Columbia Climate School
Lamont-Doherty Earth Observatory

2021

MEETING THE MOMENT

THE SOLUTIONS SCIENCE IMPERATIVE
ANNUAL REPORT 2021

Annual Report 2021

MEETING THE MOMENT

The Solutions Science Imperative

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Message from Director

Maureen E. Raymo

Dear Friends,

The past year has been extraordinary in many ways. We have seen the devastating effects of our planet's climate: record-setting storms, deadly wildfires, and in the United States, the hottest June, July, and August ever. We have continued to battle a pandemic that has harmed so many of us, and has greatly disrupted our teaching and research mission. At the same time, we have seen how high-quality science can provide solutions to some of humanity's most pressing challenges.

I have hope that this year will be a turning point for climate action. We are seeing new commitments from companies and governments to cut emissions, hasten our energy transition, and invest in smart solutions. Yet there is much, much more to be done, and the world needs the best science to make the best choices. I am proud to continue to lead the world's premier geoscience research institution at this critical moment.

At Lamont, the past year has been one of opportunity and discovery. We are embracing the Observatory's position in the newly created Columbia Climate School. The Climate School will unite many different areas of expertise across the University and marshal the full expertise of Columbia to address the climate problem. Lamont's outstanding scientists—who have led Earth and climate discovery for more than seven decades—will be its scientific research heart. I have been appointed Co-Founding Dean and will continue to lead the Observatory as we build out new research capabilities of the School.

We continue our critical work to become a more diverse and inclusive institution. Our focus is to support the inclusion and success of historically underrepresented groups in geoscience; ensure a research and teaching environment free from explicit and implicit discrimination and bias; and create a safe and welcoming campus where everyone thrives. As a global leader in the geosciences, Lamont has a responsibility to lead. You can read more about our efforts and our progress on the next pages.

Our scientists have continued their research and their field work, in every corner of the globe. In this report, you'll read about several of our scientists and their work, so I'll highlight just a few. Mingfang Ting, an atmospheric scientist, has shed new light on how air currents high in our atmosphere may be changing--and how those changes may make a region drier or wetter in the coming decades. This work could be critical to understand how climate change will affect growing seasons across the globe.

Lamont's scientific research remains relevant to the challenges of today: we're finding new links between climate change and extreme storms, improving models of where the water from melting polar ice will end up, and leveraging technologies such as artificial intelligence to refine climate models. These investigations and more will make Lamont and the Columbia Climate School the place the world turns to for evidence-based climate solutions.

I hope you find the stories in this volume inspiring, knowing that our community at Lamont-Doherty Earth Observatory continues to generate the knowledge we need to make smart decisions for our future. Please enjoy Lamont-Doherty Earth Observatory's annual report for 2021.

Sincerely,

Maureen E. Raymo
Director, Lamont-Doherty Earth Observatory
Co-Founding Dean, Columbia Climate School
G. Unger Vetlesen Professor of Earth and Climate Science

Scientific Exploration

We highlight the range of Lamont-Doherty exploration during fiscal year 2021

GREENLAND
Northern Greenland

A new five-year project aimed at drilling through the ice to the underlying bedrock in four areas of northern Greenland promises to reveal the ice sheet's past in unprecedented detail and enable more accurate predictions of how it may add to rising seas in the 21st century.

ALASKA
Kotzebue Sound in northwestern Alaska

A multidisciplinary team led by Christopher Zappa from the Lamont-Doherty Earth Observatory has been working with community elders to study the climate-related changes in sea ice and marine life in the Kotzebue Sound. This unique community-based research project, Ikaaġvik Sikukun (Iñupiaq for ice bridges), combined decades of knowledge from the elders with data science, the use of unoccupied aerial vehicles, and documentary filmmaking to understand the impact that climate change has had on the area and the Indigenous way of life.

WESTERN COASTAL U.S.
Coastal Oregon and British Columbia

Aboard Lamont-Doherty's R/V *Marcus G. Langseth*, one of the large global-class research vessels within the U.S. Academic Research Fleet, marine geophysicist Suzanne Carbotte led a sea-going expedition to investigate the Cascadia Subduction Zone. This subduction zone has been the site of past "megathrust" earthquakes, which are the largest earthquakes that happen on Earth. The Langseth is a unique ship within the research fleet, equipped for advanced seismic imaging, with a high-quality sound source and capable of towing an array of listening devices called hydrophones up to 15 kilometers long behind the ship to listen to the echoes returned from the seafloor and deep below. The team went to find and map the hidden "megathrust" fault deep beneath the seafloor that ruptures in these giant earthquakes.

SOUTH ASIA
Brahmaputra River

By examining tree rings, which showed rainfall patterns going back centuries before instrumental and historical records, Observatory scientists studied seven centuries of water flow in south Asia's mighty Brahmaputra River. Their findings suggest that scientists are underestimating the river's potential for catastrophic flooding as climate warms.

ANTARCTICA
Amery Ice Shelf

Using a combination of radar images from satellites and a laser instrument on NASA's ICESat-2 satellite, glaciologist Jonathan Kinglake and team observed the sudden drainage of a large, deep, ice-covered lake within an Antarctic ice shelf—a rare phenomenon that could be interpreted as an ominous sign for the future survival of the ice sheet, and potential global sea-level rise.

INDIA
Mumbai

If global warming continues unchecked, summer monsoon rainfall in India will become stronger and more erratic. This is the central finding of an analysis that compared more than 30 state-of-the-art climate models from all around the world. The study, coauthored by Lamont-Doherty's Anders Levermann, predicts more extremely wet years in the future—with potentially grave consequences for the well-being, economy, and food systems of more than a billion people.

SOUTH AMERICA TO GREENLAND
Tracing the dinosaur journey from South America to Greenland

By meticulously matching up ancient magnetism patterns in rock layers at fossil sites across South America, Arizona, New Jersey, Europe, and Greenland, an Observatory study suggests that sauropodomorphs—a group of long-necked, herbivorous dinosaurs that eventually included Brontosaurus and Brachiosaurus—first appeared in what is now Greenland around 214 million years ago. To get there from South America, when the CO_2 levels dipped 215-212 million years ago, perhaps the tropical regions became more mild and the arid regions became less dry. There may have been some passageways, such as along rivers and strings of lakes, that would have helped sustain the herbivores along the 6,500-mile journey to Greenland, where their fossils are now abundant.

