Eos

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SCIENCE NEWS BY AGU

Code-Switching Consequences

Brazil's Antarctic Station Gets New Life

Moon-Making Moments

APRÈS-SNOWPACK

AS THE SNOWPACK SHRINKS, SCIENTISTS MUST CHANGE THE WAY THEY STUDY WINTER, CITY WATER PLANNERS ARE PREPARING THEIR COMMUNITIES, AND THE SKI INDUSTRY IS GETTING LOUD.

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Winter's Melting Point

When you think about snow, what comes to mind? Sledding and hot chocolate? Shoveling and wet boots?

"As a native U.S. East Coaster, I never had much of an appreciation for the importance of snow—it was exciting as a kid and can be somewhat of a nuisance as an adult," said Ellyn Enderlin of Boise State University and *Eos*'s Science Adviser representing AGU's Cryosphere section. "It's really difficult to grasp the importance of snow when you're focused on driving down slippery roads, but it's important that society collectively realizes that changes in snowpack have impacts beyond winter sports, days off from school, and difficulties commuting to work. The changes also profoundly influence the natural system, from microscopic to global scales."

Enderlin and Merritt Turetsky, our Biogeosciences Science Adviser from University of Colorado Boulder, suggested the theme of this issue and consulted on its development.

We start on page 22 with Marta Moreno Ibáñez, who writes about the challenges of forecasting polar lows—the phenomenon that can result in sudden, dangerous conditions including strong winds and heavy snowfall. Until the dawn of the satellite era, not much at all was known about polar lows. Today scientists have a better handle on why they form, but they still have to work out the nuances of the many processes involved in warning people when to take shelter from one.

Then we take a look at the planet's changing snowpack on page 28. It used to be that city planners would know how much water to anticipate in their reservoirs by measuring the snowpack at the top of the mountain. These days, one measurement isn't nearly enough to predict the runoff, leaving planners high and dry when all of the water anticipated doesn't appear. In "The Changing Climate's Snowball Effect," we look at the complex variables scientists and policymakers must start accounting for and how they work with communities that aren't always ready for change.

"Snowmelt is an incredibly important source of water in the western U.S., in terms of both human use and ecosystem services, but snowpack has decreased dramatically in the past several decades while the regional population has grown," said Enderlin. "It seems as though people are finally becoming more aware of the importance of snow, yet little action has been done to reduce the greenhouse gas emissions that are driving changes in snowpack and the timing of its melt."

Head to page 34 to read more about one industry that *is* gearing up for action. Winter ski enthusiasts are beginning to realize that climate change is coming for the sport they love, and the reckoning may be an example for us all. Just ask professional snowboarder Jeremy Jones, who founded Protect Our Winters, a nonprofit organization that recently led a campaign to oust the head of the International Ski Federation after he went on record as a climate change denier. In July, four of the biggest North American ski resorts signed on to a charter to enforce unity in climate advocacy and make real changes in their business operations—but they know they alone can't save winter. This advanced lesson in how to bring equivocators on to the boat is one we could all learn from.

Heather Goss, Editor in Chief

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SnowSchool Spans the States

Imagine young students bundling up in winter clothing, strapping on snowshoes, and trekking to a site with a thick snowpack where a volunteer instructor cuts out a refrigerator-sized block of snow. If the block stays intact, the instructor asks the students to jump on it until it fails, making them tumble into a flurry of snow. Together the teacher and students measure the density and dimensions of the snow block to calculate its weight, which can be nearly as heavy as a car. By experiencing this mini avalanche, the students might begin to fathom what a real one might feel like.

This snow stability test is among the many experiments that SnowSchool, a nationwide program run by the nonprofit Winter Wildlands Alliance, uses to seed K–12 students' interest in science and outdoor education. The curriculum integrates the local ecology for each of 81 active sites across the United States and uses snow as the medium to engage students, said Kerry McClay, SnowSchool's national director.

More than half of SnowSchool's students come from underserved populations, including numerous Title I schools—those with at least 40% enrollment from low-income families. "Every community where a SnowSchool site is located is different," McClay said. Some sites serve tribal communities on reservations. Another site ferries students from Oakland, Calif., to the Sierra Nevada, a rather lengthy trip that takes at least 3 hours.

Because SnowSchool is heavily subsidized by grants and fueled by donations, participation is often free, said McClay. The program provides gear, including snowshoes and winter clothing for students; resources and training for volunteers; and curricula for teachers. Interested schools simply need to apply and provide buses to transport students to their SnowSchool sites.

This fusion of fun science and snow "ignite[s] that sense of wonder and lets kids explore...with their curiosity in the driver's seat."

The more than 35,000 students in the program might explore how snowpack forms and melts, build igloos, or track wildlife, said McClay. A favorite activity of the students—many of whom have never seen the deep snowpack of the mountains—is sliding on their bellies through drifts. This fusion of fun science and snow "ignite[s] that sense of wonder and lets kids explore... with their curiosity in the driver's seat," said McClay.

Students and researchers perform measurements in a snow pit as part of a NASA SnowEx teaching and learning day in Grand Mesa, Colo. Credit: Kelly Elder

Snow Stratigraphy

An especially illuminating experiment, he said, begins with the classic children's activity of digging a hole in snow. The instructors and students begin by digging a trench through the snowpack, down to where the snow meets the ground, sometimes 6 feet deep (nearly 2 meters), said H.-P. Marshall, a snow scientist and professor at Boise State University who helps design materials and train volunteers for SnowSchool. "It's like looking at tree rings," he explained, except instead of years, each layer in the snow pit signifies a discrete weather event. The students learn to identify the previous night's soft snow, last week's snowstorm, and last month's ice crust left by a rainy day.

Then the students get macroscopes—like microscopes, but with a large viewing area—and they look at the changing snow crystals. "It's like a whole other universe," said Marshall.

Digging the trench serves as a window into ice core climate research, said Marshall, and lets instructors start discussions about how scientists study climate change. In the world of climate research, scientists drill many kilometers down, extracting deep ice cores that help researchers see what the climate was like and how it changed many hundreds or even thousands of years back.

Another SnowSchool project is a crowdsourced science initiative conducted in collaboration with NASA's SnowEx program. In this project, students from SnowSchool collect snow data on the ground that will ultimately help calibrate satellite data.

No Snow, No SnowSchool?

Near Boise, Idaho, the flagship SnowSchool site at the nonprofit Bogus Basin recreation area and ski resort beckons. At this location, students sometimes come from predominantly Latinx agricultural communities and typically have not spent much time in a snowy environment, said Marshall. By focusing on water availability, he viscerally links water to everyday life for students steeped in cultivating crops. Students learn the role snow plays in the water cycle, which gives them tools to talk about snow and water with their families. "Snow water resources," Marshall said, "are so impacted by climate change."

Researcher Kelsey Dean examines snow crystals with a macroscope while working in a snow pit in Fraser Experimental Forest in Colorado. Credit: Kelly Elder

With the uptick in extreme events, the snowpack atop mountains is more variable and melts faster, said McClay. "Eighty percent of our water is coming from melted snow." Students see trends with snow-sourced data and begin to consider the repercussions for water supply, irrigation, agriculture, or fires. "The list goes on."

Unfortunately, Marshall admitted, "people that live too far from the mountains can't really engage with this program." For these communities, "the SnowSchool organization put a lot of effort into videos and online material," in part as a response to travel restrictions imposed by the COVID-19 pandemic.

Marshall has found that even a cooler filled with snow excites kids.

In his visits to classrooms, Marshall has found that even a cooler filled with snow excites kids. "They want to have snowball fights, [or] see how long they can stick their hands in [it]," he said. McClay is hopeful that as SnowSchool expands, students everywhere can engage in the program—as long as there's access to snow.

"SnowSchool," said McClay, "is not as effective without snow."

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Brazil's Antarctic Station Rises from the Ashes

Brazil's new Comandante Ferraz Antarctic Station was designed by Estúdio 41. Credit: Eron Costin/Estúdio 41

On 15 January 2020, when Brazilian scientists, navy officers, and politicians celebrated the inauguration of the new Comandante Ferraz Antarctic Station in Antarctica, it was like closing a painful chapter in Brazil's history on the continent.

Almost 8 years earlier, in February 2012, the research facility was destroyed by a fire that claimed the lives of two navy lieutenants, Carlos Alberto Figueiredo and Roberto dos Santos. Located at Admiralty Bay on King George Island, the facility had been operational since 1984 and housed researchers working with PROANTAR (Programa Antártico Brasileiro, the Brazilian Antarctic Program). Caught by surprise by the fire, the country received the news with shock.

The following year, the Brazilian Institute of Architects and the Brazilian Navy organized a contest to choose the project for the building that would replace the incinerated station.

The project chosen from more than a hundred proposals from all over the world came from Estúdio 41, a Brazilian architectural office based in Curitiba, capital of the state of Paraná. "We put together a multidisciplinary team of about 15 experts in several areas, from wind resistance to geotechnics to thermal insulation, to help us think of how to respond to the harsh environmental conditions in Antarctica. As some of the competing offices had already constructed other research facilities in the continent, we knew winning would be a tough call. So getting it was really exciting," said architect Emerson Vidigal, a member of Estúdio 41's team.

The team spent 2 years—from 2013 to 2015—working on the project before China National Electronics Import & Export Corporation, a Chinese construction company, started building the station. "We spent a year on research, looking at similar buildings in Antarctica, and we were lucky to have been able to learn in detail from the Indian [Antarctic] research station Bharati. Talking to the engineers of Kaefer, the German construction company that put Bharati together, gave us a deeper understanding of what we were facing. Our partners from the Portuguese engineering office AfaConsult were also crucial in the process, as it was much more an engineering challenge than an architectural one," Vidigal added.

The new Comandante Ferraz station took almost 5 years to construct. Credit: Estúdio 41

Bigger and Better

At 4,500 square meters, the new research facility has almost twice the area of the old station and can house 64 people. The steel structure contains an exterior of polyurethane and an insulating interior of mineral wool. "Between the external and internal layers, there is a 60-centimeter buffer for temperature transition with air at 10°C on average, which helps save energy for heating," said Vidigal.

As the station's assembly had to be done during the austral summer, when ships can reach Admiralty Bay, logistics to transport construction machinery, workers, and preassembled structures had to be carefully planned. Almost 5 years and roughly $100 million later, the station was ready.

To glaciologist Jefferson Simões, a researcher at the Federal University of Rio Grande do Sul and vice-president of the international Scientific Committee on Antarctic Research, the investment has been worth the time and effort. "Snow and frozen soil would accumulate in front of doorsteps of the old structure, sometimes making it difficult to get in and out. It is very good that the new building is elevated from the soil so the wind can blow snow away underneath," he said.

Five of Comandante Ferraz's 17 planned laboratories (those focused on microbiology, molecular biology, chemistry, microscopy, and common use) are ready. These spaces are equipped with instruments that range from DNA readers to ultrafreezers and water purifiers.

"This station is a source of pride for Brazil and its science."

Wim Degrave, coordinator of FioAntar (a research project from the Oswaldo Cruz Foundation that looks for Antarctic pathogens that could threaten human, animal, and environmental health), was at the station in late 2019 to assemble the microbiology laboratory. For him, the new station will enable a significant upgrade for research.

"Usually, we had to process soil, water, plant, lichen, and other samples at a research vessel, freeze them, and wait until the ship was back in Rio de Janeiro many months later to start doing research. This isn't ideal, since some less stable microorganisms such as viruses can deteriorate. Now we'll be able to isolate and analyze fresh samples at the station. Not only the quality of research will be better, but it will also be possible to work the whole year in a continuum between sampling and analysis, gaining a lot of time," he explained.

Even research groups who will not work directly at Comandante Ferraz will benefit from it. "This station is a source of pride for Brazil and its science," said paleontologist Alexander Kellner, coordinator of Brazil's PaleoAntar project, which conducts paleontological research in Antarctica. Kellner's team often goes to James Ross Island, southeast of the Antarctic Peninsula, to look for frozen fossils. "An icebreaker would be a great addition to the new station," he added. "We would be able to do research in the whole continent."

A Strategic Place

One aspect on which most researchers agree is that a research station in Antarctica is strategic in geopolitical and scientific terms. "Only the countries that are doing research down there will have a say in the future of the continent," Simões emphasized.

"But a lot of it will depend on funding for research projects, which are quite scarce in Brazil now," he added.

To him, research in the Antarctic is far from being a luxury. Many projects focus on climate change, air pollution, the carbon cycle, and myriad other studies that directly affect life on Earth, as well as policy. For instance, Simões said, "by looking at some ice cores a few years back, we could clearly detect uranium pollution from mining in Australia in recent decades, as well as arsenic due to copper mining in Chile."

Simões said Brazil's research planning in Antarctica is being restructured. As all projects were halted during the pandemic, scientists are seeking resources that stretch beyond 2022. "We don't have a perspective for funding after that yet. The research station cannot become a white elephant. If the government granted us just a million dollars a year, we'd be able to perform miracles," Simões said.

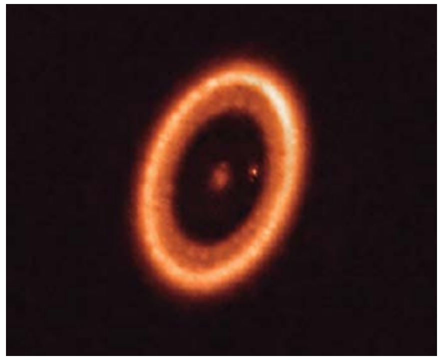
"A small fraction of the billion-dollar fund the congress is trying to approve to finance political campaigns (the electoral fund) would do a great good for Brazilian research," Kellner added.

By **Meghie Rodrigues** (@meghier), Science Writer

Where Moons Are Made

In 2019, a team of astronomers caught the first hints of a young exoplanet surrounded by the stuff needed to form satellites. Those hints now have been confirmed by high-resolution images that capture light from a potentially moon-forming swirl of dust that surrounds that planet.

The young planetary system, PDS 70, "is the first system where two growing planets, at least one with a circumplanetary disk, have been observed directly," said Stefano Facchini, an astronomer at the European Southern Observatory and a coauthor of the recent discovery. Two exoplanets have been identified in the PDS 70 system. "The circumplanetary disk around PDS 70 c today is the perfect environment to study the conditions of satellite formation."



