerated to about half a meter (20 inches) annually. Recent yearly losses have averaged about 8 billion tons of water, or the equivalent 3.2 million Olympic-size swimming pools, says Maurer. Most individual glaciers are not wasting uniformly over their entire surfaces, he noted; melting has been concentrated mainly at lower elevations, where some ice surfaces are losing as much as 5 meters (16 feet) a year.

Some researchers have argued that factors other than temperature are affecting the glaciers. These include changes in precipitation, which seems to be declining in some areas (which would tend to reduce the ice), but increasing in others (which would tend to build it). Another factor: Asian nations are burning ever-greater loads of fossil fuels and biomass, sending soot into the sky. Much of it eventually lands on snowy glacier surfaces, where it absorbs solar energy and hastens melting. Maurer agrees that both soot and precipitation are factors, but because of the region's huge size and extreme topography, the effects are highly variable from place to place. Overall, he says, temperature is the overarching force. To confirm this, he and his colleagues



Right: *oblique view of the Himalayas on the border of Sikkim, India, and eastern Nepal, captured on 20 December 1975 by a KH-9 Hexagon reconnaissance satellite. Photo by National Reconnaissance Office/U.S. Geological Survey.* ***Opposite page:*** *Khumbu glacier in the Himalayas. Photo by Joshua Maurer.*

compiled temperature data during the study period from ground stations and then calculated the amount of melting that observed temperature increases would be expected to produce. They then compared those figures with what actually happened. They matched. "It looks just like what we would expect if warming were the dominant driver of ice loss," he said.

Ice loss in the Himalayas resembles the far more closely studied European Alps, where temperatures started going up somewhat earlier, in the 1980s. Glaciers there started wasting shortly after that increase, and rapid loss of ice has continued since then. The Himalayas are generally not melting as fast as the Alps, but the overall progression is similar, say the researchers. The study does not include the huge adjoining ranges of high-mountain Asia such as the Pamir, Hindu Kush, or Tian Shan, but other studies suggest similar melting is underway there as well.

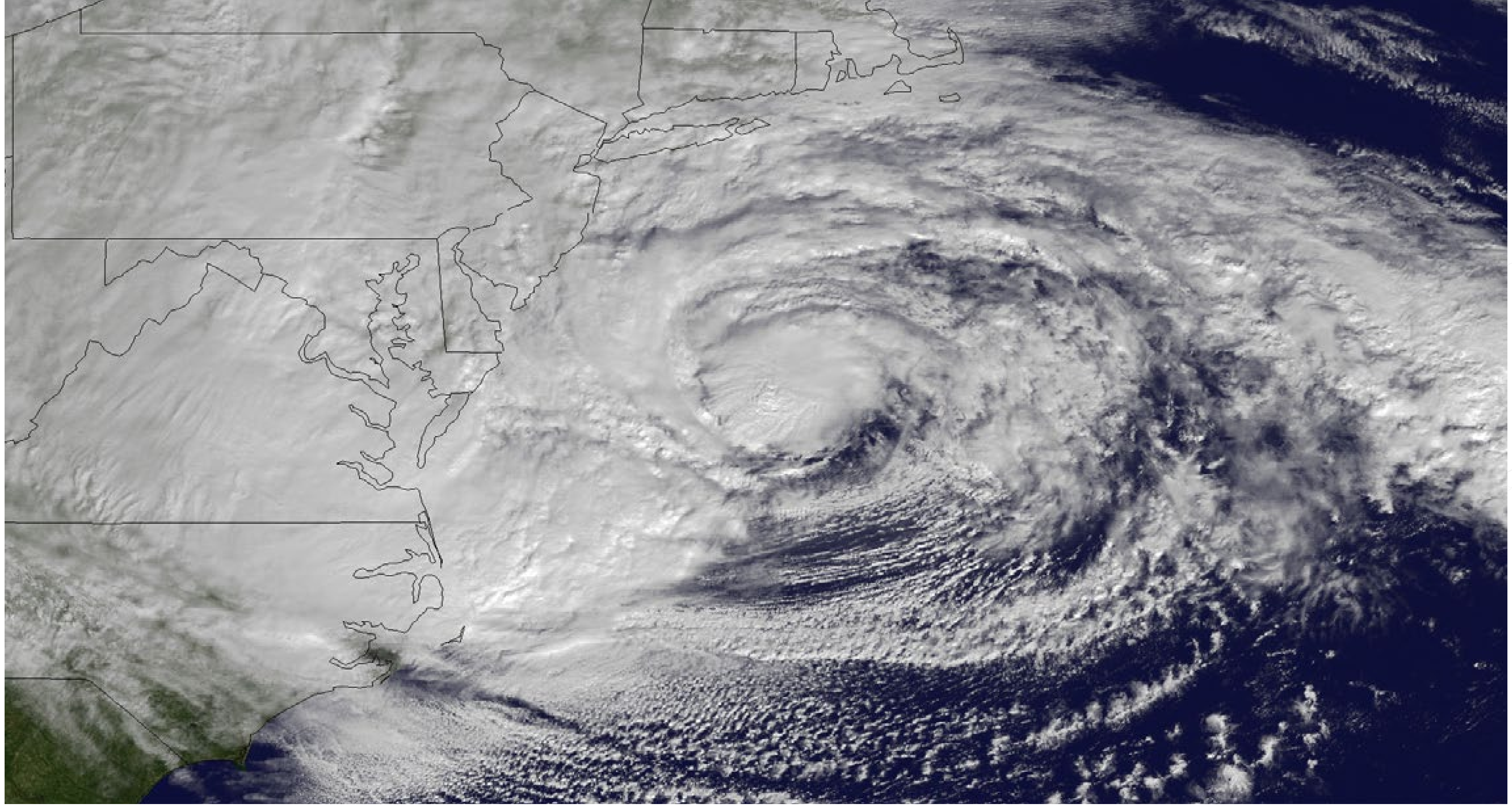
Some 800 million people depend in part on seasonal runoff from Himalayan glaciers for irrigation, hydropower, and drinking water. The accelerated melting appears so far to be swelling runoff during warm seasons, but scientists project that this will taper off within decades as the glaciers lose mass. This, they say, will eventually lead to water shortages. A separate study published this May estimates that yearly runoff is now about 1.6 times greater than if the glaciers were replenished at the same rate they were melting. As a result, in many high-mountain drainages, meltwater lakes are building rapidly behind natural dams of rocky debris; these are threatening downstream communities with potentially destructive and deadly outburst floods. Even on Mount Everest, long-lost corpses of climbers who failed to return are emerging from melting ice and snow along trails.

The study shows that "even glaciers in the highest mountains of the world are responding to global air temperature increases driven by the combustion of fossil fuels," said Joseph Shea, a glacial geographer at the University of Northern British Columbia who was not involved in the study. "In the long term, this will lead to changes in the timing and magnitude of streamflow in a heavily populated region."

"It shows how endangered [the Himalayas] are if climate change continues at the same pace in the coming decades," said Etienne Berthier, a glaciologist at France's Laboratory for Studies in Geophysics and Spatial Oceanography, who also was not involved in the study.

The study was coauthored by Lamont scientists Joerg Schaefer and Alison Corley, and Summer Rupper of the University of Utah.

"It shows how endangered [the Himalayas] are if climate change continues at the same pace in the coming decades"



Climate Change is Destroying a Barrier That Protects the U.S. East Coast from Hurricanes

By Nicole deRoberts

Above: *Hurricane Sandy, with winds of 90 mph and heavy rains, created dangerous flooding conditions along the eastern U.S. from North Carolina to New England. This NOAA GOES-13 satellite image taken on 29 October 2012 shows the storm as it was centered over Maryland and Virginia. The storm then headed in a northwestern direction toward the Delaware and southern New Jersey coasts.*

New Lamont-led research published this year suggests that climate change could soon eliminate an atmospheric barrier that protects much of the U.S. east coast from powerful hurricanes.

Severe hurricanes can cause up to hundreds of billions of dollars in damages. The destruction left in the wake of Atlantic hurricanes has been increasing in recent decades, according to scientific studies. However, it has been difficult to predict whether and how hurricanes will continue to increase in intensity and impact.

There are two main factors that contribute to hurricane development and intensity: sea-surface temperature and vertical wind shear. Vertical wind shear is the difference in wind speed or direction between the upper and lower troposphere. Warmer sea-surface temperatures and low wind shear (meaning the wind speeds and directions are similar throughout a column of air in the troposphere) both raise the potential intensity of a hurricane. Scientists knew that ocean surface temperatures are heating up, but until now it has not been clear how climate change would impact wind shear.