AFRICA

Democratic Republic of the Congo capital Kinshasa and Republic of Congo capital Brazzaville

Atmospheric scientist Daniel Westervelt and Columbia University undergraduate student Celeste McFarlane produced the first-ever ambient fine particulate matter (PM2.5) dataset in Kinshasa and Brazzaville and found average PM2.5 concentrations that suggest unhealthy levels of human exposure, which, over time can lead to cardiopulmonary problems and premature death.

UNITED STATES

U.S. Agricultural Regions

Lamont-Doherty researchers studied hour-by-hour rainfall patterns recorded by hundreds of weather stations in the agricultural regions of the U.S. West, South, and Northeast each year from 2002 to 2017 and compared the rainfall patterns to crop yields. They found that intensified rain storms predicted for many parts of the United States as a result of warming climate may have a modest silver lining: they could more efficiently water some major crops, and this would at least partially offset the far larger projected yield declines caused by the rising heat itself.

EUROPE

France, Germany, British Isles

Lamont-Doherty researchers studying historical records, using the Old World Drought Atlas, which reconstructs soil moisture conditions over Europe, find that the devastating European Great Famine of 1315-1317 occurred at a time of excessively wet conditions, which made planting difficult, crop yields poor, and frequently made it difficult to transport what could be harvested to market. The consequence was massive crop and market failures, which led to widespread death and starvation; in some places, infanticide and cannibalism were reported, which purportedly gave rise to the Hansel and Gretel fairy tale. Famine spread across the British Isles, France, the low countries, and Germany, and approximately 10-25 percent of Europe's population perished. These findings leave open critical questions about how to interpret the risks of droughts and deluges into the next century and how they will be influenced by both natural variability and the ever-evolving effects of human-caused climate change.

Marco Tedesco: Snow Man

"Never in my life did I think I would see rain on Summit. It is called the dry snow zone of Greenland for a reason. The imbalance of the Arctic system is screaming that there is substantial change going on characterized by multiple events rather than a single snapshot. It's consistent with what we were expecting to see based on models and our understanding of the physical processes. There is very little hope that things will be reversed because the processes we know are driving the acceleration of melting in Greenland and Antarctica have been there a while and cannot be easily stopped without drastic intervention on CO_2 concentrations in the atmosphere."

MARCO TEDESCO

Lamont Research Professor, Marine Geology and Geophysics, Lamont-Doherty Earth Observatory; Adjunct Scientist, NASA Goddard Institute for Space Studies; Faculty Member, M.S. in Sustainability Science Program, Columbia Climate School

Glaciology was not an obvious career path for Italian-born Marco Tedesco. Growing up in his hometown of Avellino, on the mountainside near Naples, his parents had very different expectations for him. Get your degree, get a job. Tedesco found himself with other plans. Today, having traveled to Greenland eleven times and twice to Antarctica (not to count the many times he visited mountain regions); authored a book, The Hidden Life of Ice: Dispatches from a Disappearing World (a National Geographic and Washington Post Best Travel Book of 2020); and published almost 150 peer-reviewed research papers, Tedesco is among the most well-respected and quoted polar experts in the world.

He frames his passion for studying snow and ice as a kind of love story. His father was a construction supervisor, working ten hours a day in every type of weather. While Tedesco studied electrical engineering at the University of Naples and was on a path his parents assumed would lead to an industry job with a good salary, he found himself drawn to a life of research.

"I was always attracted to science and an academic career. Nobody in my family has done that, so there is no history. I applied for a PhD in Florence. I didn't get in at first. I decided I'm going to get ready for next time to apply." But a month later, his university advisor called him.

"My advisor said, 'look, we have a project on snow. Are you interested?' I said yes. And that was my key. I started to work on snow; I fell in love with the work. I went into the mountains and basically married this medium."

Ultimately, he received his PhD in Italy from the Italian National Research Council in Florence, focusing on the interaction of electromagnetic waves and snow particles for satellite applications.

"My first day of PhD, my advisor came to me with three books totaling about 1000 pages and told me to come back to him once I had finished absorbing them. I only had a desk and a lamp, not even a computer." Three months later, Tedesco went to his advisor, having finished the books and with a draft of a first paper.

In 2002, Tedesco began a research appointment at NASA Goddard Space Flight Center, left Avelino, and moved to Washington, D.C.

“I had one thousand dollars in my pocket, and my wife was pregnant with our first daughter,” said Tedesco. He also had a one-way hour-and-a-half commute across the city each day. He used the time on the train and bus to read and study, learning to speak and write better English.

In 2008, Tedesco moved to the City College of New York (CCNY) as an Assistant Professor, where he was promoted to Associate Professor in 2012. At CCNY, he founded and directed the Cryosphere Processes Laboratory and was a rotating program manager at the National Science Foundation between 2013 and 2015. In January 2016, Tedesco joined Lamont. Here, he continues researching the dynamics of seasonal snowpack and ice sheet surface properties and pursues fieldwork exploring exoplanetary biology on icy surfaces and global climate change and its implications on the economy, real estate, and socially vulnerable populations.

Much of Tedesco’s work and writings have focused on the remarkable decline of Arctic ice. During the summer of 2021, Tedesco and other climate scientists recorded daily melt rates seven times higher than usual.

A mid-August heatwave led to the first-ever recorded rainfall at Summit Camp, at the ice sheet’s highest point. Seven billion tons of water fell on the ice sheet.

Tedesco called the rain event unique and alarming.

“Never in my life did I think I would see rain on Summit. It is called the dry snow zone of Greenland for a reason,” he said. “The imbalance of the Arctic system is screaming that there is substantial change going on characterized by multiple events rather than a single snapshot. It’s consistent with what we were expecting to see based on models and our understanding of the physical processes. There is very little hope that things will be reversed because the processes we know are driving the acceleration of melting in Greenland and Antarctica have been there a while and cannot be easily stopped without drastic intervention on CO_2 concentrations in the atmosphere.”

“Changes are happening even faster than the most dire predictions are suggesting.”

Tedesco observes the speed at which projected changes to polar ice are materializing with great concern.