The planet-forming disk in the PDS 70 system (bright outer ring) is home to the young planet PDS 70 c (bright dot to the right of center), which itself hosts a smaller disk that may be forming satellites. Credit: ALMA (ESO/NAOJ/NRAO)/Benisty et al., CC BY 4.0 (bit.ly/ccby4-0)

The Testing Grounds

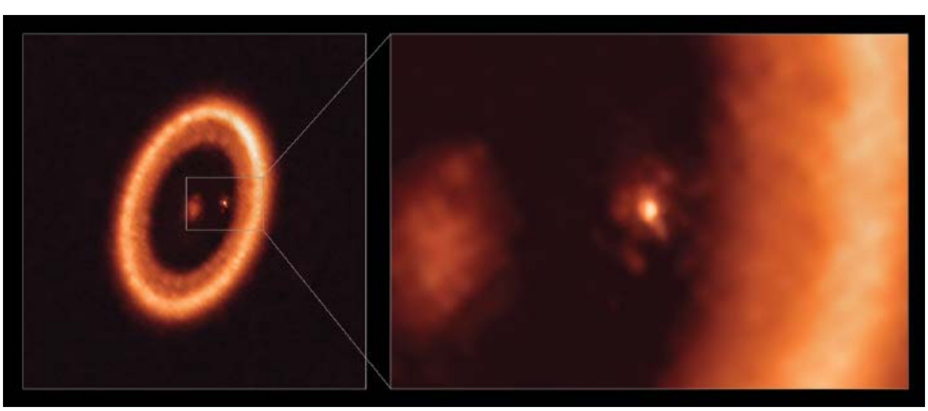
It takes millions of years to form a planetary system from an interstellar cloud of gas and dust. Gravitational instabilities in a cloud will cause it to slowly collapse onto itself until the temperature at the center is hot enough to ignite a protostar. Most of the remaining material falls onto the star, and the remainder flattens out into a disk (called a circum*stellar* disk) that might, after millions more years, form planets.

This same process is thought to repeat itself on a smaller scale when planets try to form their own moons (instead of capturing them): After a young planet accumulates enough mass to carve out gaps in the circumstellar disk, dust and gas still surround the growing planet and can flatten out into a smaller disk around it. That circum*planetary* disk can then coalesce into one or more satellites. The four Galilean moons of Jupiter are thought to have formed in this way, but the only way to prove that this mechanism forms moons is to catch it in the act.

Enter PDS 70, a star merely 5.4 million years old that is still surrounded by a circumstellar disk. Two gas giant planets that are still accumulating mass have so far been detected as they carve gaps and shape rings within the circumstellar disk.

Upon a closer look at the outer planet PDS 70 c, which is a few times Jupiter's mass and orbits its protostar slightly farther than Neptune does from the Sun, astronomers detected a faint, fuzzy emission haloing it. They tentatively identified that fuzz as a circumplanetary disk. "The planet has already acquired most of its mass during its past evolution," Facchini explained. "As for the moons, theoretical models show that satellite formation is possible precisely when the accretion rate onto the planet is low, of the order of what we are observing today."

After that first identification 2 years ago, the team pushed to observe this still-forming planet and the satellites it could be growing. With the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile, the team was able to capture high-resolution images of the entire PDS 70 system at wavelengths favored by planet-forming dust. When combined with previous observations, the images revealed that the dust surrounding PDS 70 c extends one Earth-to-Sun separation (1 astronomical unit) from the planet. "Today the circumplanetary disk has a dust mass that is at least three Moon masses," Facchini said, "but during the remaining lifetime much more dust mass can be acquired by the system," maybe as much as an Earth mass of material. The team published this discovery in *Astrophysical Journal Letters* (bit.ly/PDS-70-c).



The outer of the two young planets in the PDS 70 system (left) is surrounded by a cloud of dust (right) that spans the distance separating the Sun and Earth and is a likely site for exomoon formation. The disk itself is entirely contained within the brightest spot of the image; the fuzzy edges around the planet are noise from the instrument. Credit: ALMA (ESO/NAOJ/NRAO)/Benisty et al., CC BY 4.0 (bit.ly/ccby4-0)

Up Next: What Moons Are Made Of

"Our work presents a clear detection of a disc in which satellites could be forming," lead author Myriam Benisty of the University of Grenoble in France and the University of Chile said in a statement. "Our ALMA observations were obtained at such exquisite resolution that we could clearly identify that the disc is associated with the planet and we are able to constrain its size for the first time."

So far, the team has been able to measure the dust component of the circumstellar and circumplanetary disks. However, there might be 100 or 1,000 times more gas than dust in the disk that hasn't yet been mapped. The team is currently using ALMA to study how that gas moves throughout the system, Facchini said. With ALMA and also future observatories, the researchers hope to determine the chemical composition of the material that is forming the atmospheres of PDS 70 c, the inner planet PDS 70 b, and any moons that may be growing around them.

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

Eddy Killing in the Ocean

Eddies encourage the ocean's absorption of carbon dioxide from the atmosphere and help regulate Earth's climate. Now scientists have more details about how these ephemeral ocean features die.

Eddies are circular currents that wander around the ocean like spinning tops, ranging from tens to hundreds of kilometers in diameter. They mimic weather systems in the atmosphere and serve as feeding grounds for sharks, turtles, and fish. Eddies often spin off major ocean currents and typically die within a matter of months.

Some fundamental questions in physical oceanography center around the life cycle of eddies: What gives rise to them, and how do they die? "It's a big puzzle that's been long-standing in the community," said fluid dynamicist Hussein Aluie from the University of Rochester in New York.

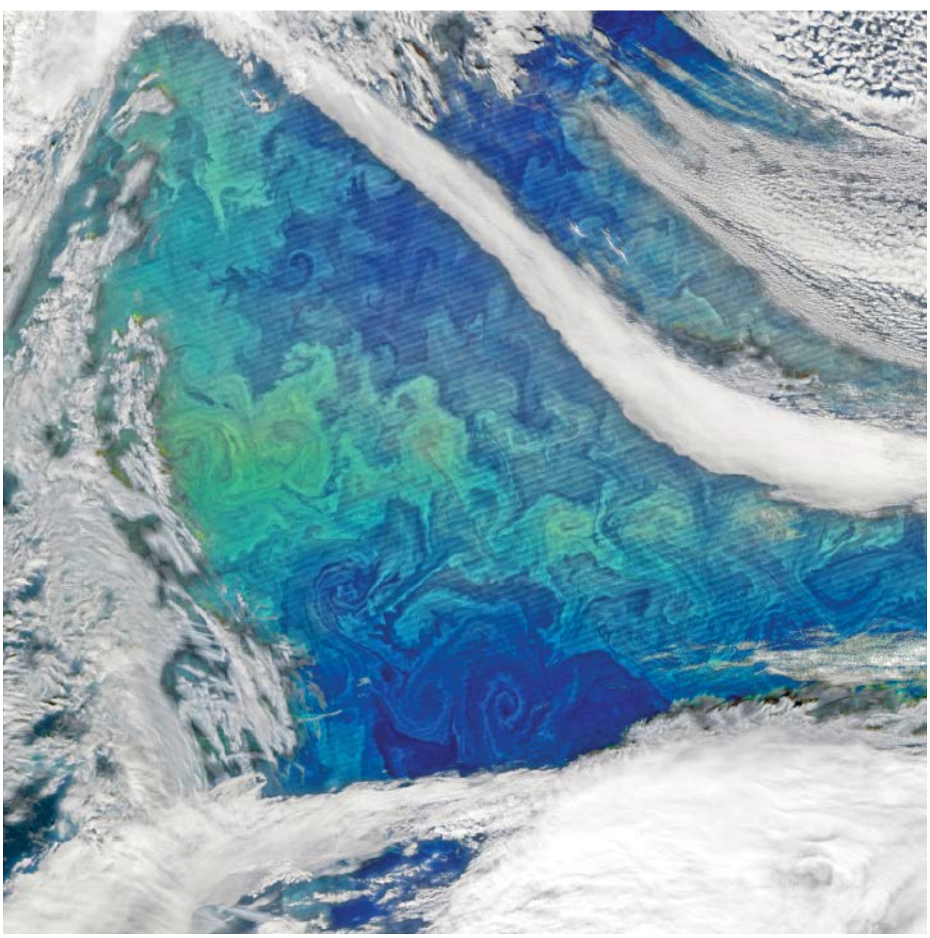
Aluie and his colleagues found that when it comes to eddy killing, the planet's winds are partly to blame.

Their innovative analysis of satellite data suggested that wind sucks energy out of the ocean from features smaller than 260 kilometers—features that include most eddies. Wind continually extracts about 50 gigawatts of energy from eddies around the world. The scientists published their research in *Science Advances* (bit.ly/eddy-killing).

"Fifty gigawatts is equivalent to detonating a Hiroshima nuclear bomb every 20 minutes, year-round," said lead author Shikhar Rai, a doctoral student at the University of Rochester. "It is equivalent to operating 50 million microwave ovens continuously throughout the year."

Although it's long been suspected that wind zaps eddies of their spin, the latest study provides a seasonal signal and an estimate of wind power loss in major currents. Although wind may be a killer of eddies, it supercharges larger-scale ocean circulation. Wind adds about 970 gigawatts of energy to features larger than 260 kilometers, the recent research found.

Eddies boost ocean heat intake, ocean mixing at the surface, and the exchange of gases with the atmosphere, so calculating these processes relies on accurate depictions of eddies in computer models.



Phytoplankton blooming in the North Atlantic Ocean reveal the complex stirring from ocean eddies and currents. Credit: Norman Kuring/VIIRS/NASA

Blowing in the Wind

Eddies likely form from interconnected physical forces in the ocean that include density-driven motion from water of different temperatures or salinities.

Wind destroys ocean eddies by applying stress to the ocean's surface and slowing eddies' spin to the point of extinguishing them. Because wind stress hinges on the difference between the speed and direction of wind compared with the speed and direction of the ocean's surface flow, wind categorically slows eddies rather than quickening them.

Eddy killing happens year-round, but the effects are particularly strong in winter, when winds grow stronger because of storms, according to the new study.

Most eddies come from western boundary currents like the Gulf Stream in the Atlantic and the Kuroshio in the Pacific, and the latest results revealed just how much energy relative to the total input wind removes from these currents' eddies: 50% from the Gulf Stream and a whopping 90% from the Kuroshio.

"The movement of the ocean is critical in regulating the climate of the Earth," Aluie said. Eddies can affect the trajectories of major currents: For example, eddies are widely believed to play a crucial role in causing the warm waters of the Gulf Stream to curve away from the eastern United States, keeping the climate of Canada, Greenland, and the Labrador Sea cold.

The research adds to the building evidence that wind stifles eddies. Chris Hughes, a professor of sea level science at the University of Liverpool and author of a 2008 study that found that wind sucked 60 gigawatts of energy from the ocean, said, "It's nice to see this confirmed independently and some new diagnostics shown."

A Blurred Photograph

The research team used an emerging method in physical oceanography to conduct the new work. Typically, researchers study how the ocean changes over time. But in the latest analysis, the scientists looked at differences over space, not time.

The latest study "represents a novel application of the newly developed coarse-grain method," said physical oceanographer Xiaoming Zhai of the University of East Anglia, who was not involved in the research.

Coarse-graining analysis can be explained with a simple example, said Aluie. Imagine a flower in a photograph. If you blur the photograph, you can't see the texture of the flower's petals, the grains of pollen on its anthers, or the edges of the sepals. If you now take the unblurred photo and subtract the blurry one from it, you get only the fine details of the flower.

The new study used measurements taken between 1999 and 2007 from NASA's QuikSCAT satellite scatterometer. By "blurring" the satellite information, Rai and his colleagues used coarse-graining analysis to see the details of small-scale ocean flow, which included eddies. The method allowed them to pinpoint the 260-kilometer cutoff.

Coarse-graining analysis subtracts a blurred version of data (right) from a precise version (left). Credit: Paul Green/Unsplash

Sadly, QuikSCAT died in 2009, but an upcoming NASA mission, Surface Water and Ocean Topography (SWOT), along with wind data from other satellite missions could soon provide Rai and others with higher-quality data.

The team will continue to use spatial techniques like coarse-grain analysis in future work, which will include a look into the other side of an eddy's life cycle: its birth.

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Testing on the Tundra: NASA Snow Program Heads North

Mary Szatkowski, a graduate student at the University of Alaska Fairbanks, takes notes for snow water equivalent calculations in Arctic Alaska. Credit: Svetlana Stuefer

Seasonal snowpack covers 46 million square kilometers annually—31% of the land area on Earth—but that number is shrinking. Snowpack is accumulating later, melting earlier, and retreating at an even faster rate than Arctic sea ice. This reduction in snowpack has implications for water locally and climate globally.

"Snow is an enormous regulator of heat on Earth because of its high reflectivity," said Matthew Sturm, group leader of the Snow, Ice and Permafrost Group at the University of Alaska Fairbanks Geophysical Institute. "The Earth gets rid of enormous amounts of heat by painting itself white in the winter, and that's going away."

Just how substantial will changes brought by shrinking snowpack be? SnowEx, a multiyear NASA research program, hopes to find out. SnowEx has tested sensors in western states since 2017; this winter the research continues in Alaska, a state with applicable infrastructure, experience, and plenty of snow.

A Satellite for Snow

Every 10 years, an independent panel assesses NASA's satellite fleet and recommends research areas that are currently unmet. The 2017 decadal survey suggested snow (and, specifically, snow water equivalent) as a possible mission focus for NASA's Explorer program.

"[Snow water equivalent] is a critical component of hydrologic cycling and the Earth's energy balance, but it's really difficult to measure," said Carrie Vuyovich, project scientist for SnowEx Alaska and a research physical scientist at NASA's Goddard Space Flight Center. Field observations provide valuable data, but only in limited areas. "It means a huge amount of landscape is missing information," she said. "Satellites are really the ideal observers to cover that amount of area."

"The Earth gets rid of enormous amounts of heat by painting itself white in the winter, and that's going away."

(left) Matthew Sturm, who specializes in tundra research, probes for snow depth using a GPS-enabled automatic depth probe. (right) Charlie Parr, a research technician at the University of Alaska Fairbanks, measures the density of layers of snow. Credit: Matthew Sturm

To prepare for a potential satellite mission, SnowEx scientists are developing and refining aircraft-mounted sensors adaptable across a range of conditions. There's no guarantee of a satellite launch—"It's a competitive process," said Vuyovich—but the snow science community can prepare for the potential opportunity by testing sensors calibrated to the temporal and spatial intricacies of snow.

Tundra Crust and Taiga Woods

A snow-focused satellite should work in all regions, from deep mountain powder to dense

A knife provides scale for sastrugi, snow ridges shaped by wind, in the Imnavait area of northern Alaska where the SnowEx tundra research will take place. Credit: Matthew Sturm

tundra crust. Sensors must also react to complicated conditions: wet snow, deep snow, snow covered by trees. SnowEx's mobility allows it to refine algorithms and accuracy in various conditions, and Alaska is essential for testing those abilities.

"The large fraction of global snowpack is here at higher latitudes," said Svetlana Stuefer, an associate professor of civil and environmental engineering at the University of Alaska Fairbanks. As deputy project scientist for SnowEx Alaska, Stuefer is helping coordinate the campaign and identifying locations that represent the world's two largest snow biomes: Arctic tundra and boreal forest, also called taiga.

"Tundra and taiga take up a lot of room, but they pose two different problems," said Sturm, a senior adviser to SnowEx Alaska.

Tundra snow is shallow, stratified, and often located on permafrost. Remote sensors must recognize and respond to those conditions. Taiga is more complex. "Sorting out what's on the ground and what's on the trees is very difficult," said Sturm. Snow suspended from tree branches reflects light (which is good for climate control) but may sublimate into the atmosphere without contributing to groundwater. A snow-focused satellite would need sensors attuned to both climate and water issues.