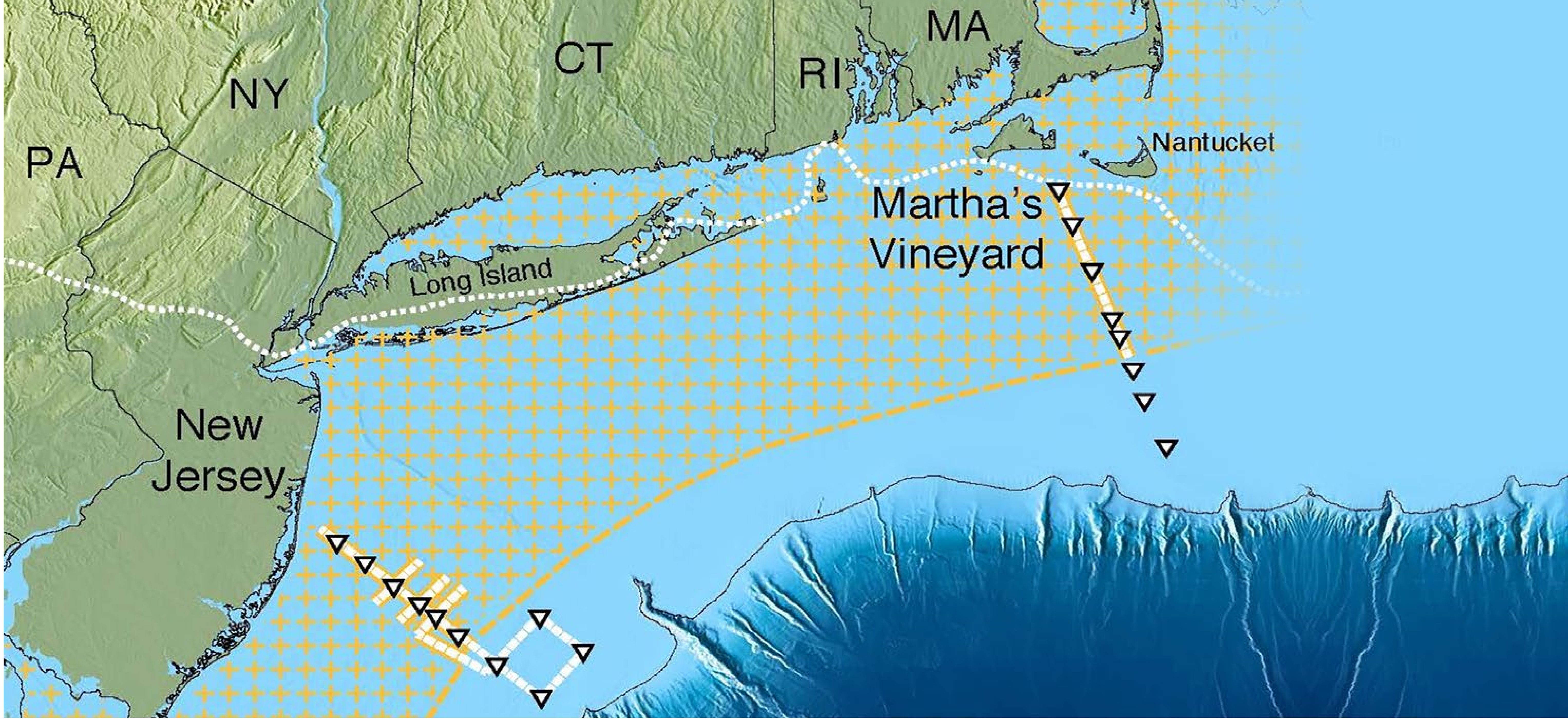
The study, authored by Lamont scientists and colleagues at the National Oceanic and Atmospheric Administration, found that climate change could alter wind shear in a way that could deliver more powerful hurricanes to the East Coast.

The new paper builds off a talk given by NOAA's James Kossin at an Extreme Weather and Climate Initiative meeting at Columbia University in 2017. Kossin spoke about how, as hurricanes move northwestward out of the tropical Atlantic, a strong vertical wind shear along the east coast prevents the storm from gaining strength, thus providing a protective barrier to the landfall of strong hurricanes. Lamont Research Professor Mingfang Ting had the idea to build on Kossin's findings with the application of her own modeling to explore how a changing climate might affect this wind shear pattern.

Ting and Kossin, along with Lamont researchers Suzana Camargo and Cuihua Li, used model simulations to examine the effects of climate change on hurricanes that reach the United States. The group found that these hurricanes will be affected in two different ways. As earlier studies have shown, rising sea-surface temperatures will lead to an increase in hurricane intensity. But this study was the first to find that rising anthropogenic greenhouse gases in the atmosphere will weaken the vertical wind shear along the east coast, which will, in turn, enable further intensification of hurricanes that make landfall in the region.

"Once the natural protection is eroded by greenhouse gas warming, we may experience unprecedented hurricane intensification along the east coast that can lead to stronger landfalling storms and higher storm surges in the future," Ting explains. "This is on top of the stronger tropical cyclone strength expected from the warmer sea-surface temperature that we are already aware of. Home owners and policy makers have to take this into account when planning for coastal development and protection."

Although climate change is typically a slow process, the models point to the possibility of these anthropogenic effects emerging quickly. One of the models with a large number of simulations indicated that these effects could start to be seen around the year 2040. A timeline like that gives us only about 20 years to try to change course by taking actions to reduce climate change and, at the very least, prepare for more extreme weather events.



Scientists Map Huge Undersea Fresh-Water Aquifer off U.S. Northeast

By Kevin Krajick

Above: *yellow crosses show the approximate extent of an aquifer beneath the U.S. Atlantic margin mapped by marine electromagnetic measurements. Solid yellow or white lines with triangles show survey tracks by the research vessel Marcus G. Langseth. A dotted white line near shore shows the edge of a glacial ice sheet that melted about 15,000 years ago. Farther out, in dark blue, the continental shelf drops off into the Atlantic abyssal plain. Adapted from a figure from Gustafson et al., 2019.*

In a survey of the sub-seafloor off the U.S. northeast coast, marine geophysicists at Columbia University's Lamont-Doherty Earth Observatory have made a surprising discovery: a gigantic aquifer of relatively fresh water trapped in porous sediments lying below the salty ocean. It appears to be the largest such formation yet found in the world. The aquifer stretches offshore from at least from Massachusetts to New Jersey, extending more or less continuously out about 50 miles to the edge of the continental shelf. If found on the surface, it would create a lake covering some 15,000 square miles. The study suggests that such aquifers probably lie off many other coasts worldwide, and could provide desperately needed water for arid areas that are now in danger of running out.

The researchers employed innovative measurements of electromagnetic waves to map the water, which remained invisible to other technologies. "We knew there was fresh water down there in isolated places, but we did not know the extent or geometry," said lead author Chloe Gustafson, a Ph.D. candidate in the Department of Earth and Environmental Sciences. "It could turn out to be an important resource in other parts of the world." The study appeared in June in the journal *Scientific Reports*.

> *"It could turn out to be an important resource in other parts of the world"*

The first hints of the aquifer came in the 1970s, when companies drilled off the coastline for oil, but sometimes instead hit fresh water. Drill holes are just pinpricks in the seafloor, and scientists debated whether the water deposits were just isolated pockets or something bigger. Starting about 20 years ago, study coauthor Kerry Key, now a Lamont geophysicist and associate professor in the Department of Earth and Environmental Sciences (DEES), helped oil companies develop techniques to use electromagnetic imaging of the sub-seafloor to look for oil. More recently, Key decided to see if some form of the technology could also be used to find fresh-water deposits. In 2015, he and Rob Evans of the Woods Hole Oceanographic Institution spent 10 days on the Lamont research vessel *Marcus G. Langseth* making measurements off southern New Jersey and the Massachusetts island of Martha's Vineyard, where scattered drill holes had hit fresh-water-rich sediments.

They dropped receivers to the seafloor to measure electromagnetic fields, and the degree to which natural electromagnetic waves are influenced by subsurface structure. An apparatus towed behind the ship also emitted artificial electromagnetic pulses and recorded the same type of reactions from the subseafloor. Both methods work in a simple way: salt water is a better conductor of electromagnetic waves than fresh water, so the freshwater stood out as a band of lower conductance. Analyses indicated that the deposits are not scattered; they are more or less continuous, starting at the shoreline and extending far out within the shallow continental shelf – in some cases, as far as 75 miles. For the most part, they begin at around 600 feet below the ocean floor, and bottom out at about 1,200 feet.

The consistency of the data from both study areas allowed the researchers to infer with a high degree of confidence that fresh-water-filled sediments continuously span not just New Jersey and much of Massachusetts, but the intervening coasts of Rhode Island, Connecticut, and New York. They estimate that the region holds at least 670 cubic miles of fresh water. If future research shows that the aquifer extends farther north and south, it would rival the great Ogallala Aquifer, which supplies vital groundwater to eight Great Plains states, from South Dakota to Texas.