Of particular concern, the injustice of climate change consequences. Too often, the communities that generate the least of the greenhouse gases that contribute to global warming are the people who suffer the most severe climate consequences.

During the summer of 2021, Tedesco and colleagues published The Socio-Economic Physical Housing Eviction Risk (SEPHER) dataset. It integrates socio-economic information with risk from wildfires, drought, coastal and riverine flooding, and other hazards, plus financial information from real estate databases and ethnicity, race, and gender data. The goal is to account for the economic vulnerability associated with the housing market that accounts for racial, gender, and ethnicity factors so that stakeholders can take appropriate action to protect vulnerable populations. SEPHER covers the entire United States, and Tedesco has made one of the pillars of this project that all data must be publicly accessible.

“The tool is aiming at quantifying objective analysis of the role of climate impacts in social and racial injustice, as in the case of climate gentrification and displacement or climate injustice.”

Tedesco will take his next expedition to Greenland in 2022 when he and Lamont paleoclimatologist Brendan Buckley go to a forest in southern Greenland to take tree ring samples to work on climate reconstruction of Greenland back to the 1800s.

“We want to know what happened before we were able to measure things,” he said. Since trees can live for hundreds—and sometimes even thousands—of years, a tree can experience various environmental conditions: wet years, dry years, cold years, hot years, early frosts, forest fires, and more. Tree rings can indicate how old the tree is and what the weather was like during each year of the tree’s life. “The plan is to reach the only forest in Greenland, a patch of land no more than six miles, close to the place where Erik the Red arrived and named Greenland as we know it today. It is going to be an exciting trip!"

The pandemic forced a delay of this field study, which was slated for last year. The pandemic and its many restrictions also illuminated something for Tedesco, something disturbing, considering the kind of global collaboration required to cut greenhouse gas emissions and stave off some of the most catastrophic future climate consequences.

"As a species, we were not able to come together with masks and vaccines. If we can't come together with such a great and imminent threat [as COVID-19], how can we convince people that we need to take action for future generations? In this regard, the pandemic has given way to questions about the world around me." However, Tedesco remains optimistic, especially when he thinks about the power of new generations, to adopt a lifestyle that considers economic and financial aspects and one sustainability and moral and ethical values.

Heat, Wind and Fire: Mingfang Ting's Atmosphere Investigations

"We don't even know what's coming in the future—how extreme or how fast. Some of what we're seeing is already exceeding our most severe predictions. I worry that we may be underestimating the severity of the impacts of climate change."

MINGFANG TING

Associate Director, Lamont Research Professor,
Ocean and Climate Physics, Lamont-Doherty Earth Observatory;
Adjunct Professor, Department of Earth and Environmental Sciences;
Co-Director, Masters in Climate and Society Program,
Columbia Climate School

For Mingfang Ting, a lifelong endeavor to understand climate through the prism of atmospheric science began with a suggestion. The Lamont-Doherty Earth Observatory research professor was born and raised in a Chinese province north of Shanghai during a time when going to college was highly regulated. The country had one college entrance exam for everyone who wanted to attend. After passing the test, prospective students had to fill in the form where and what they wanted to study. Ting filled in Peking University—considered the best in China—and wrote that she wanted to study physics or mathematics. When administrators read her file, it occurred to them that Ting might be a good fit to study Earth science, so they asked her.

"Do you want to study Earth science? I had no idea what that meant, but I said yes. If I had said no, maybe I could still go to university but not to Peking University. It was quite a nice coincidence that they put me in there, and I still enjoy it," said Ting, who has been pursuing and accomplishing remarkable discoveries in a scientific discipline that has become a central concern for the world.

Ting received the 2021 Distinguished Scientific/ Technological Achievement Award in Climate Variability and Change from the American Meteorological Society. The award recognizes her important contributions to our understanding of climate dynamics, often drawing upon ingenious generalizations of the stationary Rossby wave concept. Said Ting of the honor, "I was really blown away by that description of my work. I appreciate my colleagues out there who remember me and give me this honor."

Ting studies Rossby Waves, which are planetary undulations that form due to the rotation of the planet. They play a significant role in shaping Earth's weather. Ting explores how they change with global warming and how they trigger changes. Ting says Rossby waves and their propagations are fundamental ways the atmosphere carries its signal (low and high-pressure anomalies) from one location to another—El Niño-Southern Oscillation being one of the good examples.

"My research tries to address questions about how regional climates are changing and why." In particular, she seeks to find out how these shifts are linked to wave dynamics and remote forcing. "So, questions about why one particular region is drier or wetter than normal drive my work. Are changes in Rossby wave propagation the reason?"

When Ting discovers dynamics where Rossby waves trigger regional changes, she probes more deeply to determine why the wave propagation is changing. Atmospheric Rossby waves are also crucial in shaping the storm tracks, preferred paths for midlatitude weather disturbances.

“Another question of my research also focuses on how storm tracks and Rossby waves interact with each other. If we can better understand these questions, it will help us predict regional climate anomalies, such as droughts and extreme heat conditions, that could—for example—harm crop production. We can inform stakeholders in those regions, and they can work to mitigate the effect.”

Ting is currently leading a study on heatwaves, exploring how changing Rossby waves may cause more heat wave phenomena and whether co-occurrences of heat extremes at different locations are becoming more prevalent. The project is investigating two types of heat extremes—dry heat and high heat and humidity.

“We look at how these two types of extreme events are generated differently. Is the humid heat extreme increasing more than the dry heat or vice versa? What are the impacts of the two types of extremes on agriculture and human health, for example.”

So far, Ting and collaborators have surveyed the dry and humid heat globally, identifying the trend in terms of population and land areas affected by each type. The study will include a close examination of last summer’s extraordinary Pacific Northwest heat extremes.

Ting is concerned about the extreme events the world has been experiencing as the global mean temperature continues to rise.

“We don’t even know what’s coming in the future—how extreme or how fast,” Ting said. “Some of what we’re seeing is already exceeding our most severe predictions. I worry that we may be underestimating the severity of the impacts of climate change.”

Changing Ice, Changing Coastline

The world's glaciers are in trouble. These spectacular formations, created over tens of thousands of years, cover about one-tenth of Earth's landmass, mainly in Greenland and Antarctica.