"I'm excited to see where [SnowEx] goes. They have a lot of challenges ahead of them, but I think it can be an important tool," said Daniel Fisher, a senior hydrologist with the U.S. Department of Agriculture's Alaska Snow Survey who was not involved in the project. "I don't think [remote sensing] will ever be a silver bullet, but I do think it will play an important role in understanding and measuring the snowpack across the state," he said.

Fixing the Data Drought

SnowEx scientists plan to fly lidar and stereophotogrammetry sensors in Alaska this winter. Another aircraft will carry the Snow Water Equivalent Synthetic Aperture Radar and Radiometer (SWESARR), a specialty SnowEx instrument developed at Goddard to calculate snow water equivalent (SWE) using active and passive microwaves. Field staff will measure snow conditions on the ground to compare observations.

Better snow data could benefit a range of interests, from road crews to flood forecasters to subsistence trappers. Increased SWE data would particularly help water managers; one in six people relies on seasonal snowpack for drinking water.

Then there are the recreationalists, like backcountry skiers, who scan avalanche reports while brewing their morning coffee.

"Right now, operationally, we are extremely reliant on point-based observations," said Andrew Schauer, a lead forecaster for the

"The large fraction of global snowpack is here at higher latitudes."

Chugach National Forest Avalanche Information Center who was not involved in SnowEx. Avalanche centers are challenged by a lack of data, he said, but aerial observations could fill that gap if updated quickly. "I'm excited to see what becomes of the SnowEx program," he said.

By preparing sensors for all winter conditions, SnowEx scientists hope to be ready should NASA ask for a mission proposal. Research in Alaska is an important step to reaching that goal.

"[SnowEx Alaska] positions us to be competitive," said Sturm. "I don't think there's any question that a satellite for snow would help humanity."

By **J. Besl** (@J_Besl), Science Writer

The Who, What, When, Where, and Why of the Polar Vortex

The polar vortex is a media darling. Headlines frequently announce that it's coming, collapsing, or splitting, and articles often tout its role in record-setting winter storms. But misconceptions about this atmospheric phenomenon abound, and scientists are still untangling its effects on our weather. Here's a rundown of what the polar vortex really is.

Changes in the stratospheric polar vortex can trigger record-breaking weather. Credit: iStock.com/DenisTangneyJr

Swirling Air in the Stratosphere and Troposphere

First off, a definition: The term, a shortening of circumpolar vortex, typically refers to a swirling mass of air at far northern or southern latitudes. "It's a region of high wind speed that encircles the pole," said Jacob Shultis, an atmospheric scientist at Johns Hopkins University in Baltimore.

There's a polar vortex in the planet's stratosphere, and that's the one that usually makes the news. But there's also a similar structure lower in the atmosphere: the tropospheric polar vortex. Also known as the jet stream, the tropospheric polar vortex functions to corral cold air near the pole. Like its higher-altitude cousin, the tropospheric polar vortex is a region of westerly (west to east) flowing winds. However, it's significantly larger—it can extend antipoleward to latitudes of roughly 40°–50°. (Its winds explain why eastbound flights across the United States take less time than westbound flights.)

These two polar vortices appear at different times of the year: The stratospheric polar vortex develops in the fall and dissipates in the spring, whereas the tropospheric polar vortex is a year-round phenomenon. When these vortices do happen to overlap temporally, they're still separated by kilometers of vertical airspace, however. "More often than not, they're kind of doing their own thing," said Laura Ciasto, a meteorologist at NOAA's Climate Prediction Center in College Park, Md.

The Flow Breaks Up

That sometimes changes, however. Undulations in Earth's atmosphere caused by temperature gradients—known as Rossby waves—can travel from the troposphere to the stratosphere, where they can disrupt the stratospheric polar vortex and cause its westerly winds to weaken. When that happens, the stratospheric polar vortex stops being a circular flow centered on the pole and instead becomes more wavy, said Ciasto. "You tend to see more north-south flow rather than just west-east."

"It can split apart into two separate vortices."

These events, which are known as sudden stratospheric warmings, can have extreme effects on the stratospheric polar vortex, said Zachary Lawrence, an atmospheric physicist at the University of Colorado Boulder. "It can split apart into two separate vortices. It can be pushed very far off the pole."

These variations in the stratospheric polar vortex can have far-reaching effects, beyond the upper atmosphere—they can affect the weather that we experience on the planet's surface. That's because sudden stratospheric warmings can cause the tropospheric polar vortex to expand equatorward, sending blasts of cold air to lower latitudes. That's likely what happened in February of this year, when a record-setting ice storm pummeled wide swaths of North America.

Using satellite data, it's possible to detect sudden stratospheric warmings, which occur about once or so every year. But it's impossible to know how the tropospheric polar vortex will respond and what regions might be subject to a cold snap, said Ciasto. "Even though there might be a sudden stratospheric warming, that doesn't necessarily mean that the United States is going to feel the impact."

Environmental and Climatic Links

Environmental conditions can also affect the behavior of the stratospheric polar vortex. For instance, recent decreases in Arctic sea ice cover—triggered by climate change—have been linked to a more unstable stratospheric polar vortex.

Climatic phenomena can play a role, too. For instance, El Niño conditions—warmer-than-average surface waters in the Pacific and weaker-than-normal easterly trade winds—boost the probability of sudden stratospheric warmings. That's because they can drive the formation of destabilizing Rossby waves, said Lawrence. "El Niño events affect the generation of waves in the troposphere."

Peering at Other Worlds

Polar vortices aren't unique to Earth. Venus, Mars, and several of the gas-dominated bodies in the outer solar system all have them, too. Shultis and his colleagues are studying the polar vortex on Titan, Saturn's largest moon, using data collected by the Cassini spacecraft.

"Any planet that has a substantial atmosphere could possibly have one."

Shultis and his collaborators run computer models based on Cassini data to better understand the structure of Titan's polar vortex. Modeling is important, because the observations—amassed over 13 years while Cassini was orbiting Saturn—don't extend over a full Saturnian year, said Shultis. That makes it difficult to trace the seasonal evolution of Titan's polar vortex, he said. "We're really interested in looking at how it evolves over time."

So far, the researchers have found hints that Titan's polar vortex weakens in the middle of winter. That's very unlike the behavior of Earth's stratospheric polar vortex and a big surprise, said Shultis. Titan's global circulation patterns might be at play, the researchers hypothesized: Air is known to descend over the pole that's experiencing winter, and that movement compresses the air, warming it. That warming, in turn, decreases the local temperature gradient that powers the polar vortex, Shultis and his collaborators suggested.

Polar vortices likely exist on other unstudied worlds, too. "Any planet that has a substantial atmosphere could possibly have one," said Shultis. New instruments will extend our ability to study celestial bodies farther out in the solar system—and possibly beyond—but Earth's polar vortices will likely always be around for a close-up look. They've persisted for billions of years, and they show no signs of relinquishing the spotlight anytime soon.

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

In a Twist, a Greek Volcano Ruled by the Sea

A clay statue of a sphinx perches above the flooded caldera of the Santorini volcano in Greece. Credit: iStock.com/ProjectB

For thousands of years, the Greek volcano Santorini has blasted, bubbled, and burned in the Aegean Sea. Now scientists suspect that the volcano's fiery bursts are the cause of rising and falling sea levels. The findings reveal a novel connection between the planet's molten innards and its climate.

During the past 360,000 years, the volcano, officially known as Thira and historically as Thera, has erupted more than 200 times.

Sea levels retreat when the planet grows large ice sheets and glaciers; ice ages have much lower sea levels than interglacial periods.

Researchers from the United Kingdom and Sweden found that these lower sea levels tend to disrupt Santorini's volcanic slumber. During the past 360,000 years, the volcano, officially known as Thira and historically as Thera, has erupted more than 200 times. All but three of those eruptions happened during or just following periods of low sea levels.

Because most volcanoes on Earth sit within or near oceans, Santorini's tale could apply to other volcanoes around the world.

Santorini's Cliffs

Santorini has had a violent past—explosive eruptions have shattered the volcano into slivers of islands.

The most recent explosive eruption, in the 1600s BCE, sent 100 cubic kilometers of material into the air, 4 times that of the 1883 eruption of Krakatoa. The volcano's caldera collapsed into the sea and flooded, leaving an 11-kilometer-wide crater. (The cataclysm may have inspired Plato's story of Atlantis, too.)

Over the past 50 years, geologists discovered mounting evidence that the comings and goings of ice sheets revved up volcanoes in

Iceland, the western United States, France, Germany, and Chile. The ice sheets bore down on Earth's crust, but when they melted away, the crust decompressed and fractured. Magma shot up into the cracks and fueled eruptions.

Sea level, the new paper argues, has the same effect on Earth's crust. "The only thing that's different is in one case you have ice, and in the other case you have water," said Earth scientist Chris Satow from Oxford Brookes University, who led the research.

But finding evidence of sea level's effect on volcanoes has been much harder—until now. A quirk of Santorini's landscape gave scientists a unique chance to connect the pieces.

Millions of tourists flock annually to the volcano's cliffs overlooking the turquoise bay annually, and Satow and his team did the same—but to sample layers of volcanic ash. Eruptions leave unique chemical fingerprints of iron, silica, potassium, sodium, and other elements buried in ash layers. "Not many other volcanoes have this amazing record on display for us to see and investigate," said Satow.

The researchers measured the chemical fingerprints of each ash layer and matched them with layers in marine sediments. Crucially, the marine sediments also contained records of sea level rise and fall over time.

Satow and eight others published the research in the journal *Nature Geoscience* (bit.ly/Santorini-activity).

The cliffs on Santorini reveal layers of whitish ash deposits from past volcanic eruptions. The largest white layer in the middle distance is from Santorini's Vourvoulos eruption 126,000 years ago. Credit: Ralf Gertisser/Keele University

Stifled by the Sea

The results could explain recent behavior at Santorini. The volcano threatened to erupt as recently as 2011–2012 when new magma flooded the volcano's shallow magma chamber. "The fact that an eruption did not happen may be due to the sea levels being high," Satow said.

Santorini is a collection of five islands about 200 kilometers southeast of the Greek mainland. Credit: NASA/GSFC/METI/ERSDAC/JAROS

But major eruptions can still happen; Santorini is one of the world's Decade Volcanoes, sites identified in light of their history of large, destructive eruptions and proximity to densely populated areas. "The large volumes of magma involved [in explosive eruptions] could by themselves create the required fractures in the crust, even without the help of low sea levels," Satow said. The massive event that took place in the 1600s BCE, nicknamed the Minoan eruption after the region's distinct Bronze Age civilization, was one of three eruptions that blew during periods of high sea levels.

Climate change is melting ice sheets and boosting sea levels, but it's too early to know how that could affect volcanic activity. A study on the volcanic Caribbean island of Montserrat, for instance, proposed that rapid sea level rise could amp up volcanic activity, an affect opposite that seen at Santorini.

"We need more of these detailed and comprehensive studies to get a complete picture," said Julie Belo, a scientist at the GEOMAR Helmholtz Centre for Ocean Research Kiel who did not participate in the work.

Next, Satow hopes to investigate greenhouse gas emissions from volcanoes. "It would be really interesting to know if the amount of carbon dioxide that volcanoes worldwide produce is also related to sea level change," he said.

"The large volumes of magma involved [in explosive eruptions] could by themselves create the required fractures in the crust, even without the help of low sea levels."

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Desert Life Conjures Organic Carbon from Thin Air

Photosynthesis is thirsty work—it requires just as much water as it does carbon dioxide, and in deserts, it can all but shut down. Without the organic carbon photosynthesis provides, life in arid climes must either compete for scraps blown in from afar or wait for rain. But despite the twofold challenge of drought and starvation, microbes in many desert soils somehow manage not only to survive but also to flourish.

"The enigma has always been, Why are deserts diverse?" said Sean Bay, a microbial ecologist at Monash University in Melbourne, Australia. "Why do we see so many rich microbial communities?"

Bay and his colleagues may have found an answer in the hyperarid soils of Israel's Negev Desert, where microbes are pulling off a metabolic magic trick. By "burning" traces of hydrogen gas scavenged from the air, they can scrape together enough energy to survive dry spells—and some can even use hydrogen to fuel carbon fixation. The researchers announced their findings in the *ISME Journal: Multidisciplinary Journal of Microbial Ecology* (bit.ly/desert-bacteria).

The Negev Desert is a natural experiment in how microbes adapt to aridity. "Over a relatively short spatial scale—[the farthest sampled] soils were approximately 160 kilometers apart—you have distinct climatic zones," said Bay. Driving south from the Judean Hills, the landscape of green chaparral gives way to dramatic swaths of chalky brown and tan. The researchers gathered 72 soil samples along this natural climatic gradient for analysis in their Melbourne lab, where they hoped to discover genetic or chemical clues explaining the unexpected diversity of microbial communities in arid environments.

Researchers tested the hyperarid soils of Israel's Negev Desert and learned how some hardy microbes scrape together enough energy to survive dry spells—and use hydrogen to fuel carbon fixation. Credit: Sean Bay

Desert Microbes Run on Hydrogen Fuel

Specifically, Bay and his colleagues wanted to find out how the Negev Desert microbes might be using hydrogen for survival.

"In these large swaths of arid ecosystems, trace gas metabolism is likely a really important part of microbial metabolism," explained Laura Meredith, an environmental scientist at the University of Arizona who was not involved in the new research. Trace gases like hydrogen and methane are naturally present in the air, together accounting for about 0.1% of atmospheric gases. Some microbes have specialized enzymes that can capture trace gases and exploit them for energy when there are few other resources available.

Previous studies showed that microbes can use hydrogen to run their life-support systems while waiting for favorable conditions in a kind of stasis, or dormancy. And Bay suspected that hydrogen might be fueling carbon fixation in deserts, too.

"Something seemed off about the accepted model," he said. "These [photosynthesizing] communities of cyanobacteria—which are in really, really low abundance in these soils—are providing enough energy, or organic carbon?"

Bay's bet on hydrogen appears to have been justified. He and his colleagues discovered that genes associated with hydrogen metabolism were widespread across the samples and enriched in samples from drier soils. Microbes inhabiting the driest soils consumed hydrogen 143 times faster than those in samples collected from the greener Judean Hills. The research team even found evidence that soil microbes from across the climatic gradient will "burn" hydrogen to power carbon fixation as a supplement to photosynthesis when provided with a bit of water.

"It's like adding another ecological player, another strategy," said Meredith.