The water probably got under the seabed in one of two different ways, say the researchers. Some 15,000 to 20,000 years ago, toward the end of the last glacial age, much of the world's water was locked up in mile-deep ice; in North America, it extended through what is now northern New Jersey, Long Island, and the New England coast. Sea levels were much lower, exposing much of what is now the underwater U.S. continental shelf. When the ice melted, sediments formed huge river deltas on top of the shelf, and fresh water was trapped there in scattered pockets. Later, sea levels rose. Up to now, the trapping of such "fossil" water has been the common explanation for any fresh water found under the ocean.

But the researchers say the new findings indicate that the aquifer is also being fed by modern subterranean runoff from the land. As water from rainfall and water bodies percolates through onshore sediments, it is likely pumped seaward by the rising and falling pressure of tides, said Key. He likened this to a person pressing up and down on a sponge to suck in water from the sponge's sides. Also, the aquifer is generally freshest near the shore, and saltier the farther out you go, suggesting that it mixes gradually with ocean water over time. Terrestrial fresh water usually contains less than 1 part per thousand salt, and this is about the value found undersea near land. By the time the aquifer reaches its outer edges, it rises to 15 parts per thousand. (Typical seawater is 35 parts per thousand.)

If water from the outer parts of the aquifer were to be withdrawn, it would have to be desalinated for most uses, but the cost would be much less than processing seawater, said Key. "We probably don't need to do that in this region, but if we can show there are large aquifers in other regions, that might potentially represent a resource" in places such as southern California, Australia, the Mideast, or Saharan Africa, he said. His group hopes to expand its surveys to other continental margin regions.

Opposite page: *deployment of an electromagnetic receiver by the research vessel Marcus G. Langseth. Photo by Kerry Key.*

Short-Term Ocean Temperature Shifts Are Affecting West Antarctic Ice, Study Shows

Above: *an orca, or killer whale, in McMurdo Sound, Antarctica, during an expedition to the Antarctic Dry Valleys in the austral summer of 2018-2019. Photo by Jennifer Lamp.*

Scientists have known for some time that ice shelves off West Antarctica are melting as deep, warm ocean waters eat at their undersides, but a study published in August 2019 shows that temperatures, and resultant melting, can vary far more than previously thought, within a time scale of a few years. The findings could have implications for estimates of future sea-level rise.

Oceanographers studying seawater temperatures in the Amundsen Sea – host to ice shelves off the West Antarctic Ice Sheet – found a cycle of warming and cooling in the ocean over the 16 years of observations. They showed for the first time that while mass loss from the ice sheet increased during a warm period, it steadied and in some cases decreased during cooler phases. The authors found evidence that the changes are linked to El Niño–Southern Oscillation, a cyclic warming of the tropical Pacific Ocean that takes place about every 3 to 7 years.

Lamont oceanographer and study coauthor Pierre Dutrieux said, "the study contributes an important foundation for predicting global sea-level rise. Our understanding of ice sheet-ocean interactions has progressed rapidly over the past decade. The seemingly immovable ice giants are actually very dynamic systems that respond quickly to a broad range of spatial and temporal changes in the ocean and the atmosphere."

Above: the South Korean research vessel Araon has been one of several used to document relatively rapid recent changes in ocean temperatures off West Antarctica. Photo by Pierre Dutrieux.

During eight Antarctic summers from 2000 to 2016, a team from the United Kingdom, the United States, and South Korea used research vessels to observe changes in ocean temperature, salinity, and currents near the Dotson Ice Shelf – an area of floating ice more than seven times the size of New York City. They found that temperature fluctuations in the relatively warm water in that area cause far greater changes in melting than occur along other parts of the Antarctic coastline where ocean temperatures are lower. It was the first time a complete multi-year cycle of ocean temperature changes and resulting changes in ice shelf melting have been documented in this region. Deep water in the Amundsen Sea ranges from about 0.5 to 1 °C (about 33 or 34 °F), while water in colder regions can go down to about –2 °C, or about 28 °F.

Adrian Jenkins, an oceanographer at the British Antarctic Survey and lead author of the study, said, "[We] saw melt rates of Dotson Ice Shelf climb dramatically and then fall back. In the future it will be critical to understand the duration and severity of the extremes in seawater temperature, whatever the cause, because we now see how quickly the glaciers respond to them."

The melt rate at the base of the Dotson Ice Shelf was high between 2006 and 2009 (a warm period), and much lower in 2000 and during 2012-2016 (both cool periods). In the recent cooler part of the cycle, outflow from the ice sheet slowed, and the sheet's mass actually increased. This result indicates that even on a time scale of a few years, the ice can respond if deep ocean temperatures drop below or rise above the average.

Coauthor Stan Jacobs, also from Lamont, said, "This work confirms the theory that the ice sheet is sensitive to deep ocean temperatures. Further observations and a deeper understanding of what drives changes in those temperatures are critical."

Although the study demonstrates that ice-shelf melting can vary widely in the short term, other recent research has confirmed that, overall, West Antarctica is losing ice.

Scientists from the Korea Polar Research Institute, Inha University (South Korea), and the Institute of Arctic and Alpine Research at the University of Colorado also coauthored the paper. The research was supported by the UK Natural Environment Research Council, the U.S. National Science Foundation, and the Korea Polar Research Institute.

"In the future it will be critical to understand the duration and severity of the extremes in seawater temperature"

A Milestone for Forecasting Earthquake Hazards

By Kim Martineau

Above: *in this false-color radar image, a section of California's San Andreas Fault follows the Crystal Springs Reservoir (center left, in black), with San Mateo (in pink) to the east, June 2009. Photo from a Gulfstream-III aircraft based at the NASA Dryden Flight Research Center (now the Armstrong Flight Research Center).*

Earthquakes pose a profound danger to people and cities worldwide, but with the right hazard-mitigation efforts, from stricter building requirements to careful zoning, the potential for catastrophic collapses of roads and buildings and loss of human lives can be limited.

All of these measures depend on science delivering high-quality seismic hazard models. And yet, current models depend on a list of uncertain assumptions, with predictions that are difficult to test in the real world due to the long intervals between big earthquakes.

Now, a team of researchers from Lamont, the University of Southern California, the University of California at Riverside, and the U.S. Geological Survey has come up with a physics-based model that marks a turning point in earthquake hazard assessment. Their results appeared in Science Advances in August 2018.

"Whether a big earthquake happens next week or 10 years from now, engineers need to build for the long run," says the study's lead author, Bruce Shaw, a geophysicist at Lamont. "We now have a physical model that tells us what the long-term hazards are."

Simulating nearly 500,000 years of California earthquakes on a supercomputer, researchers were able to match hazard estimates derived from the state's leading statistical model, which is based on a hundred years of instrumental data. The mutually validating results add support for California's current hazard projections, which help to set insurance rates and building design standards across the state. The results also suggest a growing role for physics-based models in forecasting earthquake hazard and evaluating competing models in California and other earthquake-prone regions.

The physics-based model produced its results after simulating nearly 500,000 years of California earthquakes. A randomly selected 3,000-year segment is visualized here. (Courtesy: Kevin Milner, University of Southern California)

The earthquake simulator used in the study, RSQSim, simplifies California's statistical model by eliminating many of the assumptions that go into estimating the likelihood of an earthquake of a certain size hitting a specific region. The researchers, in fact, were surprised when the simulator, programmed with relatively basic physics, was able to reproduce estimates from a model that has improved steadily for decades. "This shows our simulator is ready for prime time," says Shaw.

Seismologists can now use RSQSim to test the statistical model's region-specific predictions. Accurate hazard estimates are especially important to government regulators in high-risk cities such as Los Angeles and San Francisco, who write and revise building codes based on the latest science. In a state with a severe housing shortage, regulators are under pressure to make buildings strong enough to withstand heavy shaking while keeping construction costs down. A second tool to confirm hazard estimates gives the numbers added credibility.

"If you can get similar results with different techniques, that builds confidence you're doing something right," says study coauthor Tom Jordan, a geophysicist at USC.

A hallmark of the simulator is its use of rate- and state-dependent friction to approximate how real-world faults break and transfer stress to other faults, sometimes setting off even bigger quakes. Developed at UC Riverside more than a decade ago, and refined further in the current study, RSQSim is the first physics-based model to replicate California's most recent rupture forecast, UCERF3. When results from both models were fed into California's statistical ground-shaking model, they came up with similar hazard profiles.