From 1994 to 2017, they shed 28 trillion tons of ice, and the melt is accelerating. The latest report from the Intergovernmental Panel on Climate Change notes, "The global nature of glacier retreat, with almost all of the world's glaciers retreating synchronously, since the 1950s is unprecedented in at least the last 2000 years."

What the glaciers do in the next century will affect nearly everyone. About 2.5 billion people live within 60 miles of the ocean, and billions more depend on the maritime economy and transportation routes. Understanding the future of the glaciers is critical to understanding what our planet will face during the next century and beyond.

That's why our scientists are traveling to the ends of the Earth: to see firsthand what's happening, work with communities that stand to be affected, deploying new sensory and imaging technologies, and driving new scientific discoveries. Here are a few of their innovative approaches to their work.

Joerg Schaefer and Gisela Winckler, geochemists and paleoclimatologists at Lamont, do a forensic analysis of glaciers past and present. "We try to understand how ice responded to temperature changes in the past so we can calibrate the sensitivity of it and then better predict what's coming in the future," says Schaefer.

The team uses a method called cosmogenic dating. First, they identify suitable rocks or sediment left behind when a glacier retreats. They then chip away to take samples, bring those rocks to their lab, and analyze them for the presence of beryllium-10, an isotope formed from cosmic rays in Earth's atmosphere; it's present on the rock when the ice doesn't cover it. Counting atoms of beryllium-10 on the rocks' surface helps scientists to determine precisely how long ago it was uncovered by ice—in turn showing how the glacier behaved in the past.

Schaefer plans to use this same dating process in a new ambitious enterprise, GreenDrill, which will drill into the ice sheet at four sites at the island's northern end. "With this project, we're entering an entire zone of the Earth that nobody has systematically studied," Schaefer says. From the start, the researchers are working with communities that stand to be affected by the shrinking ice to co-produce knowledge together. This approach can be used as a model for other researchers in their fieldwork, which can improve the science and serve as a model for producing knowledge ethically.

How can we use technology to see inside the ice sheets? That's the question that Alexandra Boghosian, a postdoctoral researcher at Lamont, has been exploring. She and a team of programmers and scientists have been developing an augmented reality program to allow researchers to see data from radar and satellites in an entirely new way. Being able to "walk" through a virtual ice sheet in three dimensions and take measurements in the simulation promises to redefine data exploration and interpretation.

Marco Tedesco, a glaciologist at Lamont and author of The Hidden Life of Ice: Tales from a Disappearing World, conducts on-the-ground fieldwork to supplement data from drones and satellites. "Remote sensing, fieldwork, and models complement each other and help us project future changes," he says. In 2020, Tedesco led a study that quantified the retreat of Greenland's ice sheet—600 billion tons of ice in two months in mid-2019, with the potential to raise global sea levels by 2.2 millimeters. Tedesco and the researchers attributed the loss to warmer temperatures and new atmospheric circulation patterns.

Decarbonization Research: Clearing the Air

Lamont's Decarbonization Technologies Take a Giant Step Forward

"We wanted to figure out the cheapest way to take carbon dioxide out of the air and we came up with something very simple. Take limestone, cook it. Now you have CO_2, to store or use, and calcium oxide. Put the CaO out in the weather. It will draw down CO_2 from air, to make limestone again. Repeat. This is so simple, it is almost stupid. But we are finding that we can convert 75% of CaO to limestone in less than two weeks, just reacting with air in the lab. And, because the process is so simple, it currently has the lowest peer-reviewed cost estimate, of any proposed method for Direct Air Capture."

PETER KELEMEN

Arthur D. Storke Memorial Professor, Department of Earth and Environmental Sciences, Geochemistry, Lamont-Doherty Earth Observatory, Columbia Climate School

Carbon dioxide (CO_2) levels today are higher than at any point in the past 800,000 years or more.

During a year when terms like carbon neutrality and net zero have become more and more commonly used, it appears the world is waking up to the imperative underscored in every high-level climate assessment—humanity needs to make a drastic change to stem the most catastrophic climate change consequences.

Climate impacts are happening more quickly than many scientists had predicted. Greenhouse gases are making the planet hotter. That rise in temperature is disrupting the weather and climate system in profound and cascading ways. For example, the western United States' unprecedented drought has set up this region for devastating consecutive fire seasons. The rise in temperature triggers the air to hold more moisture, creating conditions for record breaking rainfall in the northeast, intensifying hurricanes, flooding neighborhoods, and threatening communities. The warmer temperature is also disrupting food webs. In the Arabian Sea, a strangely resilient and previously rare plankton species has ravaged the fishing industry.

In its 2020 report, The UN Environmental Programme (UNEP) concluded that despite a slight dip in atmospheric CO_2 created by the pandemic lock down in 2019, "the world is still heading for a catastrophic temperature rise in excess of 3°C this century—far beyond the Paris Agreement goals of limiting global warming to well below 2°C and pursuing 1.5°C." It goes on to say, to avoid the worst consequences of global warming, we need to remove ten billion tons of CO_2 from the air by 2050.

In other words, in addition to drastically cutting global fossil fuel emissions, society needs to develop and use technologies to remove the CO_2 already in the atmosphere. This is a huge undertaking, but one that scientists at Lamont-Doherty Earth Observatory have been striving towards for more than a decade.

Decarbonization, the process of capturing CO_2 from the air and from industrial processes, has been in various stages of development at Lamont-Doherty for several years. One of many strategies that researchers are developing involves harnessing a natural process by which the Earth itself takes back CO_2 from the air, and CO_2 generated by power production.

Geologist Peter B. Kelemen is a research scientist at Lamont-Doherty Earth Observatory and the Arthur D. Storke Memorial Professor in the Department of Earth and Environmental Sciences. He has been a key architect of the Oman Drilling Project, an initiative involving more than 200 international scientists from disciplines such as geophysics, geochemistry, geology, biology, and physics who are working on research topics related to a unique geological feature in the Oman desert. In this region, the oceanic crust and its underlying mantle rocks have been thrust up onto the surface, creating the largest on-land exposure of ocean crust and upper mantle in the world.

Atmospheric CO_2 spontaneously reacts with rocks from the Earth's interior, the mantle, to form "carbonate" minerals, both removing CO_2 from air, and permanently storing it in solid form. This is driven by the chemical energy due to disequilibrium between mantle rocks and the atmosphere.