Implications for the Carbon Cycle

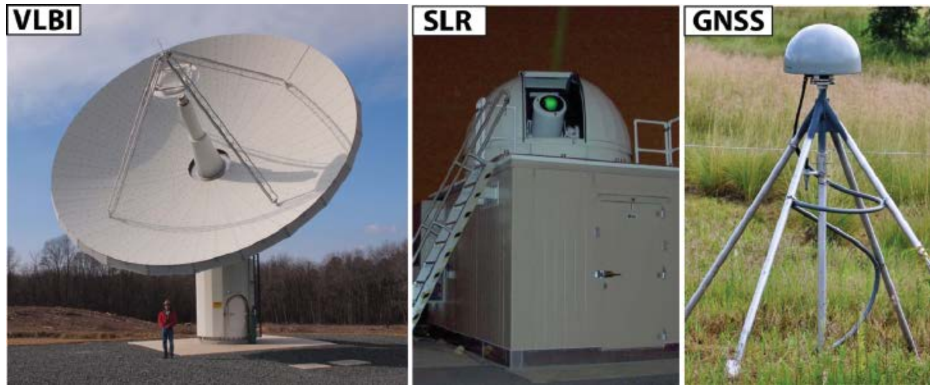
Bay saw the results as evidence that trace gas metabolism is far more widespread than previously thought—not a niche process used by a handful of exotic bacteria, but something that takes place across entire ecosystems. And according to Meredith, microbes that use trace gases like hydrogen to maintain and create new biomass could also be tinkering with Earth's carbon cycle.

"Carbon cycling in arid ecosystems, we know, is a leading contributor to overall carbon cycle variability at a global scale," she said, "so anything that's contributing to carbon fixation or carbon stabilization in the massive swaths of arid lands around the world is also important."

Bay agreed. "I think that's a really exciting part of this research...it's not just about discovering curious new ecosystems or curious new processes. There are actually really important implications."

By **Elise Cutts** (@elisecutts), Science Writer

Evolving the Geodetic Infrastructure



The three main measurement systems of the geodetic infrastructure are very long baseline interferometry (VLBI, which provides information on Earth orientation and scale), satellite laser ranging (SLR, which provides information about Earth's center of mass and scale and a backup for orbit determination), and the Global Navigation Satellite System (GNSS, which allows tens of thousands of GNSS receivers on spacecraft, aircraft, ships, and buoys and in local geodetic arrays to access or connect to the International Terrestrial Reference Frame). Credit: NASEM

The shape and position of Earth are constantly changing. Geodesy is the branch of geophysics that studies these properties, which are crucial for answering important Earth and space science questions: How will sea levels rise in the coming decade? What are the precise orbits of satellites? What are the patterns in a volcano's magma migration? How is elevation determined? Pursuing these questions requires maintenance and improvement of the geodetic infrastructure—the instruments, software, and expertise that provide precise measurements.

"It's like a freeway system or something—it's really fundamental," said David Sandwell, a marine geophysicist at Scripps Institution of Oceanography in San Diego. Sandwell chaired the committee behind a report addressing geodetic infrastructure (bit.ly/geodetic-infrastructure), released in 2020 by the National Academies of Sciences, Engineering, and Medicine (NASEM). The report provides recommendations to ensure that researchers will be able to continue using geodetic approaches to tackle diverse Earth science questions, from sea level changes to weather models to geological hazards. These research areas were highlighted in an earlier decadal survey funded by NASA, NOAA, and the U.S. Geological Survey (USGS).

Terrestrial Reference Frame

The primary need for the geodetic infrastructure is to define a terrestrial reference frame, a set of 3D coordinates organized around Earth's center of mass. The more correct this reference frame is, the more accurate and stable satellite orbits are. This accuracy provides scientists with better data sets.

The terrestrial reference frame relies on four techniques. Very long baseline interferometry (VLBI) measures radio signals from distant quasars to measure Earth's orientation in space and scale. Satellite laser ranging (SLR) relies on short pulses sent to satellites; the return times can be used to trace satellite orbits and calculate Earth's center of mass and scale. The Global Navigation Satellite System (GNSS), which includes GPS, and the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system provide additional global measurements. Raw data from these systems are combined and analyzed to produce the International Terrestrial Reference Frame (ITRF). The ITRF is a group effort, the report describes: "All parties involved work in an open international collaborative environment to provide the most accurate reference frame for science and applications."

The report recommends the deployment of more VLBI and SLR stations and the establishment of more receivers that can interface multiple GNSS systems. Such improvements would provide more coverage and improve the accuracy and stability of the terrestrial reference frame.

Geodetic infrastructure like this is critical for determining the precise orbits of satellites described in the decadal survey, said Shin-Chan Han, a geodesist at the University of Newcastle in Australia. "Such precise orbit is mandatory to achieve all the identified important science problems," he said. Han reviewed the NASEM report but wasn't directly involved in its preparation.

Monitoring Land Subsidence

Geodetic infrastructure is also crucial in hydrology. GPS and interferometric synthetic aperture radar (InSAR), a satellite-based technique for measuring land deformation, have transformed how scientists study land elevation changes due to groundwater removal and recharge.

"I just can't imagine waking up one morning and saying, 'oh, the GPS constellation isn't working anymore,'" said Michelle Sneed, a USGS hydrologist who was part of the committee that authored the NASEM report. One area that Sneed monitors is the San Joaquin Valley, an agriculture region in central California that has changed dramatically because of groundwater pumping for irrigation. From 1925 to 1977, the land surface in this area subsided about 9 meters because of compaction. Sneed and colleagues used continuous GPS and InSAR to assess land subsidence in the west central San Joaquin Valley and explored potential risks to the California Aqueduct.

The techniques also indicated that Coachella Valley has stabilized, likely because of projects that increased recharge and reduced reliance on groundwater. "The integration of these different geodetic techniques...adds different pieces to the stories," Sneed said. "InSAR is this great spatial tool. But if you want a daily value of the land surface at any one point, then you need continuous GPS."

Additional Infrastructure

Maintaining geodetic infrastructure faces significant challenges, the NASEM report notes. Making the software for processing raw geodetic data widely available is one such challenge, and compensating for an aging workforce is another. "I'm concerned about a shortage [in the] geodesy workforce," Han said.

Maintenance and enhancement of geodetic infrastructure will be crucial for addressing the Earth science questions outlined in the decadal survey. As described in the report, "the international geodetic infrastructure is the largely invisible foundation of Earth system science and applications."

By **Jack Lee** (@jackjlee), Science Writer

Soil Saturation Dictates Africa's Flood Severity

Huts are submerged in the Barotse floodplain in Zambia. Credit: iStock.com/Gerrit Rautenbach

In the summer of 2020, deadly floods ravaged Africa, affecting nearly a million people and killing hundreds. However, the physical causes of floods across the continent's diverse climate and terrain are gravely understudied. Lacking a broad network of water gauges, researchers have focused primarily on specific countries or single bodies of water. "The large extension of ungauged areas [has prevented] significant studies [from being conducted both] quantitatively and qualitatively," said Mohamed El Mehdi Saidi of Cadi Ayyad University in Morocco.

That now has changed, thanks to a 2-year project by an international team to curate the most complete hydrological data set for the African continent to date. This massive compilation combines on-the-ground and remote sensing measurements covering nearly 1,500 stream gauges and more than 11,000 flood events spanning at least 3 decades. The team's analysis, the first continent-wide study of flood drivers in Africa, suggested that the largest yearly floods are more strongly linked to regions' annual peaks in soil moisture than to annual peaks in precipitation. The findings, the first of their kind, were published in *Water Resources Research* (bit.ly/Africa-flood).

An 11,000-Piece Puzzle

Other research teams have conducted several continent-wide studies of flood drivers across the United States, Europe, and Australia. Higher data coverage of stream flows and flooding patterns across these landmasses has led to a stronger understanding of when and why damaging floods occur. These continents, however, differ drastically from Africa climatically and geographically, leading scientists to suspect that the triggers of African floods are unique.

Africa's largely arid climate, with the Sahara covering 25% of the continent's landmass, is part of that equation. "You additionally have this ability to study a climate largely free of snow, which is a complicating factor when studying floods," said infrastructure engineer Conrad Wasko of the University of Melbourne in Australia who was not involved in the study. With deadly floods becoming increasingly frequent in Africa as climate change worsens, hydrologists felt compelled to improve their data collection across the continent's widely varying river basins.

"Floods are always *caused* by precipitation. But the difference in soil moisture conditions before a flood event can strongly modulate its magnitude."

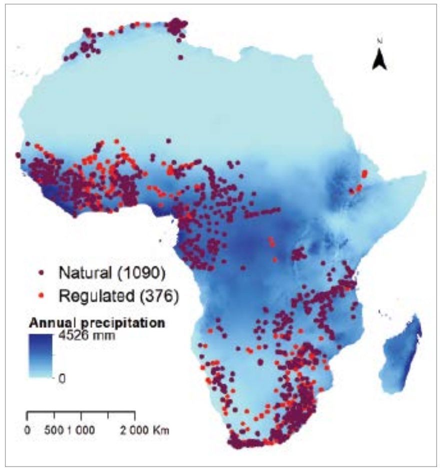
The team's African Database of Hydrometric Indices (ADHI), published in *Earth System Science Data* (bit.ly/hydrometric-indices), includes hydrological parameters from watersheds across Africa spanning 33 years on average. Given the sparseness of data across the continent, the team took laborious steps to ensure that records from different sources were of similar quality. "The most important thing was to manually and visually check each [measurement] independently," said Yves Tramblay, a hydrologist at the French National Research Institute for Sustainable Development and lead author of the study.

For regions lacking in ground observations, the scientists incorporated Climate Hazards group Infrared Precipitation with Stations (CHIRPS), a series of remote sensing estimates from a hybrid satellite and ground data set, to obtain a homogeneous average of precipitation across all of Africa. They validated these measurements with gauged data when possible. The team's thorough approach impressed Wasko: "Within engineering, we have a predisposition to collect [on-the-ground] data. New technologies, like remote sensing, are becoming essential to understanding hydrology in remote areas," he said.

A New Flood Driver Takes the Stage

The ADHI data set allowed the team to compare the timing of several parameters relevant to floods. To determine which ones aligned most strongly with the largest floods each season, they isolated the dates when floods occurred and rigorously compared them to the timing of heavy rainfall and soil moisture conditions using directional statistics—a method that accounts for the direction data follow (in this case, the timing). The analysis revealed that high soil moisture levels showed a stronger correlation to the onset of flooding than to other parameters, most notably, rainfall.

When ground already contains a lot of water, heavy rainfall mostly runs off the surface rather than being absorbed into soils—greatly increasing the chances that even modest precipitation will create floods. "It was kind of surprising because we always thought that soil moisture in arid catchments was not a strong driver, but we find that overall it's still a valuable one," Tramblay said. "A common assumption is that floods are driven by extreme precipitation events. That's true: Floods are always *caused* by precipitation. But the difference in soil moisture conditions before a flood event can strongly modulate its magnitude."



This map shows the distribution of measurement stations across Africa. Note the sparseness of data in the central and northeastern regions of the continent. Credit: Tramblay et al., 2021, https://doi.org/10.5194/essd-13-1547-2021

The new approach invites further research on floods across Africa, Tramblay noted. The team plans to continue conducting targeted studies across many sites to "get a much clearer picture of the differences [in flood drivers] at a regional scale," he said.

Tramblay also hopes the work will help future scientists and emergency planners across Africa prepare for each year's flood season by having a better grasp of whether a region might be particularly susceptible. "[This is] an incentive to not look only at extreme rainfall when you're doing flood projections, but to look at other land surface variables, including soil moisture, vegetation coverage, and change in land use," said Tramblay. "There's more recognition that if we're going to be forecasting floods and designing infrastructure [to mitigate them], it's not just rainfall we need to be thinking about, but all the other factors that affect flooding."

By **Ellis Avallone** (@ellantonia_), Science Writer

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Climate Litigation Has a Big Evidence Gap

Climate change has found its way into courtrooms around the world more and more often in recent years: Plaintiffs have brought more than 1,500 cases of climate litigation since 1986, and an increasing number of cases are filed each year.

"In the last few years we've seen lawsuits in the Netherlands, Germany, Ireland, Belgium, and elsewhere that have shown that successful climate litigation is possible," said Rupert Stuart-Smith, who researches climate systems and policy at the University of Oxford's Sustainable Law Programme in the United Kingdom. In most of those cases, courts ruled that a country's or a company's climate targets or progress toward meeting those targets needed to be significantly improved. "The power of the courts as a force of climate action really should no longer be in dispute."

However, climate litigation has failed more often than not to hold greenhouse gas emitters accountable for climate-related impacts like flooding and damage from drought or wildfires. For lawsuits that try to establish a causal link between a defendant's emissions and the impacts on plaintiffs, Stuart-Smith and his team sought to understand why those types of cases tend to fail.

"Why aren't these cases winning?" he asked. "What is the evidence that is being used in these cases, how does that compare to the state of the art in climate science…and how have the courts interpreted it?"

A Failure to Make the Connection

The researchers examined 73 cases across 14 jurisdictions worldwide that made a claim that a defendant's emissions negatively affected the plaintiffs. In those cases, courts did not dispute the general idea that greenhouse gases cause climate change. "What was more of a challenge," Stuart-Smith said, "was establishing a causal relationship between greenhouse gas emissions of an individual entity…and specific impacts on a specific location." Making that causal connection is key for the success of climate litigation, he said, and is the goal of climate attribution science, or science that quantifies the extent to which climate change alters an event.

However, 73% of the cases the team examined did not bring forward peer-reviewed climate attribution science as evidence. Of the 54 cases that claimed that an extreme weather event caused the impacts suffered by plaintiffs, 26 claimed that climate change caused the extreme weather event but did not provide evidence of that claim. Six more did provide such evidence, but that evidence did not quantify how much more likely or how much worse climate change made the extreme weather event.

"We found that there is a clear role for attribution science evidence in these lawsuits," Stuart-Smith said. In the few cases where climate science was submitted as evidence, "the evidence submitted and referenced in these cases does lag considerably behind the state of the art in climate science. And as a result…the evidence provided was not sufficient to overcome causation tests."

Of the 73 cases they examined, only eight have been successful so far. (Thirty-seven are pending, and 28 have been dismissed.) The researchers suggest that "growing use of attribution science evidence which is specific to the impacts experienced by plaintiffs… could overcome some of the key hurdles to the success of climate-related lawsuits." These results were published in *Nature Climate Change* (bit.ly/climate-litigation).

Establishing a Dialogue

Not every extreme weather event is caused by or made worse by climate change, but an increasing number of them are: Anthropogenic climate change has been making hurricanes, drought, and wildfires stronger and more frequent; has been tied to worsening health conditions around the world; and has started a climate refugee crisis. As recently as a decade ago, Stuart-Smith pointed out, climate science wasn't advanced enough to claim that climate change caused any single extreme weather event, but that is no longer the case. For example, the World Weather Attribution initiative, an international collaboration of climate scientists, has already established that the June 2021 extreme heat wave in the North American Pacific Northwest "was virtually impossible without human-caused climate change" and that "this heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution."

This study highlights that "we need better paths of communication between the legal and scientific communities," Stuart-Smith said. Lawyers need to be able to explain to climate scientists what type of evidence will be helpful and ensure that the claims they're bringing forward are actually attributable to climate change. Climate scientists, too, need to consider providing evidence to litigators as "an opportunity to make one's research relevant to important ongoing issues in the courts.… It's got to come from both sides."