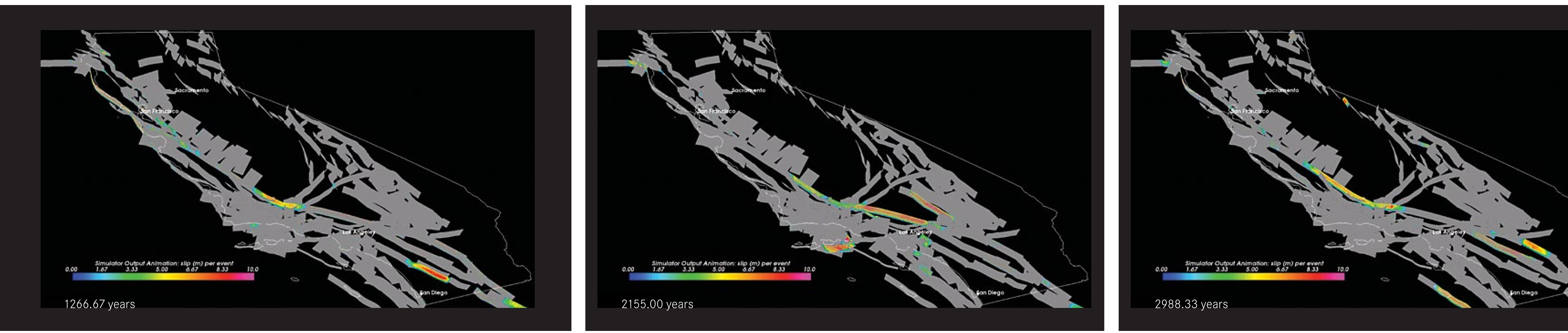
John Vidale, former USC seismologist who at the time this study was published was director of the Southern California Earthquake Center, which helped fund the study, says the new model has created a realistic 500,000-year history of earthquakes along California's faults for researchers to explore. Vidale predicted the model would improve as computing power grows and more physics are added to the software. "Details such as earthquakes in unexpected places, the evolution of earthquake faults over geological time, and the viscous flow deep under the tectonic plates are not yet built in," he said.

The researchers plan to use the model to learn more about aftershocks, and how they unfold on California's faults, and to study other fault systems globally. They are also working on incorporating the simulator into a physics-based ground-motion model, called CyberShake, to see if it can reproduce shaking estimates from the current statistical model.

"As we improve the physics in our simulations and computers become more powerful, we will better understand where and when the really destructive earthquakes are likely to strike," says study coauthor Kevin Milner, a researcher at USC.

The study was funded by the National Science Foundation, Southern California Earthquake Center, and W. M. Keck Foundation. The other authors are Ned Field, U.S. Geological Survey; Jacquelyn Gilchrist, USC; and Keith Richards-Dinger and James Dieterich, UC Riverside.

Below from left to right: *visualization of a randomly selected 3,000-year interval of earthquakes in California from a physics-based simulation. Sequence by Kevin Milner, University of Southern California.*



Study Finds Sewage Bacteria Lurking in Hudson River Sediments

By Kevin Krajick

Above: *The Hudson River, New York City, and the George Washington Bridge as seen from the New Jersey Palisades. Photo by Kevin Krajick.*

A study published in December 2018 by Lamont biologists shows that fecal bacteria from sewage are living in far greater quantities in near-shore sediments of the Hudson River than in the water itself. The river's pollution levels are generally monitored with samples of clear water, not sediments, so the findings suggest that people stirring up the bottom while wading, swimming, or kayaking may face previously unrecognized health risks. Germs may persist for long periods or even reproduce in the sediments, say the authors. The study appeared in the journal *Science of the Total Environment*.

The researchers sampled 11 sites along the river banks in suburban Rockland and Westchester counties, and in eastern Queens. At some sites, they found as much as 10 times more fecal bacteria in sediments as in overlying water. Water near the most polluted sediments tended to have elevated levels of bacteria and vice versa, suggesting an interchange between the two. Sites with sandier bottoms tended to have fewer germs, while levels were higher in fine, mucky organic-rich deposits.

"These organisms originate in the human gut, where it's organic-rich and dark," said Andrew Juhl, a Lamont biologist and coauthor of the study. "The water in the river is neither organic-rich nor dark, but the sediments on the bottom typically are, and that makes them a better environment for potentially harmful microorganisms." While the findings make common sense, it is one the first studies to test the idea in a river estuary, and is the first one in this region.

"This shows we have to think beyond just the [pollution] indicators we see in water," said lead author Gregory O'Mullan, a microbiologist at Queens College and an adjunct at Lamont.

***This page (above):** the research vessel Marcus G. Langseth passing under the Verrazzano-Narrows Bridge in New York Harbor. Photo by Bob Vergara, A.P.S.* ***Right:** Lamont researchers collecting sediment near New York Harbor for the study of bacterial content. Photo by Kevin Krajick.*

A 2017 review of previous research coauthored by O'Mullan and Juhl says that, globally, human contact with polluted coastal waters causes more than 50 million severe respiratory infections and 120 million cases of gastrointestinal diseases, along with eye, ear, and skin infections. In the United States, water at thousands of beaches is tested weekly during warm weather, and each year, high bacteria readings result in tens of thousands of beach-closure days. Some scientists have sampled beach sands and found high bacteria levels there as well, but such studies are still infrequent. "You have to think about this. I used to take my young daughter to the beach, and she didn't get that much water in her mouth–but she was always covered with sand," said O'Mullan.

O'Mullan and Juhl looked at two standard indicators of sewage contamination: the bacteria *Enterococcus* and *Escherichia coli*, which occur abundantly in the human gut. The bacteria can cause infections, but rarely serious ones; they are used instead as a proxy signal that less abundant but much more potent pathogens also excreted by humans are probably also present.

In the lower Hudson, most such germs probably get into the river from human sewage released through outfalls, leaks, and overflows. Wildlife may play a smaller role, and in other systems farm runoff can also be an important source of bacteria. Many of these bacteria are not floating freely, but rather clinging to tiny particles of organic matter, said Juhl. In open, flowing water, pathogens are constantly washed downstream and diluted, and sunlight kills many within hours or days. However, depending on water flow, tides, and topography, many particles may settle down and pile up in the cozier, more stable environment of the bottom. Here, bacteria or viruses could potentially persist for weeks or even months. Feeding off organic-rich muck, they may even reproduce, say Juhl and O'Mullan.

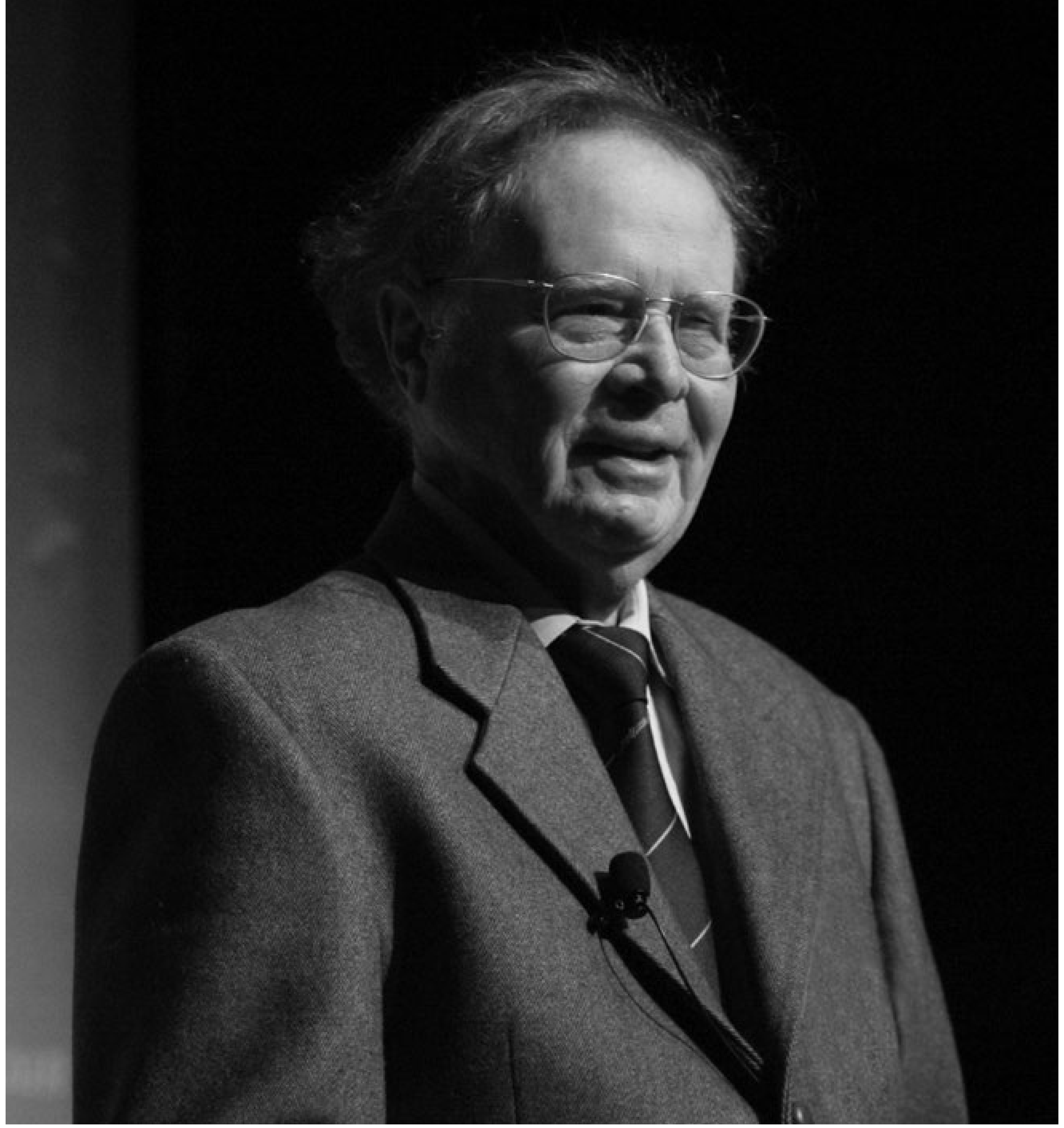
As part of the study, Juhl and an assistant waded into 8 to 10 inches of water in a few spots near Piermont, N.Y., in order to stir up near-shore sediments (They wore calf-high boots.) Then they took samples of the muddied water. As expected, lab analyses demonstrated that stirring up the sediments heightened bacterial levels in the water. "If bacteria are going from the water to the sediment, does it work the other way around?" asked Juhl. "I think it does." Piermont, with its fine, muddy bottom, showed some of the highest bacteria readings in both water and sediment, along with three sites around Queens' Flushing Bay.