Kelemen studies the chemical and physical processes of reaction between fluids and rocks. Kelemen's primary focus now is on CO_2 removal from air and permanent storage via engineered methods that emulate natural carbon mineralization. While his work in this area began in 2006, during fiscal year 2020, his discoveries have begun to fuel exciting industry investment and commercialization. First came a major innovation.

Kelemen and co-workers have developed several patents for processes that harness this naturally available chemical energy to yield low cost CO_2 removal from air and geological storage.

"We wanted to figure out the cheapest way to take carbon dioxide out of the air and we came up with something very simple. Take limestone, cook it. Now you have CO_2, to store or use, and calcium oxide. Put the CaO out in the weather. It will draw down CO_2 from air, to make limestone again. Repeat. This is so simple, it is almost stupid. But we are finding that we can convert 75 percent of CaO to limestone in less than two weeks, just reacting with air in the lab. And, because the process is so simple, it currently has the lowest peer-reviewed cost estimate, of any proposed method for Direct Air Capture."

Two start-up companies are putting Kelemen's innovation to work. Heirloom Carbon Technologies based in California is committed to removing one billion tons of CO_2 from the air by 2035 by "looping" CaO and $CaCO_3$ as described above.

Meanwhile, 4401.Earth based in Oman is focusing on storage of CO_2 removed from air, by forming solid carbonate minerals below the surface.

Both represent a profound advancement in the practical application of decarbonization science.

"It's the most promising I've seen so far. And so it's very gratifying to finally see these things moving toward tests on the field scale," said Kelemen.

Decarbonization Research: Game Changer

Off-Shore Decarbonization

Another of Lamont's decarbonization breakthrough processes involves technologies with the ability to capture and turn CO_2 into stone.

Geophysicist David Goldberg, and Lamont's Deputy Director as of July 2021, has been involved in recent projects that have demonstrated that when you inject CO_2 and water into basalt rock, the silicate material takes up the gas and turns it into carbonate rock. If this natural process can be enhanced, scientists believe it could be a valuable tool to solve the crisis-level airborne carbon dioxide in Earth's atmosphere.

Under an Iceland-based pilot project called CarbFix—designed and carried out with Columbia leadership—researchers proved that basaltic rock units react rapidly with CO_2 captured from a power plant. The team mixed gasses generated by the Hellisheidi geothermal power plant with water and reinjected the solution into the volcanic basalt below. In nature, when basalt is exposed to carbon dioxide and water, a series of natural chemical reactions takes place, and the carbon precipitates out into whitish, chalky minerals—carbonates. But before CarbFix, no one knew how fast this might happen if the process were harnessed for carbon storage. Previous studies had estimated that in most rocks, it would take hundreds or even thousands of years. In the basalt below Hellisheidi, 95 percent of the injected carbon was fixed as carbonates within less than two years. This proof of concept was an important step.

"Now it's all about scale," said Goldberg.

CarbFix currently injects and stores about 10,000 tons of CO_2 per year in solid carbonate minerals, below the land surface near the power plant. Looking to scale-up this process, Goldberg and colleagues seek to capture millions of tons of CO_2 from more distant industrial sources—such as fossil fuel power plants, manufacturing plants, and refineries—and inject it into submarine basalts off the coast of Washington and Oregon.

With the Solid Carbon project, the team aims to conduct offshore geophysical surveys, study the basalt reservoir, and set up a pilot injection and monitoring experiment at a site in Cascadia, at approximately the scale of the CarbFix project in Iceland.

"The big idea is to get this demonstration project funded and completed," said Goldberg. "But the even bigger picture is to then scale this up and establish a climate solution that allows for direct capture of CO_2 from ambient air with permanent offshore storage. So, once these carbon capture and undersea technologies are successfully demonstrated together, we can multiply the process in many locations and really make a difference.

Modeling Future Climate

Transformational Steps Forward

"With LEAP STC, we will directly partner with NCAR to increase the projection skill of their Community Earth System Model. This is a deeper partnership focused on improving key components of the representations of physics and biogeochemistry. We are also building better datasets with which to validate the models."

GALEN MCKINLEY

Professor, Department of Earth and Environmental Sciences, Geochemistry, Lamont-Doherty Earth Observatory, Columbia Climate School

Our planet's climate is changing, shifting more rapidly than at any other time in human history, imperiling society with extreme heat, wildfire, floods, and more. A crucial challenge for climate science is determining when the most severe climate-related impacts are likely to happen.

Since the changes Earth is experiencing are different from any other time in our understanding of planetary history, the work of projecting the future must rely on evolving calculations of emerging data.

Climate models help researchers forecast these impacts. They are based on well-documented physical processes to simulate the transfer of energy and materials through the climate system to help scientists look at complicated problems and understand complex systems.

At Lamont-Doherty Earth Observatory, the work of modeling has a rich history and continues evolving.

This year, to help researchers bring greater precision to this work, the National Science Foundation (NSF) has selected Columbia to lead a Science and Technology Center (STC) called Learning the Earth with Artificial Intelligence and Physics (LEAP).

The center will develop the next generation of data-driven physics-based climate models in collaboration with the National Center for Atmospheric Research (NCAR), NASA's Goddard Institute for Space Studies (GISS), and partner universities. It will also train a new wave of students fluent in climate science, climate modeling, and modern machine-learning algorithms.

The center's larger goal is to provide actionable information for societies to adapt to climate change and protect the most vulnerable. Among those leading the LEAP center is Lamont oceanographer and carbon cycle scientist Galen McKinley.

"With LEAP STC, we will directly partner with NCAR to increase the projection skill of their Community Earth System Model," said McKinley. NCAR created the Community Earth System Climate Model or CSEM in 1983 as a freely available global atmosphere model for the broader climate research community.

According to McKinley, while Lamont scientists have worked with CSEM in the past, "This is a deeper partnership focused on improving key components of the representations of physics and biogeochemistry. We are also building better datasets with which to validate the models."

In July 2021, atmospheric scientist Robert Pincus joined Lamont. He works at the intersection of clouds and radiation and has had a career of breakthrough work in climate modeling. Pincus believes the LEAP project has the potential to be transformative.