Although climate attribution cases haven't been very successful in the past, "it doesn't seem farfetched anymore to suggest that future cases will force companies to pay compensation to communities impacted by climate change," either after damage is already done or as communities try to mitigate or adapt to future impacts, Stuart-Smith said. "But that is only going to be the case if…the evidence submitted to courts clearly substantiates the alleged relationship between the defendants' emissions and the impacts suffered by plaintiffs."

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

Code-Switching and Assimilation in STEM Culture

Picture a young weather enthusiast walking across the stage to receive their meteorology degree. They feel pride in this culmination of their years of hard work. They also recall how that hard work always seemed to appear to others. Friends and family called them "proper" during visits home from school, creating a distance that lingered. Their colleagues and peers frequently offered their own unsolicited impressions:

"You are so articulate!"

"You need to be more professional."

"You cannot show up like that."

"You are not like those other Black people."

Or in another common story, an early-career scientist reflects on the cost of their profession. They earned a degree, but they had to permanently relocate for school and the only career opportunities available to them. Visiting home and family is emotionally exhausting because it is a constant reminder of what was given up to focus on those limited opportunities. They raise a new family away from their abuelitos, missing out on making tamales with their tías or dancing to cumbia at their cousin's quinceañera. As they slowly lose their grasp of their native language, they fear their children will also lose that deep connection with their Latino heritage. Sí se puede, but is it worth it?

Pursuing careers in this extremely white dominated field requires us, more often than not, to assimilate either internally or externally to the culture, to code-switch.

On the surface these stories may sound and feel similar to most of us who pursued higher education or careers in academia. Who hasn't felt inadequate, had trouble finding their place in a new environment, or ultimately felt as though they did not belong? The difference we want to express is that although the situations and experiences may sound similar, the consequences of these experiences for Black, Indigenous, and people of color (BIPOC) professionals in the geosciences are very different. Additional stress, emotional labor, and baggage cause long-lasting trauma for BIPOC professionals. We feel this trauma. It is visceral. And it bubbles to the surface even as we write this article. Pursuing careers in this extremely white dominated field requires us, more often than not, to assimilate either internally or externally to the culture, to *code-switch*. In the process, we lose our authenticity.

This assimilation, however, is counterproductive to the creation of a richly diverse and inclusive scientific community that is prepared to address the questions of our modern world, and more important, it is deeply disrespectful and harmful to the BIPOC scientists whom the community boasts about recruiting. We are asking our colleagues to form a better awareness of code-switching, why BIPOC scientists perform it, and how we can address the deficiencies in our community that require it.

The term code-switching originates from linguistics, meaning "the practice of alternating between two or more languages or varieties of language in conversation." The concept of code-switching has evolved to describe the changes in speech, appearance, and behaviors by an individual to adjust to the norms of the dominant culture in a given space. We have all code-switched at some point, but for BIPOC it can be a mandatory coping strategy to protect ourselves from judgment, discrimination, hypervisibility, and tokenism [*Dickens et al.*, 2019].

Initiatives to increase the number of BIPOC in science, technology, engineering, and mathematics (STEM) have been working, if slowly, and now these folks are attempting to exist and thrive within the white-centric environments of academic institutions, scientific laboratories, and private industries. Wanting to fit in and be comfortable, BIPOC learn to assimilate cultural norms by "deemphasizing a negatively-valued identity and replacing it with a positively-regarded identity," also known in psychology literature as *identity shifting* [*Dickens and Chavez*, 2018, p. 761].

These shifts can be intentional or unintentional as we evaluate the level of risk associated with the possibility of making white people uncomfortable. For example, when we're asked to participate in a diversity panel again, should we express to our white colleagues that we feel used as a prop, or just stay quiet and humbly accept the invitation? Will we be seen as problematic or ungrateful? Even through editing of this writing, we felt conflicted over appeasing the editors and staying true to our story, appreciating the critique yet not wanting to lose our voice. The risks can range from feeling embarrassed or worried you made a bad impression to being harassed and fearing for your life and safety.

Some BIPOC grow up in segregated communities, learning to identity shift only after they leave home and experience predominantly white spaces such as a university, a scientific conference, or an internship at a national lab. Even within historically Black colleges and universities, academic spaces where Black culture is championed, a Black

STEM student may still feel like an outcast if they feel the need to hide their perceived nerdy self to belong, as nerdiness is stereotypically associated with whiteness.

The Cost and Consequences of Code-Switching

The inner turmoil created by shifting identities can often manifest as physical and mental ailments [*Dickens and Chavez*, 2018]. Code-switching is exhausting, taking up mental capital that should be devoted to our research. We just want to be scientists, without having to separate our culture from our profession, and to be able to present ourselves authentically without needing to constantly account for potentially negative reactions from others.

Instead, we live with that constant nagging in the back of our minds, reminding us that we have to say the right things, react the right way, and behave in a manner that draws attention away from the obvious difference we present. When we are not able to blend in, we falsely believe that we don't belong and fear being called out as incompetent. This phenomenon is often called imposter syndrome. This explanation, however, identifies the person feeling it as the responsible party—the one who needs to change. Imposter syndrome is, instead, a scapegoat that takes focus away from addressing the culture of bias and systemic racism that exists for women and BIPOC scientists [*Tulshyan and Burey*, 2021].

We strongly believe we should elevate and celebrate the people within our scientific communities, not ask them to assimilate.

For BIPOC in the geosciences, those feelings are compounded because of the more extreme cultural isolation that exists in the field compared with other STEM fields. In the geosciences, we are often not just one in a historically excluded group but the *only one* in our field or lab.

What does a reliance on code-switching force us to give up? We become accustomed to adjusting to norms within our professional workplace (e.g., at the office, at conferences, during a field campaign or expedition) or, often, in the neighborhoods we're required to move to. Those adjusting behaviors start to become unconscious, even dominant. We start to lose our native and colloquial language and cultural norms. Returning home can make us feel like outsiders looking in. We lose the thread that connects us with the people we grew up with and the people who raised us. Ultimately, we are left to wonder where we fit in.

We are never white enough in our professional environments but become too white in our home communities. Some of us self-exclude and choose not to be seen altogether, not wanting to lose ourselves or be the representative of an entire race of people. But by choosing to stay in the shadows, we also lose the opportunities and recognition that make any profession worth pursuing.

We are taught to be professional, but let's consider the origins of present-day professional standards. In the broadest sense, the concept of professionalism encompasses the conduct by which one is expected to present oneself in formal settings, often customized to one's discipline.

For geoscientists, these settings include job interviews, research seminars, conferences, classes, labs, and field campaigns. The standards are taught by mentors and in professional development seminars that focus on how to modify people's behavior rather than how to evaluate, modernize, or fix the many problems in the culture. We persist in perpetuating professional standards that were established by white men many decades ago when women and BIPOC were not represented. Ethnically and culturally traditional attire, hairstyles, and vernacular were inconceivable when present-day professionalism was defined. Some scholars contend that this bias in professional standards is a form of white supremacy.

BIPOC resort to code-switching to boost their perceived professionalism—we assimilate [*McCluney et al.*, 2019]. Code-switching, then, becomes a barrier to true inclusivity [*Goldstein Hode*, 2017], which should be the ultimate goal of modern professional behavior based on mutual respect and ethical integrity. Inspired by the perspectives of *Halsey et al.* [2020], we strongly believe we should elevate and celebrate the people within our scientific communities, not ask them to assimilate.

A Path Forward Isn't Easy

The need for code-switching will persist until we can eradicate the systemic, institutional, and personal racism against which we need a shield. The onus should be on the larger community, not on BIPOC alone, to develop strategies that lead us to modern-day professionalism that is inclusive and respectful of everyone.

How can we collectively create an inclusive community and environment where we can each be our authentic selves? It's not easy, and we don't have all the answers. It requires all of us to challenge professional standards.

Professionalism should require mutual respect, not assimilation to a single specific set of behaviors. Everyone, but especially those in leadership or supervisory positions, should seek out and recommend professional development opportunities on cultural competencies. Look around your workplace and take steps to evaluate and assess the culture and climate, then use these data to modernize your policies and practices to focus on equitable inclusion. Understand and listen to the variety of experiences of the people around you, in particular, those of your BIPOC colleagues. Accept BIPOC colleagues for who they are. By doing so, you'll show everyone around you how to change the culture rather than changing the people. By working together, we will become better together.

Ultimately, code-switching negatively affects the individual BIPOC professional as well as the entire science community. As challenging as it can be, we are passionate about the science we pursue and desire to contribute to it. But the more we assimilate, the less diverse our science and our ideas become. This lack of diversity makes code-switching and the persistence of the institutions that require it a detriment to the advancement of our knowledge of our rapidly changing world.

To our BIPOC friends, peers, and colleagues: We carry hope in each other, knowing that we can look across the conference table, the poster session, or the Zoom room and be able to lock eyes and feel comfort and community. We want future generations to be empowered to show up as their authentic selves and focus their time and effort on great science, without interference and the additional labor of code-switching.

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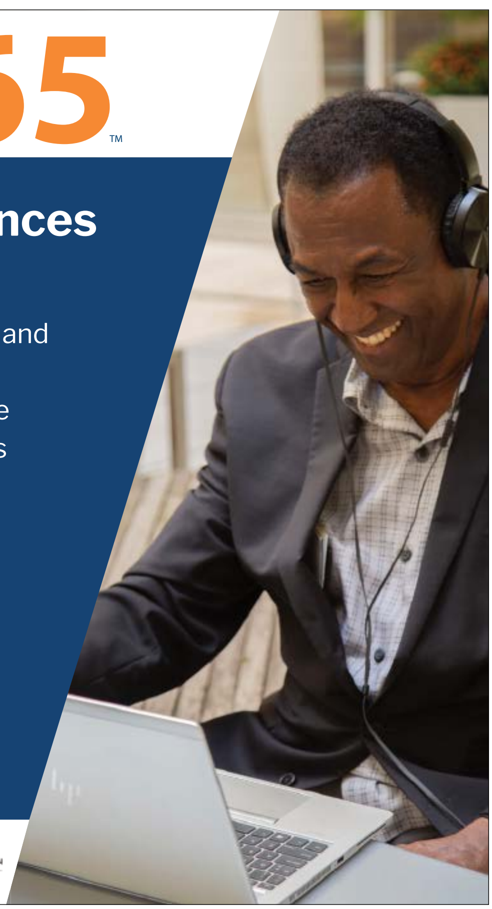

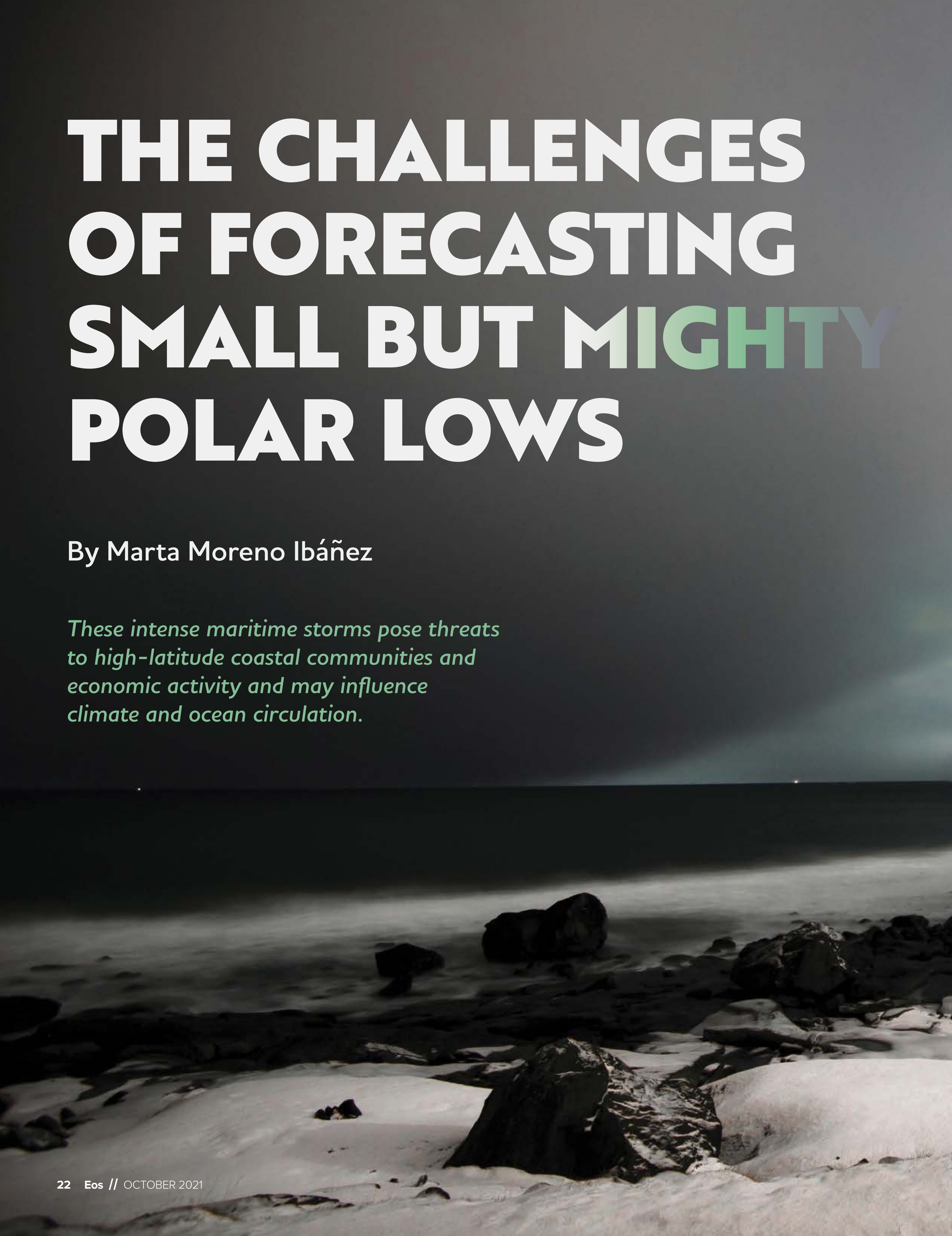

THE CHALLENGES OF FORECASTING SMALL BUT MIGHTY POLAR LOWS

By Marta Moreno Ibáñez

These intense maritime storms pose threats to high-latitude coastal communities and economic activity and may influence climate and ocean circulation.

An incoming polar low drives clouds and waves toward the Lofoten Islands in northern Norway in 2015. Credit: Room the Agency/ Alamy Stock Photo

The area around Tromsø, Norway, seen here, is affected by polar lows during the Northern Hemisphere winter. Credit: Marta Moreno Ibáñez

Sailors in Scandinavian countries have told tales about dangerous encounters with small, intense storms since time immemorial. These maritime storms, known as polar lows, are believed to have claimed many small boats in North Atlantic waters [*Rasmussen and Turner*, 2003]. In a case in October 2001, strong winds associated with a polar low that developed near the Norwegian island of Vannøya capsized a boat, causing the death of one of its two crew members.