"Our data would suggest that there's a health risk with people splashing around in the water and resuspending stuff from the bottom. But we'd have to say that at this point it's hard to quantify," said Juhl.

O'Mullan pointed out that some municipalities along the river stop chlorinating their sewage during cold weather, on the theory that no one is swimming nearby, and that pathogens will be long gone by the time the recreational season returns. "Our results suggest that might not be such a good idea," he said. "Putting sewage into the sediments is like putting it into the refrigerator–it lasts a lot longer."

The study was supported by the Hudson River Foundation, Riverkeeper, and the U.S National Science Foundation.

human contact with polluted coastal waters causes more than 50 million severe respiratory infections and 120 million cases of gastrointestinal diseases, along with eye, ear, and skin infections



Lamont's Wally Broecker

(1931 - 2019)

By Peter de Menocal

Above and right: *photos courtesy of Lamont-Doherty Earth Observatory.*

Pairing monumental intellect with unbridled curiosity, Wallace Smith Broecker, known to everyone as Wally, defined much of our present understanding of the climate system and its inner workings. His path-breaking career spanned nearly seven decades, during which he made the first coordinated measurements that defined the grand structure and flows of the oceans. He was instrumental in discovering the ocean's role in global climate change and carbon cycling, and he used records of past climate to inform mechanisms of climate change and their implications for our collective future. A wellspring of transformative ideas, Broecker inspired generations of researchers to think expansively about the Earth.

Broecker was driven by nature's puzzles. He regularly produced neat, elegant solutions to complex Earth science problems, discoveries that would then reshape entire disciplines. He was a prolific scholar, authoring over 500 publications and 17 books. He possessed a warm, direct midwestern sensibility, a wry smile, and a penetrating gaze, and he was known to be an epic prankster. He was famously supportive of younger, early-career scientists who shared his appetite for hard problems. He was equally famous for his impatience and explosive temper with sloppy science.

Raised in a conservative Christian family in Oak Park, Illinois, Broecker initially attended Wheaton College in Oak Park, where he pledged to eschew smoking, drinking, dancing, and attending movies. A series of events led him to pursue his own path, and in 1952 he joined Columbia University as an undergraduate transfer student, working at the Lamont Geological Observatory. For the remainder of his prolific 67-year career, he stayed at Lamont, an institution he would later call his "Garden of Eden."

Broecker married Grace Carder when he was an undergraduate, and together they had six children. Grace died in 2007, and Broecker subsequently married Elizabeth Clark, a research assistant who shared his love for travel and adventure.

Completing his undergraduate and graduate studies at Columbia, Broecker set to work in Lamont's radiocarbon counting lab, formulating new protocols that improved dating accuracy and developing a method for dating dissolved inorganic carbon in seawater. In the 1950s, physical oceanographers were developing a theory of global ocean circulation whereby surface waters cool and sink at high latitudes, forming cold deep waters that ventilated the abyss, but the time scale of this process was unknown.

Using large-volume water samples collected by Lamont's research vessel *Vema*, Broecker demonstrated that Atlantic deep waters were only one to two centuries old, providing critically important constraints on deep-water formation rates. This discovery linked theory and observations and showed that the oceans were far more dynamic in transporting heat and energy than previously thought. This finding would later prove to be critically important for understanding past and future climate change.

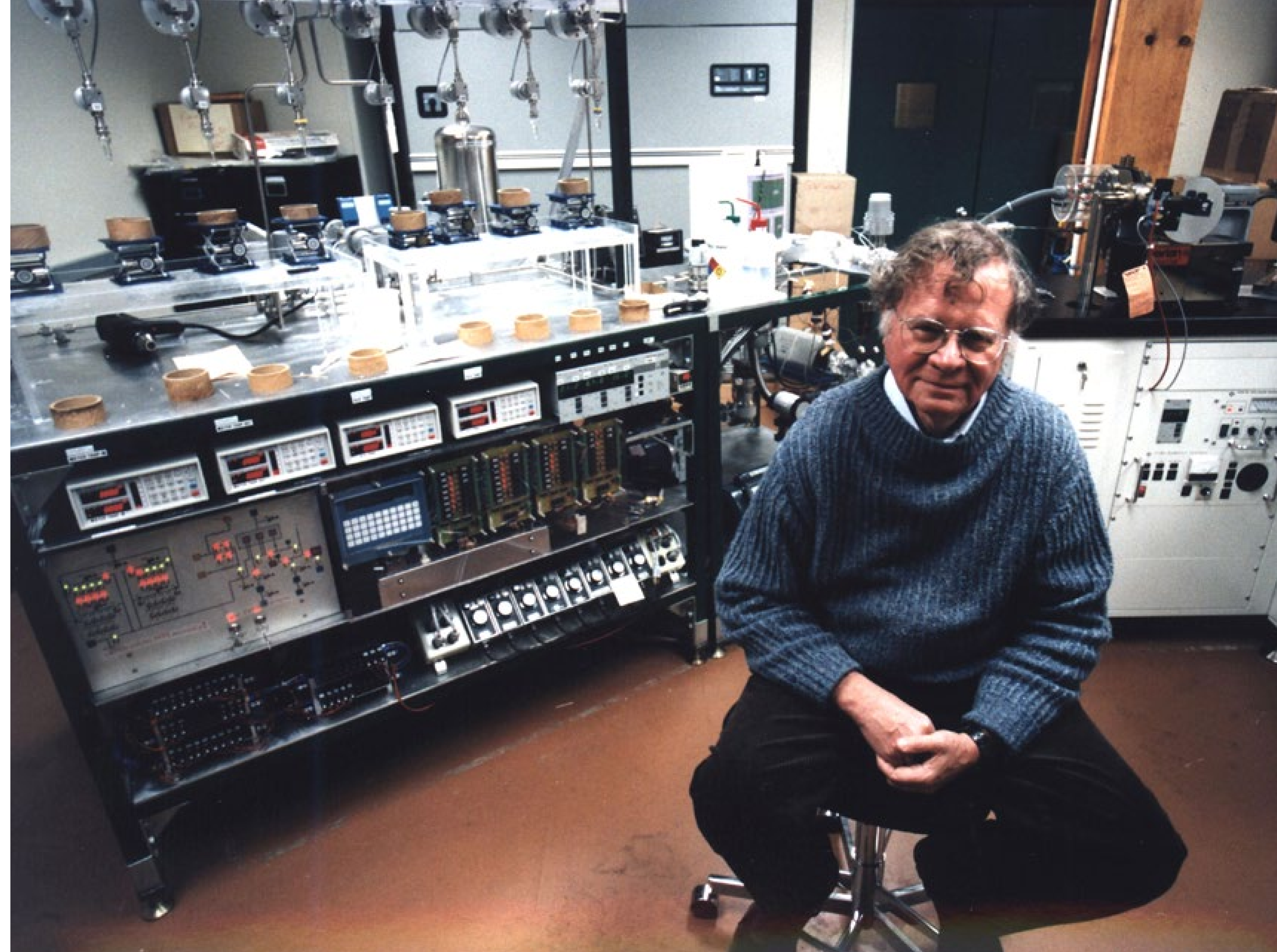
These initial profiles inspired the first global ocean sampling program, the Geochemical Ocean Sections Study (GEOSECS), in the 1970s. Dozens of oceanographic expeditions measured transects of vertical temperature, salinity, nutrients, carbon, and stable and radioisotope profiles. These transects provided the first global-scale, three-dimensional picture of ocean circulation and chemistry, and for decades they would be used to answer fundamental questions about rates of ocean circulation, productivity, gas exchange, and carbon cycling. Generations of marine geochemists were trained using Broecker's GEOSECS-inspired book, *Tracers in the Sea*, a masterful tome complete with "Superproblems" designed to stump even the cleverest students. Since the ocean contains roughly 60 times more carbon than the atmosphere and is responsible for nearly half of the global poleward heat transport, Broecker presciently noted that modest ocean circulation changes can have potentially huge impacts on global climate.