"The community has tried several promising ideas to try to sharpen predictions, but they've all been based on having a cartoon of the world in our minds. LEAP has the potential to step around that," says Pincus. "The promise of machine learning at the process level is that we can use the way the world behaves now, all the rich behavior we can observe directly, to tell us how the entire climate system will behave in the future."

The Hazard Resiliency Imperative

Much of the world has witnessed the stakes involving our changing climate. During the summer of 2021, in particular, several regions of the planet experienced unprecedented extremes.

Among the most dramatic examples is the Pacific Northwest's heat dome, which led to hundreds of deaths in Oregon, Washington, and British Columbia. Temperatures rose to levels eclipsing all-time record high heat. The west endured another spike in wildfires fed by heat and drought. Thanks to the work of Lamont adjunct professor and bioclimatologist Park Williams, we know that there is a connection between warming temperatures, drought, and the incidences of wildfires.

This year also marked the second record-breaking hurricane season. This was also the summer Europe experienced deadly flooding.

On September 2, 2021, Tropical Storm Ida moved through the New York metropolitan area, killing dozens in extraordinary, first-time flash flooding that led to millions of dollars in damage. What does it mean? Are these extremes the new normal? The answers vary; the threat looms. The science of understanding risk is pivotal to creating a resilient future. Lamont science has continued groundbreaking work to explain to the world what to expect.

“Climate change has shifted the statistics, loaded the dice so heat waves are more frequent and more intense than they would've been without climate change,” said Lamont climate scientist Radley Horton.

Atmospheric science studies at Lamont have identified a trend, a marked change in the way the Jetstream behaves.

“Climate models have underestimated the range of possible outcomes. From a risk management perspective, society should wake up to the plausibility of a future with very different summer weather than any experts anticipated just a decade ago,” said Horton.

“And from an impacts perspective, are we going to see transformational increases in fire risk, along with ecosystems shifts far more profound than those types of models would suggest? The scientific community used to generally agree these were low-probability, high-consequence scenarios, but in my opinion, scientific confidence about the ‘low probability’ part of this equation is eroding,” continued Horton.

The health impacts of extreme heat are known to be significant as well.

“If you increase the most extreme temperatures from say, 100 degrees to 103 degrees, and you have far more 100 degree days than you had in the past, you're going to see major increases in human suffering and major decreases in human productivity. We have to do everything we can to reduce greenhouse gas emissions dramatically, and we have to protect the most vulnerable people,” said Horton.

Suzana Camargo, the Marie Tharp Research Professor at Lamont, studies climate change and its impact on hurricanes. Camargo says climate scientists that anthropogenic climate change is increasing the impacts of hurricanes for three reasons. Climate change is rising sea levels. So, flooding associated storm surge generated by hurricanes has a head start and creates more pervasive inundations. Climate change also increases the amount of rainfall and precipitation.

“In a warmer climate, the amount of water vapor in the atmosphere increases, which contributes to an increase in the occurrence of extreme rainfall,” said Camargo. “We have seen an increase in the frequency of extreme rainfall events, including those associated with hurricanes.” For example, Hurricane Harvey, the devastating Category 4 hurricane that made landfall on Texas and Louisiana in August 2017, causing catastrophic flooding and more than 100 deaths. Various studies attributed an increase of six to 15 percent in storm rainfall due to climate change.

Also, while global warming isn't necessarily triggering more hurricanes, it is "loading the dice" for more intense hurricanes based on theories and models. And while attribution science around climate's impact on hurricane frequency is ongoing and constantly evolving, Camargo asserted the importance of respecting the risk.

"If you live in coastal areas, you should always be worried. One is enough. It doesn't matter if the season is super active or calm. One category three or category five that hits where you live. That's enough," said Camargo. In fact, the 1992 season that delivered Hurricane Andrew—a potent and destructive Category 5 Atlantic hurricane that struck the Bahamas, Florida, and Louisiana—was calm in terms of the number of hurricanes.

"But you had Hurricane Andrew, which left devastation and death and all kinds of problems. So if you live in a hurricane-prone area, you should always be prepared."

Diversity, Equity, Inclusion (DEI) and Anti-bias at Lamont

In July 2020, the Lamont-Doherty Earth Observatory Directorate established the Lamont Diversity, Equity, and Inclusion (LDEI) Task Force to develop recommendations around three important themes:

1. Supporting the inclusion and success of historically underrepresented groups in geoscience.
2. Ensuring a research and teaching environment free from explicit/implicit discrimination and bias.
3. Creating a safe and welcoming campus where everyone thrives and is respected.

In January 2021, the 25-member Task Force delivered a final report that identifies friction points, priority areas, and actionable goals for advancing Diversity, Equity, Inclusion, and Anti-Bias (DEIA) priorities on our campus. It serves as a roadmap as we navigate toward a more diverse and inclusive future.

Barriers to progress on DEIA are complex and interwoven, and addressing them requires the combined commitment of our institution and all individuals in our community. As we collectively work to address inequity and increase diversity at our institution and in our discipline, it is incumbent on all of us to take an active role in creating a more inclusive culture.

Accelerating institutional and cultural change at Lamont to address DEIA priorities requires additional staff and resources. In response to this growing need, institutional commitment has increased over several months, and several new DEIA-focused positions have been established. This includes an Assistant Director of DEIA for Lamont and the Columbia Climate School, an Assistant Dean for DEIA in the Climate School, and an Associate Director for DEIA at Lamont. In addition, a new DEIA Standing Committee is being formed at Lamont to help provide input to the Directorate on DEIA planning and activities. The Standing Committee members will liaise with Lamont divisions and other DEIA efforts across campus units and at Columbia. The committee will also contribute to creating a Lamont-wide DEIA annual report that will include information from divisions/units and outline activities and progress toward our goals.

"Together, we can make Lamont a place where everyone can thrive, and live up to our reputation as the premier campus for cutting-edge geoscience research; not just for some, but for all" (LDEI report, 2021).

Education and Outreach 2021

The Office of Education and Outreach at Lamont-Doherty Earth Observatory has completed another successful year of programming, both in-person and online. Generous support from our partners and donors has allowed us to develop and deliver innovative programming throughout the COVID-19 pandemic and continue to engage learners of all ages in the Earth and environmental sciences.