Polar lows not only are found in the North Atlantic, but also are common in the North Pacific and Southern Ocean. In Japan, for example, tragedy struck in December 1986, when strong winds from a polar low caused a train crossing the Amarube Bridge to derail and fall onto a factory below, killing six people [*Yanase et al.*, 2016].

With their high winds and waves, polar lows threaten many communities and ecosystems with extreme weather as well as with potential coastal erosion and effects on ocean primary productivity.

Forecasting these systems remains challenging because of their relatively small size, rapid formation, and short duration (most last less than 2 days). However, as global warming and receding sea ice make the Arctic more accessible and increase the vulnerability of coastal populations and ecosystems, it will become increasingly important to forecast these dangerous storms accurately. Studying the effects of a warming climate on where these storms form, and on their frequency, lifetime, and intensity, is also vital, because this work will help determine which regions will be most affected by polar lows in the future.

Dangerous High-Latitude Storms

Polar lows are a little-known part of the wider family of polar cyclones, which include polar mesoscale cyclones less than 1,000 kilometers in diameter as well as larger, synoptic-scale cyclones. With diameters between 200 and 1,000 kilometers—and most often 300–400 kilometers—polar lows are a subset of mesoscale cyclones.

The relatively small storms differ from other polar mesoscale cyclones in that they develop over the ocean and are especially intense. Polar lows are often associated with severe weather like heavy snow showers and strong winds that can reach hurricane force. Thus, they sometimes lead to poor visibility, large waves, and snow avalanches in mountainous coastal regions. Changes in meteorological conditions can be abrupt, with winds increasing from breeze to gale force in less than 10 minutes, for example. Such severe weather can force affected countries to close roads and airports.

Polar lows can even cause the formation of rare, extreme storm waves known as rogue waves. One such wave, named the Draupner wave, was observed in the North Sea in 1995 and reached a height of 25.6 meters [*Cavaleri et al.*, 2016].

With their high winds and waves, polar lows threaten many communities and ecosystems with extreme weather as well as potential coastal erosion and effects on ocean primary productivity. They also pose significant risks to marine-based industries, such as fishing and onshore and offshore resource extraction. Roughly 25% of the natural gas and 10% of the oil produced worldwide come from the Arctic, and—despite the strong influence of fossil fuel use on continuing climate change—interest in further extraction of offshore resources in this region is growing.

In addition, as summer sea ice extent decreases because of climate change, shipping seasons will become longer and new shipping routes will open up, making the Arctic more accessible and potentially increasing the likelihood of storm-related accidents. The possibility of shipping accidents or other disasters causing oil spills in the Arctic is particularly concerning because the lack of infrastructure in this remote region means that it could take a long time to respond to spills. With so many concerns and at-risk communities, there is a pressing need to improve forecasting of polar lows and other extreme Arctic weather to reduce risk.

Weather forecasting in polar regions remains challenging because atmospheric models still struggle to correctly represent certain key processes, such as air-sea interactions.

Where Do Polar Lows Form?

Polar lows are predominantly a cold-season phenomenon, developing near the sea ice edge and the coasts of snow-covered continents during cold-air outbreaks, when very cold air over the ice or landmass flows out over the relatively warm ocean.

Southern Hemisphere polar lows, which have received less attention from researchers, develop mainly near the Antarctic sea ice edge, far from human settlements, and they tend to be less intense than their northern counterparts. Northern Hemisphere polar lows develop above about 40°N, thus affecting several Arctic countries. They are more frequent in the North Atlantic than in the North Pacific [*Stoll et al.*, 2018], mainly forming in the Nordic Seas, the Denmark Strait, the Labrador Sea, and Hudson Bay. Every year, some of the polar lows that develop in the Nordic Seas make landfall on the coast of Norway, affecting its coastal population.

In the North Pacific, polar lows form primarily over the Sea of Okhotsk, the Sea of Japan, the Bering Sea, and the Gulf of Alaska. Densely populated areas of Japan are especially vulnerable when marine cold-air outbreaks in the Sea of Japan lead to polar lows.

An Elusive Phenomenon

The origins and characteristics of polar lows remained largely a mystery until the beginning of the satellite era in the 1960s. With resolution in atmospheric models being too coarse to capture the storms until relatively recently, satellite infrared images have been key to identifying polar lows. These images have shown that some polar lows are shaped like commas, similar to midlatitude synoptic-scale (i.e., extratropical) cyclones, whereas others are spiraliform like hurricanes (i.e., tropical cyclones; Figure 1).

How polar lows develop was long debated among researchers. Some argued that polar lows resembled small versions of synoptic-scale cyclones, which develop because of baroclinic instabilities arising from strong horizontal temperature gradients in the atmosphere. Others claimed they were akin to hurricanes, which intensify as a result of convection and are typically about 500 kilometers in diameter. Today the research community agrees that development mechanisms of polar lows are complex and include some processes involved in the formation of synoptic-scale cyclones and some involved in hurricane formation. Among these processes are transfers of sensible heat from the ocean surface to the atmosphere through the effects of turbulent air motion, which play roles in the formation and intensification of polar lows.

In general, weather forecasting in polar regions remains challenging because atmospheric models still struggle to correctly represent certain key processes, such as air-sea interactions, in these regions. Because of their small size and short lifetimes, polar lows are particularly hard to forecast compared with larger polar cyclones. Compounding the challenge is the fact that these systems develop over the ocean at high latitudes, where conventional observations (e.g., those from surface weather stations, buoys, and aircraft) are scarce.

With the advent of high-resolution nonhydrostatic atmospheric models with grid meshes of less than about 10 kilometers (which started to be implemented for weather forecasting in the 2000s), however, polar low forecasts have improved notably. Unlike models that assume hydrostatic conditions, nonhydrostatic models do not assume balance between the vertical pressure gradient force, which results from the decrease of atmospheric pressure with altitude, and the force of gravity—a balance that does not occur in intense small-scale systems. Compared with coarser models, high-resolution models better represent processes that occur near the surface (e.g., the influence of topography on wind) as well as convection, which play important roles in polar low development. Moreover, high-resolution models can better resolve the structure of polar lows (e.g., strong wind gradients).

Nevertheless, model improvements are still needed to forecast the trajectories and intensities of polar lows accurately [*Moreno-Ibáñez et al.*, 2021]. For instance, the parameterization of turbulence is based on approximations that are not valid at the kilometer scale. In addition, more conventional observations of atmospheric variables at high latitudes, such as winds and temperatures at different levels of the atmosphere, are required to improve the initial conditions fed into the models.

Several major scientific questions about these storms also remain unanswered: What are the best objective criteria (e.g., size, intensity, lifetime) for identifying and tracking polar lows using storm tracking algorithms? What is the main trigger for polar low development? And, most intriguing, what is the role of polar lows in the climate system?

Actors in the Climate System

Little is known about how polar lows contribute to Earth's climate system. A few studies have analyzed the effects of polar lows on the ocean, but results so far are inconclusive. On the one hand, the large sensible heat fluxes—which can reach more than 1,000 watts per square meter—from the ocean surface to the atmosphere that favor the development of these cyclones lead to cooling of the ocean surface [e.g., *Føre and Nordeng*, 2012]. On the other hand, the strong winds of polar lows induce upper ocean mixing, which can warm the ocean surface in regions where sea surface temperatures are colder than underlying waters [*Wu*, 2021].

The overall warming or cooling effect of polar lows on the ocean surface may influence the formation rate of deep water, a major component of Earth's global ocean circulatory system. In one study, researchers found that polar mesoscale cyclones increase ocean convection and stretch convection to greater depths [*Condron and Renfrew*, 2013]. However, this study used only a coupled ocean–sea ice model, relying on a parameterization to represent the effects (e.g., winds) of polar mesoscale cyclones in the ocean-ice model rather than explicitly resolving the cyclones. Therefore, the interactions between the ocean and the atmosphere, which are relevant for deepwater formation, were not represented. This tantalizing, but hardly definitive, result highlights the need for further study of polar lows' interactions with the ocean and climate.

Polar Lows in a Warmer Climate

The continuing decreases in Arctic sea ice extent and snow cover on land projected to occur with global warming, as well as increases in sea surface temperatures, will undoubtedly affect the climatology of polar lows. In the North Atlantic, polar lows have been projected to decrease in frequency, and the regions where they develop are expected to shift northward as sea ice retreats [*Romero and Emanuel*, 2017]. This shift means that newly opened Arctic shipping routes will not be spared these storms.

We do not know yet what will happen in other regions because research investigat-

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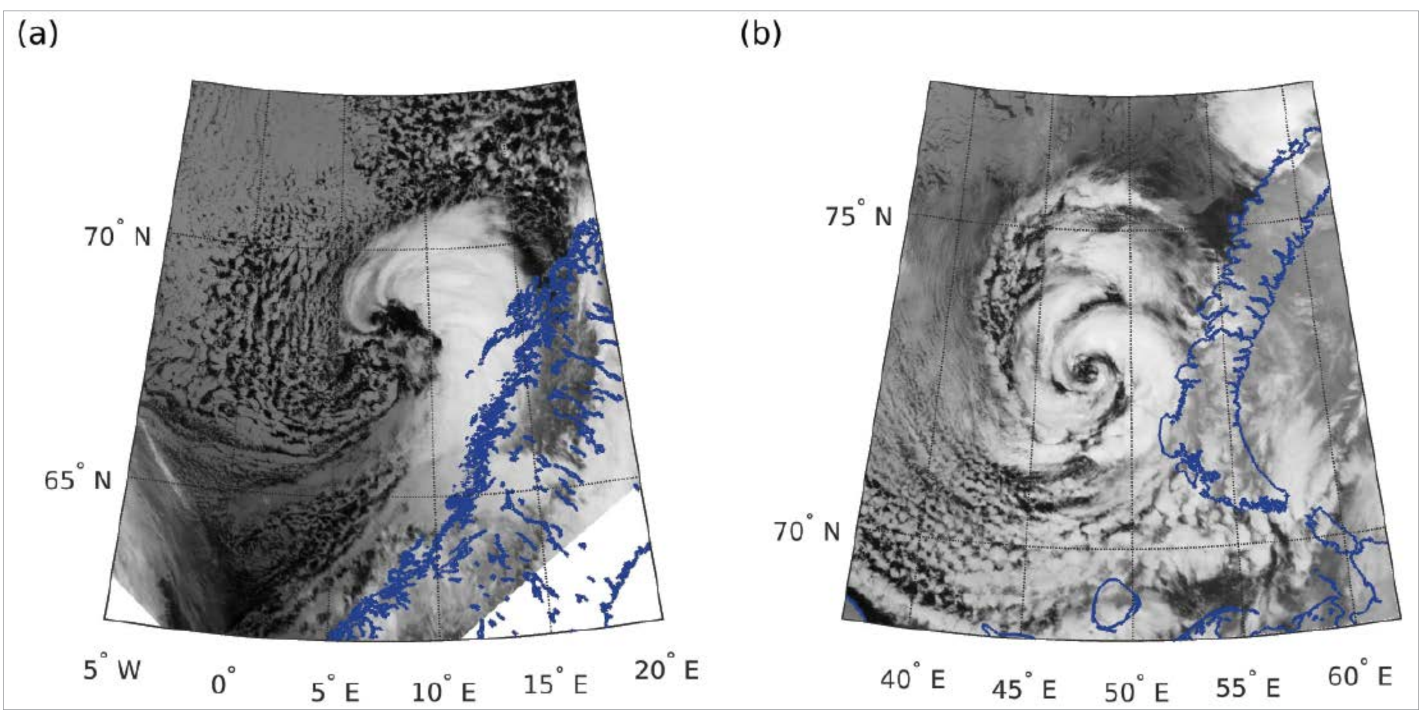

Fig. 1. These satellite infrared images show (a) a comma-shaped polar low over the Norwegian Sea (which made landfall in Norway), captured by the Advanced Very High Resolution Radiometer, and (b) a polar low with a spiraliform signature over the Barents Sea (which made landfall in Novaya Zemlya, Russia), captured by the Moderate Resolution Imaging Spectroradiometer. The blue outlining represents the coastline. Source: Moreno-Ibáñez et al. *[2021], CC BY-NC 4.0 (bit.ly/ccbync4-0)*

ing climate change impacts on the frequency, lifetime, intensity, and genesis areas of polar lows is still at an incipient stage. The few studies conducted so far have used dynamical or statistical downscaling methods to produce high-resolution information about the relatively small, localized phenomenon of polar lows from low-resolution data (e.g., from global climate models)—approaches that require far less computing resources than performing global, high-resolution climate simulations.

Unfortunately, current coarse-grained global climate models cannot resolve small-scale phenomena like polar lows. The typical resolution of the models included in the Coupled Model Intercomparison Project Phase 5 (CMIP5), endorsed by the World Climate Research Programme in 2008, was 150 kilometers for the atmosphere and 1° (i.e., 111 kilometers at the equator) for the ocean. As part of CMIP6, a High Resolution Model Intercomparison Project has been developed [*Haarsma et al.*, 2016], that includes models with grid meshes ranging from 25 to 50 kilometers for the atmosphere and from 10 to 25 kilometers for the ocean. These resolutions are fine enough to enable study of some mesoscale eddies in the atmosphere and the ocean [*Hewitt et al.*, 2020], and important weather phenomena, such as tropical cyclones, can also be simulated [e.g., *Roberts et al.*, 2020].

Nevertheless, atmospheric models at this resolution are still too coarse to resolve most polar lows. Moreover, the resolution of these ocean models is not high enough to resolve mesoscale eddies that develop poleward of about 50° latitude [Hewitt et al., 2020], so some mesoscale air-sea interactions cannot be adequately represented. Mesoscale air-sea interactions also affect sea ice formation, which influences where polar lows form. A recent Intergovernmental Panel on Climate Change report indicates that there is low confidence in projections of future regional evolution of sea ice from CMIP6 models.

Interdisciplinary Research Needed

Considering the interactions among the atmosphere, ocean, and sea ice involved in polar low development, the importance of interdisciplinary collaboration in polar low research cannot be overstated. Close cooperation among atmospheric scientists, oceanographers, and sea ice scientists is needed to enable a complete understanding of polar lows and their role in the climate system.

Improving forecasts and longer-term projections of polar lows requires coupling

> The importance of interdisciplinary collaboration in polar low research cannot be overstated.

of high-resolution atmosphere, ocean, and sea ice models. High-resolution coupled model forecasts of polar lows are already practicable. With continuing increases in computational capabilities, it may become feasible to use coupled high-resolution regional climate models and variable-resolution global climate models to better study how polar low activity may change in a warming climate and the impact of polar lows on ocean circulation. Such interdisciplinary research will also help us better anticipate and avoid the damaging effects of these small, but mighty, polar storms on people and productivity.

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The Changing Climate's Snowball Effect

By Korena Di Roma Howley

SHRINKING SNOWPACK, THAWING PERMAFROST, AND SHIFTING PRECIPITATION PATTERNS HAVE WIDESPREAD CONSEQUENCES. CAN NEW TECHNOLOGIES— AND PUBLIC POLICIES— HELP COMMUNITIES ADAPT?