The prospect of abrupt climate change was one of Broecker's most transformative ideas. Past oscillations between warmer interglacial and colder glacial climates had been documented by earlier generations of geologists, but the rates of change were largely unknown. Ocean sediments accumulate slowly but continuously on the seafloor, and they can be used as faithful recorders of past climate change. In 1970, Broecker and graduate student Jan van Donk published a sediment-core study that revealed the tempo for glacial-interglacial cycles for the first time: Large continental ice caps took many tens of thousands of years to grow, but each ice age ended rapidly, with sufficient warming that the same vast ice sheets melted away within a few thousand years. This discovery launched decades of research into the cause of this temporally asymmetric behavior. Current studies show that the global warming associated with these glacial terminations was indeed large (>10°C warming near the poles), fast (within a few decades at some locations), and intimately coupled to changes in surface and deep ocean circulation. This discovery prompted Broecker to liken the climate system to an "angry beast we are poking with sticks" as we continue to pour greenhouse gases into the atmosphere.

In 1975, Broecker published a paper in *Science* entitled "Climate Change: Are We on the Brink of a Pronounced Global Warming?" Although this paper is thought to be the first scientific use of this phrase, Wally did not want to be remembered for coining the term. He later even offered a reward to anyone who could find an earlier usage. The paper was remarkably well-timed, however, as global temperatures have consistently risen above baseline values since 1976.

Broecker's leadership would be recognized throughout his career. He received the Vetlesen Prize in 1987 (the Earth science equivalent to a Nobel prize), the U.S. National Medal of Science in 1996, and the Crafoord Prize in 2006, as well as honorary doctorates from Harvard, Oxford, Cambridge, and other universities. Over the years, he would receive millions in prize awards, most of which he used for research. He led a simple life: jeans and woolen sweaters, an older dented car, and a small, spartan apartment near Columbia.

__Below and right:__ George Denton, Richard Alley, Philip Conkling, Gary Comer, and Wally Broecker in Greenland in 2005. http://www.comerfamilyfoundation.org/articles/gary-listened-to-the-people-who-knew-what-should-be-done



In April 2002, billionaire Gary Comer contacted Broecker to help him understand why he was able to sail his yacht *Turmoil* through Canada's Northwest Passage when such passage had previously been blocked by ice. They would eventually develop a close friendship and a common interest in climate research. After enjoying a campfire picnic with scientists and students, a Lamont tradition, Comer turned to Broecker, and said, "How can I help?" Comer would eventually invest over $25 million to accelerate abrupt climate-change research in the U.S. and also build a new and much-needed geochemistry laboratory at Lamont. These investments advanced scores of early-career scientists during a period of declining federal climate research support.

Broecker's lasting scientific legacy may be that he changed the way we think about the climate system. His work invited deep, cross-disciplinary interrogation of nature's most complex inner workings. Understanding the stakes very early in his career, he held himself and the Earth science community to a very high standard. His lifelong approach to science challenges us in the research community to expand our efforts to understand how our planet is changing and to help the world understand the implications of these changes for humanity.

A version of this article appeared previously in *Nature*. Lamont hosted a symposium on Wally Broecker's life and scientific legacy on 24-26 October 2019.

Our Donors

We are grateful to the many friends and alumni who sustain our research and educational endeavors through their financial contributions. Annual support us critical to the advancement of our mission, the stability and ongoing operations of the Observatory, and the maintenance and stewardship of our campus.

These gifts were made during our fiscal year between July 1, 2018, and June 30, 2019. With appreciation, we acknowledge the generosity of the following.

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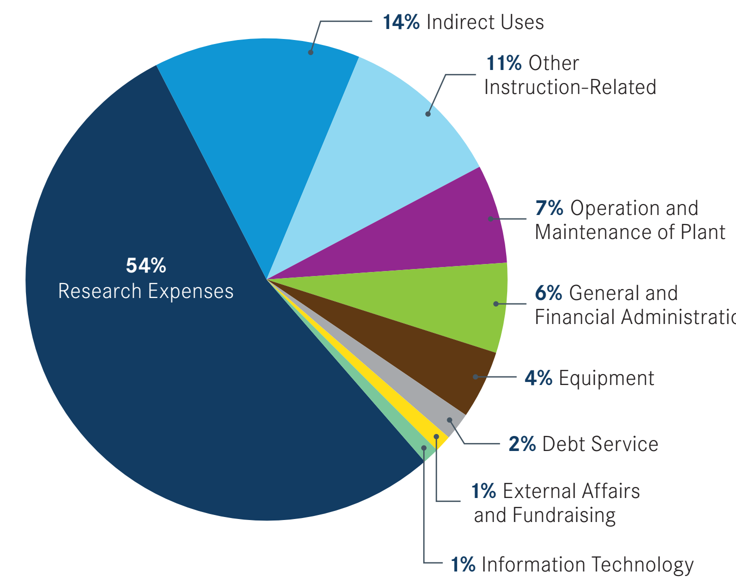
We have made every effort to ensure this listing of gift contributions is complete, and we apologize for any errors or omissions. To report corrections, please email staceyv@LDEO.columbia.edu.

Statement of Activities *(in 1,000s)*

Sources of revenue	FY'18	**FY'19**
National Science Foundation	39,998	40,101
National Aeronautics and Space Administration	4,561	4,425
National Oceanic and Atmospheric Administration	1,769	1,243
National Institute of Environmental Health and Safety	1,618	1,546
Department of Energy	1,618	676
Office of Naval Research	585	167
U.S. Geological Survey	380	364
Environmental Protection Agency	137	219
New York State	125	86
Miscellaneous Federal Funds	665	521
Total Government Grants - Direct & Indirect	**51,456**	**49,348**
Private Grants	6,089	4,043
Endowment Income	7,455	7,634
Gifts	4,037	3,088
Miscellaneous	763	501
Indirect Sources	8,535	12,161
Total Non-Government Sources	**26,879**	**27,427**
Total Sources	**78,335**	**76,775**

Uses of Revenue	FY'18	**FY'19**
Research Expenses	42,426	40,699
Operation and Maintenance of Plant	4,738	5,012
General and Financial Administration	4,318	4,561
Other Instruction-Related	9,411	10,469
Equipment	2,560	3,466
Debt Service	1,405	1,406
External Affairs and Fundraising	906	864
Information Technology	849	838
Indirect Transfers	9,672	8,304
Total Uses of Revenue	**76,285**	**75,619**
Net Operating Gain/(Loss)	**2,050**	**1,156**
Capital Expenses	(619)	(1,032)
Subtotal Non-Operating Expenses	**(619)**	**(1,032)**
Beginning Fund Balance	**11,924**	**13,355**
Ending Fund Balance*	**13,355**	**13,479**

Breakdown of Revenue Uses

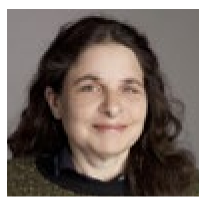


Above: *"The Blue Marble," NASA Goddard Space Flight Center. For additional information see the credit for the report cover.*

Awards and Honors

Lamont scientists are leaders in their fields and regularly garner top honors for their work. During 2019, Lamont celebrated a distinguished list of honorees, reflecting a range of early, mid-career, and senior scientists, as well as the full scientific breadth of the observatory's research talent. Lamont is home to 11 members of the National Academy of Sciences, a National Medal of Science recipient, two MacArthur "genius grant" winners, and two of the first three female winners of the Wollaston Medal of the Geological Society of London. This year, Robin Bell assumed the presidency of the American Geophysical Union, the largest Earth and space science society in the world, with more than 60,000 members in 139 countries.

Jacqueline Austermann, Assistant Professor of Earth and Environmental Sciences, will receive the 2019 Jason Morgan Early Career Award from the American Geophysical Union's Tectonophysics Section. The award honors one early career scientist per year who has made "significant early career contributions to tectonophysics through a combination of research, education, and outreach activities." Austermann studies sea-level changes over timescales ranging from past glacial cycles to millions of years in order to infer ice mass changes and ice sheet stability.