HUDSON RIVER FIELD STATION

A Year of Engaging Virtual and Field Programs

NEXT GENERATION OF HUDSON RIVER EDUCATORS (NEXT GEN)

Among our initiatives during summer 2021 was a hybrid program—three days online, two days on the river—with a group of eight high school science students and two undergraduate mentors.

Next Gen is designed to better connect groups underrepresented in STEM with a range of online and field science experiences centered on the Hudson River and the local environment.

The students, working at the Hudson waterfront in Piermont and Haverstraw, collected data on fish abundance and diversity, water chemistry, habitat assessments, soil chemistry, and lead in the soil, and also assessed lead levels in their own homes and yards.

Throughout their fieldwork, they collected and reported findings to the state. Among their findings were several newly emerging invasive species in the Hudson (Florida softshell turtle, Apalone ferox, Invasive Asian Shrimp, Palaemon macrodactylus, and a potential round goby Neogobius melanostomus). The students worked with a New York City artist, taking her into the field. They shared their research and experiences, and contributed in their own voice to her upcoming art installation about the Hudson River.

An integral part of the student experience centered on understanding and connecting with the diverse communities that live along the Hudson River. This aspect of the program had students interviewing their friends, family, and neighbors to learn about their perception of and relationship to the Hudson. These conversations enabled students to better develop and direct education and communication materials about this critical resource. They partnered with the Rockland Fish Advisory staff to create targeted messages on fishing restrictions. They developed data rich games to share during outreach events at the Field Station and outdoor science events. They created Instagram posts featuring native and invasive plant species. They crafted short single topic videos. As a final project, they drew from all of these experiences to write a blog post for Earth Institute's State of the Planet covering topics such as Environmental Justice, the long-term impacts of redlining communities, sustainable planning, the power of learning from the community voice, and Hudson River science. Through their work they developed a network of peers with common interests, links to career pathways in science, and a richer understanding of their local environment and their community.

HANDS-ON SCIENCE FOR ALL

Programs for Students, Educators, and the Science-Curious

SCIENCE SATURDAYS

We designed a range of different programs to reconnect with our neighbors as pandemic restrictions began to lift. Each Saturday, from June to Labor Day, we invited community members of all ages to join us for scientific research activities.

NEW TRAININGS TO STRENGTHEN REGIONAL PARTNERSHIPS

We offered training about the Hudson River and Climate Change to the Rockland County Conservation and Service Corps (RCSC) members, preparing them to assist us with outdoor programming during the summer. We brought on two Corps members to help us with our summer student high school Next Gen program, and we have had about a dozen other members of the RCSC team assist with Science Saturdays, Program planning days, and Hudson River Fish Counts.

TEACHER WORKSHOPS AND SUPPORTING CURRICULUM

We partnered with EI LIVE K12 to host a series of teacher-focused workshops featuring videos and a set of rich curriculum resources that are now available on our field station website.

EI LIVE K12

Our EI LIVE K12 series remained a successful staple of our education and outreach programming throughout 2021 with Observatory researchers contributing to weekly remote science sessions. From January to June of 2021, more than 1,500 people signed up to join events. Session recordings on YouTube have been viewed more than 2,000 times. On this virtual platform, the series has succeeded in bringing climate change and sustainability science to audiences nationally and internationally. The K-12 channel features experts from around LDEO, the Earth Institute, and the Columbia Climate School, as they present relevant sustainability content in 45-60 minute live sessions that are tailored for students, parents, and educators.

DAY IN THE LIFE OF THE HUDSON & HARBOR EVENT IN 2021

We hosted a successful virtual event. The archived online programming promises to be a useful and enduring resource.

COLUMBIA CLIMATE SCHOOL IN THE GREEN MOUNTAINS

Pre-College Immersive Summer Program

On June 27, 2021, we welcomed our first cohort of students into the Columbia Climate School in the Green Mountains program. The program, in partnership with Putney Student Travel, brought 80 students from around the United States to the Castleton University campus in Castleton, Vermont.

The students participated in an immersive two-week program to mobilize action, drive impact, and effect change in response to our warming planet. Students engaged with faculty and staff from the Climate School and learned about cutting-edge research and innovations in action. Students also had the chance to meet, collaborate with, and build partnerships with like-minded peers and tap into their collective strengths for action.

After 12 days of faculty-led workshops, students developed talking points around passion projects they would like to pursue which would address the effects of climate change in their hometowns. Delivered as three-minute pitches, these presentations targeted policy, infrastructure, and the environment. Ten students were selected to present their work to Columbia Climate School faculty and leadership in early August. Faculty were impressed by the depth and strength of these presentations.

We look forward to continuing this pre-college program in summer 2022.

Our Donors

We are grateful to the many alumni, friends, and supporters who sustain our research and educational endeavors through their financial contributions.

Annual support is critical to the advancement of our mission, the stability and ongoing operations of the Observatory, and the maintenance and stewardship of our campus.

With deep appreciation, we acknowledge the generosity of our donors for gifts made during our fiscal year between July 1, 2020 and June 30, 2021.

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+Deceased

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 contact us.

Financials

LDEO FY2021 Statement of Activities (In 1,000s)

SOURCES OF REVENUE	FY'20	FY'21
National Science Foundation	34,359	34,283
National Aeronautics and Space Administration	3,860	4,040
National Oceanic and Atmospheric Administration	1,085	1,471
National Institute of Environmental Health and Safety	1,077	891
Department of Energy	576	636
Office of Naval Research	124	132
Woods Hole Oceanographic Institution	451	162
U.S. Geological Survey	508	378
Environmental Protection Agency	117	86
New York State	149	253
Miscellaneous Federal Funds	486	218
Total Government Grants—Direct & Indirect	**42,792**	**42,550**
Private Grants	8,329	4,343
Endowment Income	7,686	7,274
Gifts	1,790	1,946
Miscellaneous	693	600
Indirect Sources	14,204	13,184
Total Non-Government Sources	**32,701**	**27,347**
TOTAL SOURCES	**75,493**	**69,897**

USES OF REVENUE		
Research Expenses	39,973	35,474
Operation and Maintenance of Plant	4,792	5,109
General and Financial Administration	4,635	4,296
Other Instruction-Related	11,553	10,205
Equipment	947	1,899
Debt Service	1,413	1,434
External Affairs and Fundraising	870	852
Information Technology	845	874
Indirect Transfers	10,342	10,078
Total Uses of Revenue	**75,371**	**70,221**
NET OPERATING GAIN/(LOSS)	**122**	**(324)**
Capital Expenses	(1,090)	(340)
Subtotal Non-Operating Expenses	(1,090)	(340)
Net Change in Current Fund Balance	(968)	(664)
Beginning Fund Balance	13,479	12,511
Ending Fund Balance	12,511	11,847

Awards

Lamont-Doherty Earth Observatory's outstanding scientists and researchers garnered several awards in FY2021. We are proud to share a selected list of awardees.