Sean de Guzman, California Department of Water Resources snow survey chief, measures the snowpack at Phillips Station in the Sierra Nevada in 2021. Credit: Andrew Innerarity/California Department of Water Resources

It begins at the height of winter in the mountains, when the landscape is particularly inhospitable. The surveyors arrive on skis, snowshoes, and snowmobiles. Some fly in by helicopter. Others travel the backcountry for days. When they arrive at their destination, there's critical information to collect: the depth of the snowpack and how much water it holds. For regions confronting the effects of climate change, more and more hinges on the results.

"It all boils down to how much water makes it down into the reservoir," said Sean de Guzman, chief of snow surveys and water supply forecasting at the California Department of Water Resources. De Guzman has it easier than some. Between February and May, around the first of each month, he drives to the Phillips Station snow course—a designated site for measuring the snowpack—located at around 6,800 feet (2,100 meters) of elevation in the Sierra Nevada. Once there, he manually inserts a tube into the snowpack, an instrument and method developed in the early 20th century by James Church, a professor at the University of Nevada, Reno who wanted to help put an end to local water wars by finding a way to estimate how much Lake Tahoe would rise in springtime. With the tube, de Guzman is able to measure the snowpack's snow water equivalent, or the amount of water the snowpack contains at that location.

Today there are approximately 1,600 snow courses in the United States, with around 260 in California, primarily in the Sierra Nevada and the southern Cascades. Some date back more than a hundred years. Data from these locations, said de Guzman, represent the longest-running climate record in the Sierra Nevada. In the West, manual snow surveys are augmented by data from an automated snow telemetry (SNOTEL) network maintained by the Department of Agriculture's Natural Resources Conservation Service that provides hourly snowpack measurements.

What these collective data tell snow surveyors, water resources managers, policymakers, and millions of people enduring water shortages, drought, flooding, and wildfires is that the snowball effect of climate change often begins, appropriately enough, with snow. And snow—how much falls, where and when, how much accumulates, and how quickly it melts—is changing.

"As a whole, over the last 70 years, we've seen a decline in snowpack," de Guzman said. "With the warming temperatures and a warming climate, you can expect the snow-line—basically where that snow transitions into rain, and vice versa—to increase," or climb in elevation.

Even when the snow survey data are relatively promising, other climate factors can inhibit a favorable outcome. At 59% of average on 1 April, California's 2021 winter snowpack had more snow than was measured in any of the state's 2012–2016 drought years. At the height of that drought in 2014, the snowpack on 1 April was at only 5% of average. And yet, de Guzman said, the 2021 snowpack yielded about the same amount of runoff as during those very dry years. "If you have more snow, you expect more [runoff], but that didn't happen this year," he said. The reason in part was that another low-rainfall year resulted in dry soil, which soaked up more of the runoff. "The snowpack was melting," de Guzman said, "but the rivers weren't rising."

A SHRINKING SEASON

There are different contexts and consequences across the United States, but all regions are struggling with rapid change. While the West grapples with water shortages amid severe drought, other parts of the country have become more vulnerable to extreme thunderstorms and flooding as more precipitation falls as rain rather than snow and as snowmelt occurs earlier in the spring. Increasingly, snow will also accumulate later in the season. An analysis by Climate Central showed that between 1970 and 2019, snowfall measured in 116 U.S. locations had decreased by 80% before December, and at 96 locations it had decreased by 66% after 1 March. But though historical data can reveal broad regional trends and patterns, they are becoming a less reliable forecasting tool as the warming climate throws snowfall patterns into disarray.

"The snow season is shrinking," said Hans-Peter Marshall, an associate professor in the Cryosphere Geophysics and Remote Sensing group at Boise State University. But how much snow falls within that shortened seasonal window, he said, is difficult to predict. "The main thing we know is there's going to be larger fluctuations, and the year-to-year variability is likely to increase."

That variability includes the possibility of heavier snowstorms even as temperature averages trend upward. There's no consensus on why warming has what appears to be a counterintuitive impact. According to Marshall, one reason the western United States might experience bigger storms is that a heated atmosphere can hold more water. In a warmer climate, water from the ocean could potentially make its way to the mountains, and more of that water might fall as heavy snow or torrential rain.

Meanwhile, warming Arctic temperatures may contribute to the kind of frigid blasts that reached as far south as Texas in 2021 (with catastrophic results) by disrupting the polar vortex, weakening the Northern Hemisphere's polar jet stream and causing Arctic temperatures to dip south and warmer air to move north.

In the West, as the snow season shortens and the snowpack shrinks, so too does the water supply. In August, the federal government for the first time declared a water shortage on the Colorado River, a move that will reduce the amount of water allocated to Arizona and Nevada in 2022. (Mexico will also see a reduction in its share of the Colorado.) A continued water shortage will reduce water allocated to California.

"If you're living in the West, you're going to feel it," said Amato Evan, an associate professor of climate sciences at the University of California, San Diego's Scripps Institution of Oceanography. "In regions where the snowcap is vulnerable, like California, we've had year after year of 46 drought already," demonstrating that the consequences are real.

The mountain snowpack, Evans said, acts as the state's water bank for the year, melting slowly over the course of the summer and refilling depleted reservoirs. But snow that melts too early overwhelms reservoirs and can't be captured and stored for use later in the year. And runoff that evaporates in warm, dry conditions or, as de Guzman described, gets absorbed into the earth before it reaches reservoirs, results in low water supply early on in the season.

A RECIPE FOR DISASTER

Both scenarios may have far-reaching consequences. In California, 2021's lower than forecast runoff contributed to drought emergency proclamations being declared in May, for 50 of the state's 58 counties, with state agencies directed to instigate a series of measures to conserve the water supply.

According to Marshall, the entities that decide how much water to release from dams must constantly estimate how much remains in the seasonal snowpack—decisions made more challenging by unpredictable snowfall. Though snow surveys and telemetry data provide accurate measurements for the area immediately surrounding snow courses and sensors, the data aren't necessarily indicative of what's happening between the sites. Currently, Marshall said, water managers might take a survey site's 30-year average, compare it with streamflow over 30 years, and find the statistical correlation between the two. But that approach depends on a stationary climate, and these days, Marshall said, the current year is rarely representative of the past 30.

"As predictions get harder and harder in a changing climate," he said, "we're at this point where we need to make a paradigm shift, [and go] from just looking at individual sites and correlating them over the last 30 years to actually being able to estimate how much snow is everywhere on the landscape."

Marshall and his group at Boise State are helping to fill in the data gaps by supporting NASA's SnowEx campaign, which uses coordinated airborne and field experiments to determine the best combination of sensors for measuring snow globally from space. Current monitoring from space can tell scientists where snow cover is located but not how much of it there is.

"That's one of the largest components of the water cycle that we just don't have a very good handle on," Marshall said.

When Marshall first began his work in Idaho in 2008, water managers showed less interest in new approaches than they do today. As the climate changes, weather events are altering the snowpack in unique ways, making reliable forecasting technology crucial for implementing decisions that affect water allocation for agriculture, water supply for communities, and flood forecasting.

According to de Guzman, incorporating forecasts into infrastructure operations, rather than relying on historical data, would enable water managers to better determine when to release water from reservoirs.

"A lot of the regulations and operations and maintenance manuals on how we operate reservoirs are built off old historical data," de Guzman said. "So we're operating old infrastructure in a changing climate, and that is a recipe for disaster."

ALL OVER THE MAP

In the Midwest and Northeast, less snowfall and more rain affect everything from agriculture, as farmers struggle with soil erosion, to the recreation industry, as the snow sport season shortens. In both cities and rural areas, increased rainfall and more frequent severe snowstorms will strain critical infrastructure systems and put vulnerable populations at risk.

> **"We're operating old infrastructure in a changing climate, and that is a recipe for disaster."**

In the Great Lakes region, warmer temperatures reduce ice cover on lake surfaces, leaving water open for lake-effect snowstorms. Increases in these storms in the short term could overwhelm snow and ice removal systems and affect roadways, buildings, and power lines. In the long term, as temperatures continue to climb, the air moving over the lakes will be warmer, and rain will fall instead of snow.

Abigail McHugh-Grifa is a founding member and executive director of Climate Solutions Accelerator of New York's Genesee-Finger Lakes Region, which includes the city of Rochester where the nonprofit is based. McHugh-Grifa sees signs that the climate is changing. "Certainly we are already seeing the impacts of the weather just getting weirder and more unpredictable at all times of the year," she said, adding that in the past few years, heavy snowfalls have quickly melted rather than accumulating. "It will dump a lot of snow on us and then melt and then dump a lot of snow on us and melt again. It's just all over the map."

Patterns can be difficult to tease out in an area like Rochester, where winter is the fastest warming season. The city has experienced a slight downward trend in snowfall over the past 50 years, with a more dramatic decline expected in the next 20–30 years, according to Climate Central meteorologist Sean Sublette in an interview for Rochester's WROC TV. But in the short term, Rochester, like other Great Lakes communities, will likely see more lake-effect snowstorms, followed by warming springtime temperatures that can hasten snowmelt and lead to, among other changes, disruptions to the growing season.

For McHugh-Grifa, whose organization seeks to engage the community and public officials in mapping out solutions for adapting to climate change, getting leaders to recognize the urgency of the task can be the

“Even though we are seeing extreme weather conditions and other impacts of climate change, most local municipalities and community members aren’t making the connection yet.”

biggest challenge. “I wouldn’t say that any municipality around here is being bold enough or ambitious enough in their approach,” she said. “Even though we are seeing extreme weather conditions and other impacts of climate change, most local municipalities and community members aren’t making the connection yet.”

New York is a home rule state, meaning in short that municipalities have the autonomy to pass local laws. McHugh-Grifa believes that for public policies to shift toward climate adaptation planning, multiple municipalities must get on board. “If one municipality wants to go above and beyond, it’s challenging for them because there’s a real fear that, for example, if they… demand higher standards for building efficiency, then the developer is just going to go to the next town over.”

Without increased regional cooperation and collaboration on land use, transportation, and building codes, McHugh-Grifa said, policy planning for climate change adaptation will continue to stall. In part to respond to this challenge, Climate Solutions Accelerator uses a collective impact approach, working to convene partners, ensure that the voices of those most affected are represented, and develop a shared regional plan. “No one organization or one individual or one solution can possibly meaningfully address this problem, so we need this kind of massive coordinated response,” she said.

In many urban areas where snow, and winters in general, are predicted to transform in the decades ahead, climate action plans have been developed to set goals for reducing greenhouse gas emissions. Chicago, Boston, and Philadelphia are among the U.S. cities that have joined C40 cities; a global network of so-called megacities whose mayors have pledged to deliver on climate change goals. Ultimately, with sharply divided political positions among top elected officials, local leaders may have the largest influence on whether their cities can adapt quickly enough to meet the changing climate.

A CLIMATE TO RECKON WITH

In Alaska, one of the fastest warming regions on the planet, the effects of changing winter patterns—including snowfall, snowmelt, and permafrost thaw—will have wide-ranging ramifications for the state’s human and wildlife inhabitants. Many animals and native or migrating fish depend on snow, ice, and streamflow for habitat. Communities rely on snow for transportation and recreation and on snowmelt for hydropower. Uncertainties for such key industries as timber and fisheries contribute to economic vulnerability.

In northern coastal areas, Alaska Native communities that hunt for subsistence or migrate to work depend on the sea ice and permafrost—a layer of frozen ground—for survival. As the ice melts and the permafrost thaws and becomes less stable, villages may lose homes and other structures to flooding or erosion. Diminished mobility cuts off access to hunting and fishing grounds and isolates residents from emergency services. In some cases, the thaw has proven fatal.

“In the last couple of years, we’ve had at least a dozen people go through unstable ice,” said Amy Lauren Lovecraft, director of the Center for Arctic Policy Studies and a professor of political science at the University of Alaska Fairbanks. “It’s unimaginably tragic,” she said. “It’s the people who don’t produce or produce very little carbon emissions who are most impacted.”

And yet, Lovecraft said, current and past governors have been careful to avoid politically charged policies that directly address climate change, leaving it to villages and boroughs to take on the role of strengthening their communities. “In the absence of federal or state direction, it’s happening at the local scale,” Lovecraft said, adding that, in fact, these communities know best about how changes in snow affect them. “It’s not an entirely negative thing that it has to happen from the bottom up.”

Still, there is a role for the state to play, Lovecraft said, including setting parameters, spreading information, and backing local-scale projects that address mobility, housing, hunting, and other concerns. “It’s a matter of how smooth that transition could be,” she said.

As scientists continue climate research and refine technologies for accurate forecasts and measurements, communities will need to find support for applying new methods and data and implementing policies that address specific changes in their regions. But for some areas already deeply affected by changing winters, paradoxical weather events and the vagaries of snowfall patterns, winter storms, and snowmelt may hinder efforts to communicate the urgency of taking action.

Ultimately, the question for Alaska, Lovecraft said, isn’t whether the science on climate change is correct but, rather, whether it’s a message that anyone wants to hear.

“Does Alaska really want to face the pain of doing a transition that’s conscious, or do we ignore it? Eventually, we’re going to have to reckon with it.”