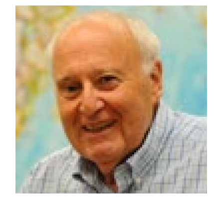
Rosanne D'Arrigo, Lamont Research Professor, was named a 2019 Fellow of the American Geophysical Union (AGU). D'Arrigo is a tree-ring scientist who studies past climate and the paleoenvironment. Fellows are recognized "for their scientific eminence in the Earth and space sciences." Just one-tenth of one percent of the members of AGU receive this honor each year.

Sonya Dyhrman, Professor of Earth and Environmental Sciences, has been elected a 2019 Fellow by the American Academy of Microbiology. A leadership group in the Academy, Fellows are elected "annually through a highly selective, peer-review process, based on their records of scientific achievement and original contributions that have advanced microbiology." Dyhrman studies how marine microbes such as phytoplankton interact with their geochemical environment, and she uses molecular-level tools to study the intersection of microbial physiology and biogeochemistry.

Göran Ekström, Professor of Earth and Environmental Sciences, was elected to the National Academy of Sciences, one of the highest honors accorded to scientists in the United States. Ekström works in global earthquake seismology, including the large-scale tectonic deformation of the crust and mantle over geologic time. He leads the Global Centroid Moment Tensor Project at Lamont, which rapidly integrates seismic data from every large earthquake to determine its source characteristics. That work has led Ekström to identify several unusual types of seismic sources, including volcanic earthquakes, glacial earthquakes, and large landslides

Vicki Ferrini, a Research Scientist at Lamont, received a Special Achievement in GIS Award from Esri, the leading software company that develops software for geographic information systems (GIS). Her research focuses on using mapping techniques to understand the processes that shape the seafloor. The award recognizes Vicki's work leading two projects that will create and publicly share a global map of seafloor bathymetry: the Seabed 2030 project and the Global Multi-Resolution Topography project.

Sarah Giles and **Aaron Stubblefield**, both graduate students in Lamont's Seismology, Geology and Tectonophysics Division, were awarded 2019 Graduate Research Fellowships by the National Science Foundation. The program "recognizes and supports outstanding graduate students who are pursuing full-time research-based master's and doctoral degrees in science, technology, engineering, and mathematics (STEM) or in STEM education." Graduate students Lloyd Anderson, Dan Babin, and Nicholas O'Mara received Honorable Mention.

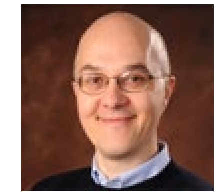


Arnold Gordon, Professor of Earth and Environmental Sciences, will receive the 2020 Henry Stommel Research Medal from the American Meteorological Society, "the highest award the Society can bestow upon an oceanographer." The medal is given "in recognition of outstanding contributions to the advancement of the understanding of the dynamics and physics of the ocean." Gordon was cited for "pioneering observational studies that have fundamentally advanced our understanding of Southern Ocean and inter-basin circulation." He has researched and taught at Columbia for more than five decades.

Michael Kaplan, Lamont Associate Research Professor, was elected a Fellow of the Geological Society of America (GSA). Kaplan studies how glaciers, climate, and landscapes have changed in the past in southern South America, New Zealand, Antarctica, and eastern North America. The Geological Society of America has a membership of more than 20,000 scientists across 100 countries. Fellowships, an honor bestowed to less than 3 percent of GSA members, recognize a "sustained record of distinguished contributions to the geosciences and the Geological Society of America."

Franziska Landes, a recent Ph.D. recipient in Earth and Environmental Sciences, will receive the American Geophysical Union's Science for Solutions Award, given annually to a student or postdoctoral scientist in recognition of "significant contributions in the application and use of the Earth and space sciences to solve societal problems." Landes is interested in environmental geochemistry and public health, especially the potential for community and public participation in science to reduce exposure to environmental contaminants while increasing environmental literacy.

Rachel Marzen, a graduate student in Earth and Environmental Sciences, received the 2018 GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins) Student Prize for her presentation at the American Geophysical Union Fall Meeting in December 2018. Rachel won for her talk "Refraction seismic constraints on less extensive CAMP magmatism localized by prior extension in the southeastern United States."



Lorenzo Polvani, Professor of Applied Physics and Applied Mathematics and of Earth and Environmental Sciences, was named a 2019 Fellow of the American Geophysical Union. His research encompasses many aspects of atmospheric and climate dynamics, including the physical response of the climate system to increasing concentrations of carbon dioxide, the chemistry and dynamics of the stratosphere, Arctic and Antarctic climate change, and past and future climate impacts of the Montreal Protocol. Fellows are recognized "for their scientific eminence in the Earth and space sciences." Just one-tenth of one percent of the members of AGU receive this honor each year.

Maureen Raymo, Bruce C. Heezen Lamont Research Professor, will receive the 2019 Maurice Ewing Medal, jointly awarded by the American Geophysical Union and the U.S. Navy in recognition of "significant original contributions to the ocean sciences." Named for Lamont's founding director, the medal has been given over the past 40 years to eight other Lamont scientists. Raymo, Director of the Lamont Core Repository, studies the planet's past climate to illuminate how climate varied before humans appeared. Her work has identified several foundational ideas in paleoceanography.

Adam Sobel, Professor of Applied Physics and Applied Mathematics and of Earth and Environmental Sciences, has been elected a Fellow of the American Meteorological Society (AMS). Sobel studies weather and climate, with a focus on extreme weather events. According to AMS, Fellows "shall have made outstanding contributions to the atmospheric or related oceanic or hydrologic sciences or their applications during a substantial period of years," and no more than "two-tenths of 1 percent of all AMS members" may be elected Fellow in a given year.

Mingfang Ting, Lamont Research Professor, has been elected a Fellow of the American Meteorological Society. Her research interests include the impact of global climate change on regional scales, particularly atmospheric stationary waves and precipitation extremes; the dynamics of naturally occurring and anthropogenically forced climate change; and the atmospheric dynamics that lead to droughts and floods.

Education and Outreach: Taking Our Science to Students and Communities

Lamont's Office of Education and Outreach focuses on furthering strategic growth in science, technology, engineering, and mathematics (STEM) education. The education and outreach team combines innovative science, pedagogical research, administrative and operational capabilities, and enthusiasm for learning. The office takes a cross-disciplinary approach to engage, train, and prepare the next generation of students to understand and practice the pursuit of new scientific knowledge. During 2019, the education and outreach team focused on informal education efforts to fulfill its mission by advancing educational research and pedagogy, creating and offering research experiences for students underrepresented in STEM fields, strengthening STEM instruction and professional development, and increasing public engagement through outreach.

Opposite page: *high school interns training to be future Hudson River educators, May 2019, at Lamont's Hudson River Field Station. Photo by Margie Turrin.*

Advancing Educational Research and Pedagogy

To help educators understand how best to cultivate student scholarship in STEM fields, we have initiated three projects funded by the National Science Foundation (NSF), and we will be adding to this portfolio this fall with a new community college project.

In our Make with Data project, funded by NSF's Innovative Technology Experiences for Students and Teachers program, we address the lack of diversity in STEM by engaging high-school-aged learners in an after-school setting, teaching them how to use open-source data to identify and solve problems for a community challenge. In the context of service-learning and constructionism frameworks, we began to study whether framing STEM practices as a way of contributing to and improving one's community might increase interest in these fields. During the first year of the project, we focused on the development of a network of students and educators, and we piloted and evaluated the activity design. Teacher and student participants came from diverse public, career, and technical high schools from each of New York City's boroughs. Stakeholders expressed specific challenges, including limited access to mental health support for K-12 students, neighborhood crime and its impact on school quality, and the unequal distribution of high-quality formal education experiences across the city. Participants involved in the project used city-wide open-source data (all New York City agencies are required by law to make their data open-source) to find correlations between their research questions and hypotheses to identify the variables and relationships at the heart of these challenges and to develop potential solutions for their neighborhoods.

With our Early Engagement in Research work, which is funded by NSF's Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science program, we implemented four summer programs modeled after Lamont's Secondary School Field Research Program (SSFRP). The first site centered on the Hudson River in Manhattan in partnership with the Hudson River Park Trust, The Intrepid, The Young Women's Leadership School, and City College. Six high school students and two undergraduate mentors studied the impacts of combined sewage outfalls on the native mussels of the Hudson and an eDNA project. The second site centered at Dominican College in partnership with Spring Valley High School, Ramapo High School, and the Spring Valley chapter of the National Association for the Advancement of Colored People. The program hosted 15 high school students with six undergraduate mentors and ran eight different team projects, studying a range of topics including microplastics in the local stream, bacteria in local ponds and streams, native ferns in the watershed, and a water-quality and composition comparison between Iona Marsh on the Hudson River and a local freshwater pond. The third site centered on the Mid-Hudson in partnership with Cary Institute, Marist College, Poughkeepsie High School, and Arlington High School. The program hosted seven high school students, four undergraduate mentors, and two teachers; all studied water quality in a local Hudson River tributary. The fourth site centered on the Bronx in partnership with The Young Women's Leadership School, The Bronx River Alliance, and the Bronx Botanical Gardens. The program hosted four high school students, one undergraduate, and one teacher, and the research focused on a comparison of water quality among the wetlands in the Bronx River in the Botanical Gardens and along other parts of the river. We also helped facilitate a fifth grass-roots group at Norrie Point, which ran a one-week program that linked into the Mid-Hudson group. Organizers hope to expand this last program in the future. It was clear to us at the end of this summer that all of these sites were well-connected and felt supported in their program efforts through a variety of co-hosted events, such as diversity panels, research focusing sessions, and a joint poster and presentation session.