RYAN ABERNATHEY
Associate Professor, Department of Earth and Environmental Sciences, and Ocean and Climate Physics Division, Lamont-Doherty Earth Observatory received the **Early Career Award** from **The Oceanography Society**.

JACQUELINE AUSTERMANN
Assistant Professor, Department of Earth and Environmental Sciences, and Seismology, Geology and Tectonophysics Division, Lamont-Doherty Earth Observatory has been selected as a **Research Fellow in Earth Sciences** by the **Alfred P. Sloan Foundation**.

VICKI FERRINI
Senior Research Scientist, Marine/Large Programs Division, Lamont-Doherty Earth Observatory was elected as one of the inaugural **Fifty People Changing the World** by **The Explorers Club**.

ARNOLD L. GORDON
Professor, Department of Earth and Environmental Sciences, and Ocean and Climate Physics Division, Lamont-Doherty Earth Observatory will receive the **2020 Henry Stommel Research Medal** from the **American Meteorological Society**.

SIDNEY R. HEMMING
Co-Chair, Department of Earth and Environmental Sciences, and Professor, Geochemistry Division, Lamont-Doherty Earth Observatory, was elected as a **Guggenheim Fellow** by the **John Simon Guggenheim Memorial Foundation**, and received the **Laurence L. Sloss Award** from the **Geological Society of America**.

YOCHANAN KUSHNIR
Lamont Research Professor, Ocean and Climate Physics Division, Lamont-Doherty Earth Observatory was elected a **Fellow** of the **American Geophysical Union**.

GALEN McKINLEY
Professor, Department of Earth and Environmental Sciences, and Geochemistry Division, Lamont-Doherty Earth Observatory received the **Ocean Sciences Voyager Award** from the **American Geophysical Union**.

MARCO TEDESCO
Lamont Research Professor, Marine Geology and Geophysics Division, Lamont-Doherty Earth Observatory was elected a **Fellow of The Explorers Club**.

Contact

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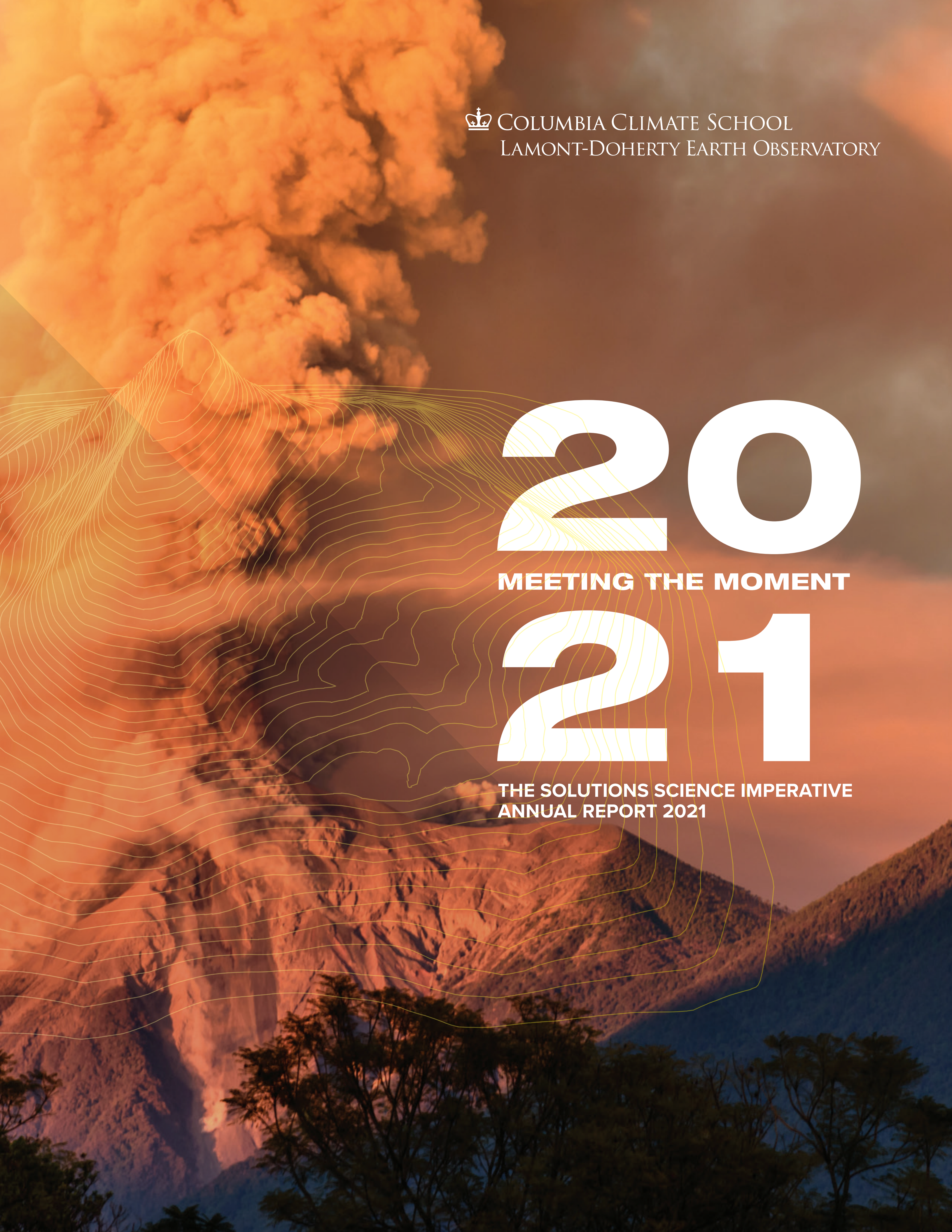

Columbia Climate School
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2021
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