This fall, we will begin a project in collaboration with six of the community colleges under the City University of New York (CUNY) system, which will aim to address the diversity challenges in the geosciences through the development of guided pathways in those fields. CUNY's community colleges are demographically diverse, comprising groups that are underrepresented in the geosciences and STEM fields. Few community colleges offer programs of study in the geosciences, and their students are not widely informed about the field as a whole. Our "Community College Compass" project will build a consortium to create and establish the guidelines needed to implement geoscience-specific guided pathways, which involves a student-centered and structured approach to community college education.

Above: *Rockland County Legislator Alden Wolfe (at right) leads a discussion about planning for a local waterfront site during the annual Rockland Planning Land Use with Students event, May 2019, at St. Thomas Aquinas College.* ***Below:*** *a team of high school students collects fish diversity data at the Hudson River Field Station on Piermont Pier for the annual Day in the Life of the Hudson River, October 2019. Photos by Margie Turrin.*

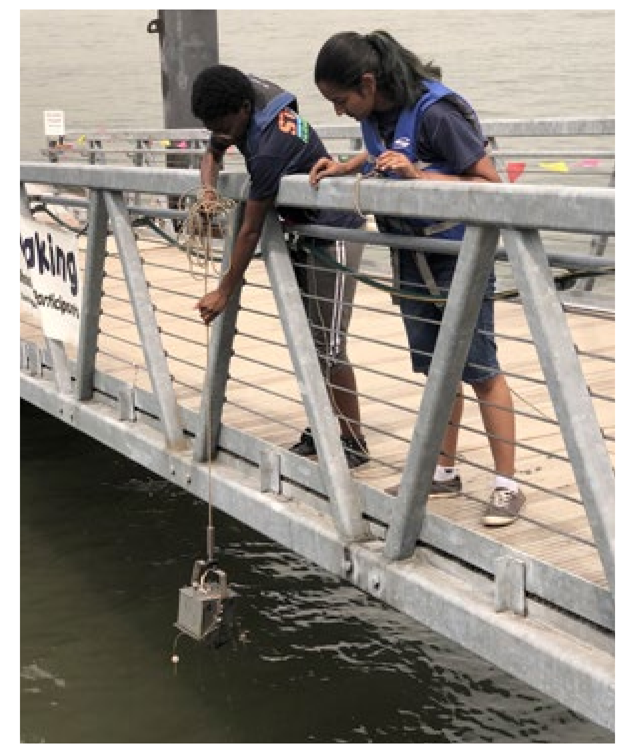
Research Experiences for Students Underrepresented in STEM

During this summer, we continued our highly successful research experience programs that offer students the opportunity to conduct research at Lamont under the mentorship of one or more of our scientific experts.

SSFRP participants worked in 15 research teams, studying topics from arsenic in wetland soils to natural carbon processing and sequestration, and Arctic sea-ice pathways. The focus of the project was for students to collect their own samples, make their own measurements, process their own data, and build conclusions. Approximately 35 Lamont scientists, many of them early-career scientists, mentored high school students individually or in pairs on Fridays over lunch.

Our summer intern program also continued this summer. A total of 32 undergraduate students from 18 colleges and universities spent 10 weeks working on research projects supervised by 34 mentors. 14 of the 32 students received support from NSF's Research Experiences for Undergraduates program. We continued to recruit underrepresented minorities in STEM through this program by leveraging strong partnerships with community colleges such as Housatonic Community College, Hudson County Community College, Kingsborough Community College, and Rockland Community College.
The summer intern program continues to offer important professional development opportunities for students, such as a workshop on reading scientific papers, career panels, workshops on proposal and reflective writing, and a research focusing session, which helped prepare students to develop their research questions into a final paper and presentation.

Lastly, it was another successful year for our Rockland Planning Land Use with Students effort. In total, we made class visits to 368 students in 16 classrooms across 10 high schools and worked closely with them on community planning projects through the use of sustainable planning concepts. This effort culminated in a symposium with 100 students, 50 community mentors, 12 undergraduate facilitators from St. Thomas Aquinas College, and 16 community facilitators. The high school students developed sustainable land-use plans for a variety of locations in Rockland County through the incorporation of planning guidelines from the Regional Planning Association. The culminating team project this year came from the Village of Haverstraw, which requested that students focus on the redevelopment of a local waterfront location in their community. This project gave students a hands-on opportunity to consider how planning, especially at waterfront locations, must address climate impacts and realities.



Above: *teachers participate in a workshop on the use of proxy data to understand past climate at the Science Teachers Association of New York State Conference, November 2018, in Rochester, NY.* ***Middle:*** *Students at an Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES) event at Hudson River Park collect a sediment sample with an Ekman dredge for their study of the concentration of heavy metals in sediments along the New York City waterfront, August 2019.* ***Below:*** *Lamont's Laurel Zaima shows off a white perch at the Hudson River Field Station, August 2019. This recently renovated station improves our ability to share how the Hudson River estuary is home to dozens of fish species. Photos by Margie Turrin.*

Below: seining Saturdays on the Hudson River, such as this event in July 2019, have become part of the weekly tradition at the Hudson River Field Station. ***Opposite page (left):*** visitors to the World Science Festival in Washington Square Park, June 2019, build a visualization of the retreat of the Greenland ice sheet by reconstructing moraine retreat from measured positions; ***(right):*** participants at the SUBMERGE Marine Science Festival at Hudson River Park, September 2019, look at dinocyst diversity and density in different parts of the Arctic basin. Photos by Margie Turrin.

Strengthening STEM Instruction

In the area of strengthening STEM education, we focused our activities on professional training of educators, designing pedagogical approaches to ensure that classroom learning in STEM subjects aligns closely with research processes, and we developed curricula grounded in project-based learning. We continued to work closely with the New York City Department of Education's Division of Teaching and Learning to run a series of professional development workshops in collaboration with staff from the Hudson River Park Trust. These lessons focused on how to explore the Hudson River using the recently adopted New York State Science Standards. Additional workshops were offered through the Science Teachers' Association of New York. Subjects included researching and modeling past climate to predict the future. Through these workshops and professional-development sessions, Lamont's Education and Outreach team has developed, tested, and shared a curriculum for middle and high school students that teaches how to use proxy data to learn more about the past. Documenting paleoclimate through proxies (e.g., tree-ring records, ocean sediments, lake records, exposure dating, ice cores) is essential to understanding climate trends and changes.

We also completed our 16th annual Day in the Life of the Hudson and Harbor program, bringing over 5000 students and teachers to the Hudson to sample the river and share their data. This year students saw the impacts of an unusually wet year, which provided an opportunity to link to the National Climate Assessment and teach students about climate change through their sampling of the Hudson River.

Increasing Public Engagement through Outreach

Our final strategic area addressed the engagement of public audiences in our ongoing scientific work so Lamont science can become more accessible to people of all ages. The outreach efforts we undertook this year focused on strategic events and partnerships that allowed us to further our community engagement efforts.

We participated in the Annual SUBMERGE festival sponsored by Hudson River Park. In the fall of 2018, 8500 New York City residents attended the event to learn about the estuary, the ocean, and human impacts. During the spring, we participated in two events at the *Intrepid* Sea, Air, and Space Museum Kid's Week and the museum's annual Science and Engineering day, and reached more than 4200 people with data about the world's oceans, plankton productivity, our explorations in Greenland and across the oceans (through the International Ocean Drilling Program), and our citizen-science X-snow project. We also participated in the American Museum of Natural History's Earthfest, which had more than 2000 attendees.

Much of our formal education is conducted through DEES, which in 2010 was named by the National Research Council the top-ranked Earth science Ph.D. program in the country, a ranking that reflects Lamont's exceptional scientists, resources, and affiliated programs. Globally, U.S. News & World Report in 2017 ranked Columbia University #4 for geoscience programs. The students in DEES bring enthusiasm and innovative ideas, lend fresh energy to our investigations, and help inspire future research. Last fall, DEES welcomed 19 new graduate students who collectively hold citizenship in four different countries. Many of our new and continuing graduate students were recipients of prestigious fellowships this year.

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Back Cover: *photos courtesy of Lamont-Doherty Earth Observatory.*

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