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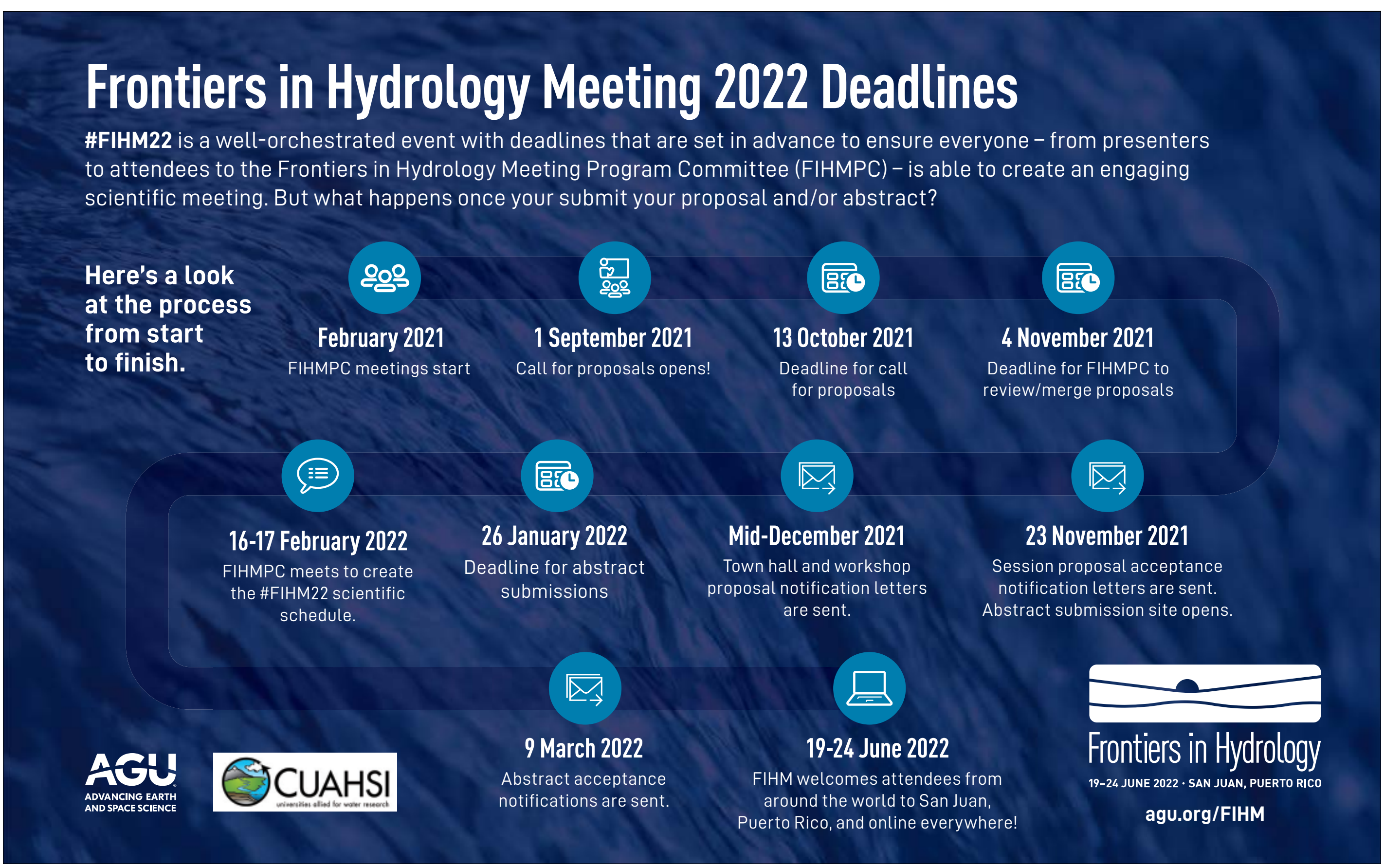

Frontiers in Hydrology Meeting 2022 Deadlines
#FIHM22 is a well-orchestrated event with deadlines that are set in advance to ensure everyone – from presenters to attendees to the Frontiers in Hydrology Meeting Program Committee (FIHMPC) – is able to create an engaging scientific meeting. But what happens once your submit your proposal and/or abstract?
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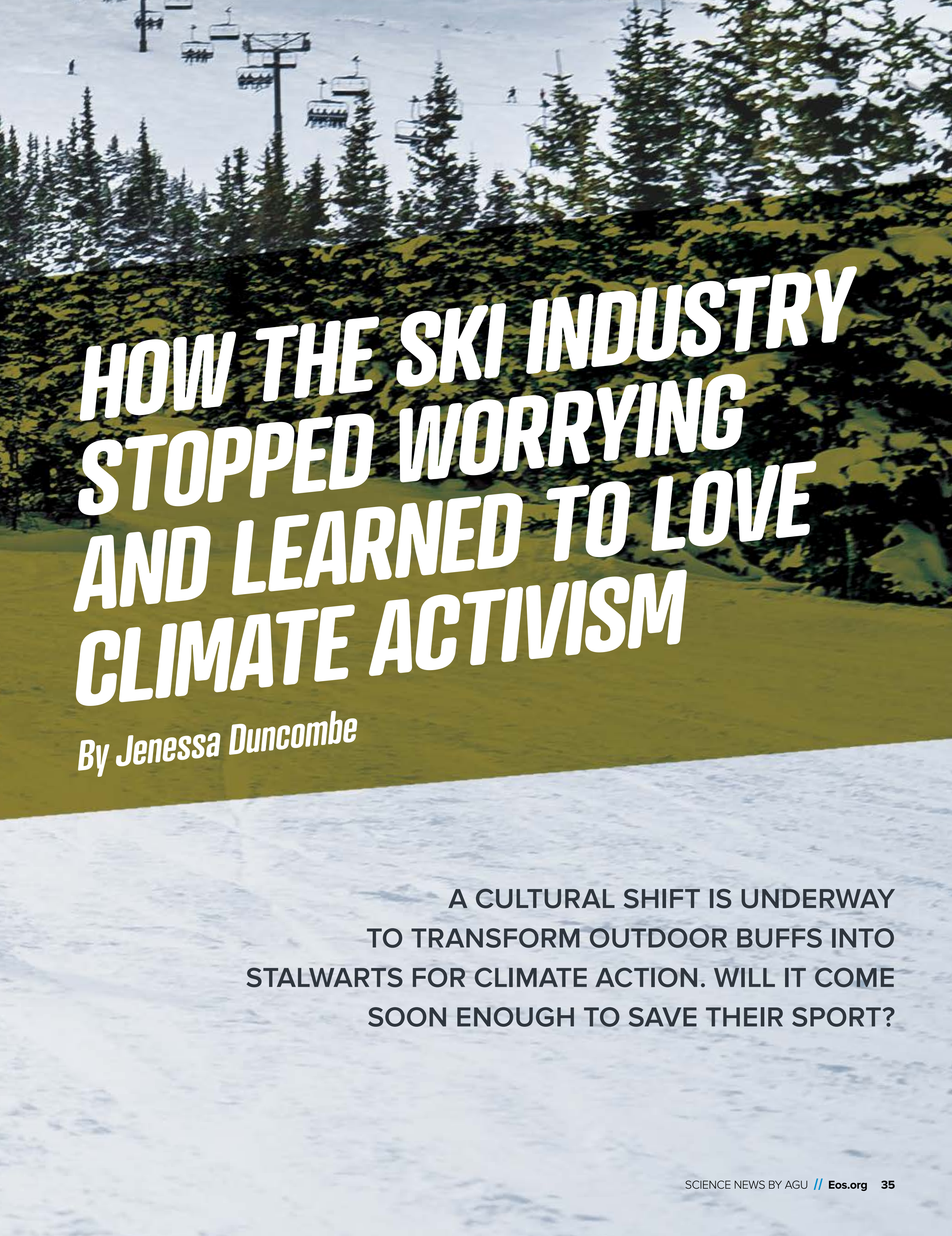


HOW THE SKI INDUSTRY STOPPED WORRYING AND LEARNED TO LOVE CLIMATE ACTIVISM

By Jenessa Duncombe

A CULTURAL SHIFT IS UNDERWAY TO TRANSFORM OUTDOOR BUFFS INTO STALWARTS FOR CLIMATE ACTION. WILL IT COME SOON ENOUGH TO SAVE THEIR SPORT?

An interview with the president of the International Ski Federation, Gian Franco Kasper, made its way around the Internet faster than locals flocking to the first chair on a powder day. In the 2019 interview, Kasper told a Swiss newspaper that he preferred working with dictators to environmentalists and that there is no proof of "so-called" climate change. The International Ski Federation represents more than a hundred national ski organizations in the world and organizes the Olympic ski events.

Many did not take kindly to Kasper's remarks. Days after an English translation of snippets from the interview was published in the sports publication *Deadspin*, the outdoor community sent a letter with nearly 9,000 signatures to the federation demanding that Kasper step down.

The letters said that climate change threatens the existence of the ski industry and that Kasper's comments went against the experience of resorts that have already closed because of climate change. "Kasper's remarks should disqualify him for a leadership position in any business capacity, let alone that of a ski federation," read the letter from the nonprofit Protect Our Winters (POW).

Kasper apologized, and 7 months later, the International Ski Federation signed on to the United Nations Sports for Climate Action Framework. This year, Kasper retired after 23 years as president and was replaced by a candidate, Johan Eliasch, endorsed by John Kerry, the U.S. special presidential envoy for climate.

Skier and mountaineer Caroline Gleich swapped her ski gear for a blazer and slacks before testifying before Congress in February 2020. Gleich is a salaried athlete influencer for the nonprofit Protect Our Winters. Credit: Caroline Gleich

The shift in perspective symbolized by Kasper's final years in office reflects a concern by the industry that winter may become a shell of its former self. Already, the snow-water equivalent in the western United States has dropped 41% since the early 1980s, and the ski season has decreased by 34 days. Half of all Northeast ski resorts may go out of business by 2050, and climate modeling predicts that 90% of ski resorts in the West won't be financially viable by 2085 if greenhouse gas emissions aren't curtailed. Not that they'll have much to drink anyway: snow melt provides up to 75% of the water supply in western states.

Until recently, "there was an ethos within the outdoor industry and even the outdoor community to try and remain apolitical, and [these groups] saw climate change as a political issue," said Mario Molina, executive director of POW, which organized the letter campaign to oust Kasper.

Social media abuse would rain down on those daring to mention climate change, Molina said. Trolls descended on athletes speaking about climate, telling them to stick to their sport. Resorts risked angering customers when unleashing new sustainability initiatives.

Outdoor enthusiasts remained ambivalent. A 2020 POW report focused on the United States concluded that members of the community—people striving for physical sensations, for inner well-being, or to achieve new personal records—"are not prime candidates for abstract communal action."

But the same report showed that 90% of outdoor enthusiasts think climate change is caused by humans. The report also found that people who participate in outdoor sports are politically diverse: Democrats make up 40% of outdoor enthusiasts, whereas 31% are Republican and 29% identify as independent. The results were based on surveys of 2,100 people across a variety of sports, interviews with professional athletes, and online focus groups.

Skiing and snowboarding produce greenhouse gas emissions by powering ski lifts, snowmaking, and lodges. Tourists fly and drive across the world to ski, staying in chateaus and drinking at heated outdoor bars. But cutting their emissions won't stop global climate change.

"Even a victory like a large corporation cutting its carbon footprint by 30 percent—the stuff of Shazam-level super-heroism and incredibly difficult to pull off—wouldn't even dent the climate problem," wrote Aspen Skiing Company senior vice president of sustainability Auden Schendler in the *Stanford Social Innovation Review* in 2021. "Systemic change is the only path to climate stability."

For their sport to survive climate change, skiers will need to not only cut their emissions (see downhill emissions) but also somehow convince the rest of the world to cut its as well.

Because the industry's longevity relies on the actions of others, it has been slowly emerging as a vocal advocate for broad-based systemic climate reform. Activists have been spinning two webs of influence to enact change: (1) creation of an influencer-led, identity-driven voter bloc and (2) a jobs-first pitch to lawmakers on Capitol Hill.

The NRA of Skiing

The National Rifle Association (NRA) is not a group most would associate with skiers and snowboarders. But Schendler said the cohorts have more in common than you might expect.

"It's a very similar group if you think about why they're motivated," Schendler said. "They're gun people in the same way that I have a friend who says, 'I don't climb, I'm a climber.' 'I don't ski, I'm a skier.'"

"Think about gun owners, and then think about who's just as amped up, passionate, influential, wealthy, crazed? Well, it's the outdoor [community]. These are all fanatics," he said. Just look at how they spend their time: Skiers hit the slopes wearing garbage bags in the rain. Climbers live in their vans chasing the next project. Runners don headlamps to clock kilometers before dawn. "This is an unmobilized cohort that could swing elections."

The NRA has outsized power in Washington despite its middle-of-the-road spending on lobbying. As *Gallup* reports, although most people in the United States approve of gun control, Congress hasn't imposed tighter regulations (bit.ly/Gallup-gun-control).

Even the NRA's election spending is a fraction of what companies or individuals invest in attempting to sway polls.

"The NRA is not successful because of its money. To be sure, it is hard to be a force in American politics without money. The NRA has money that it uses to help its favored candidates get elected. But the real source of its power, I believe, comes from voters," said Adam Winkler, a professor of constitutional law at the UCLA, School of Law and author of *Gunfight: The Battle over the Right to Bear Arms in America*, told the *Guardian* in 2018. The organization remains one of the most powerful lobbying groups in Washington.

As the chairperson of POW's board, Schendler has talked about the NRA as an inspiration for years. POW's mission is to mobilize millions of outdoorsy people to climate action. Although POW originally focused on snow sports like skiing and snowboarding, the organization's target demographic now includes climbers, trail runners, and bikers as well.

POW mobilizes its base by reframing the political identity of an outdoors person, complete with voter guides and influencers. No longer are skiers and snowboarders just people who like chasing powder for fun; they are citizens of the "Outdoor State," a body politic that demands their allegiance and fidelity.

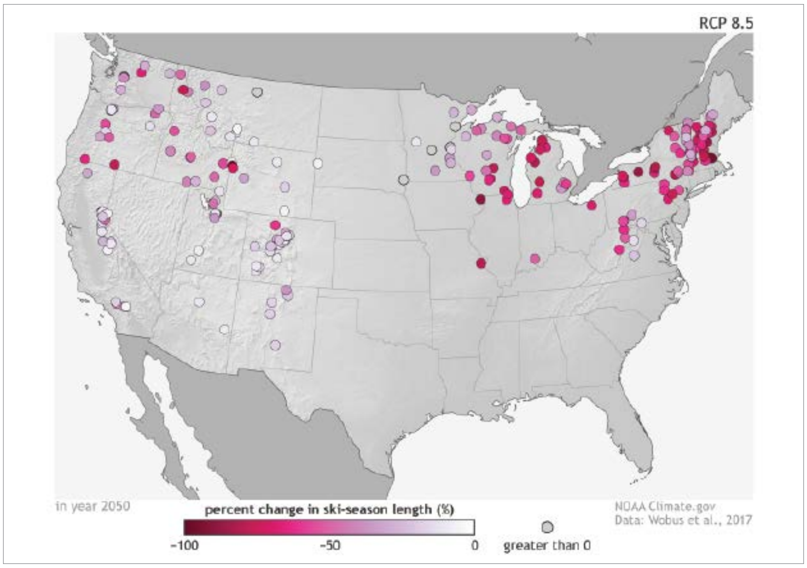
The Influencer Economy

Professional snowboarder Jeremy Jones founded POW in 2007, and ever since, the organization has recruited a collection of famous athletes to spread its message. "What makes POW different and unique—and I think where our potential really lies—is in this cadre of influencers," Molina said.

The more than 100 athletes in POW's alliance program have received training in science, advocacy, and clean energy. In exchange, they agree to appear at a certain number of public speaking events, to write op-eds and social media posts, and to generally exist as POW ambassadors. The arrangement is somewhat like the billion-dollar industry of influencers who represent corporate brands on Instagram and other social media sites. But most of POW's athletes volunteer their time apart from four paid "team lead" athletes who manage volunteers.

> *"There was an ethos within the outdoor industry and even the outdoor community to try and remain apolitical."*

Premier athletes like skier Hilaree Nelson, who boasts the first ski descent of the fourth-highest peak in the world (Lhotse, in China and Nepal), touts POW to her 59,200 followers on Instagram. Tommy Caldwell, a



If emissions remain unchecked, the snow season will be cut at least in half by midcentury at many ski resorts. Credit: NOAA

world-famous rock climber (821,000 Instagram followers), endorsed Joe Biden for president because of his climate-friendly policies and hosted an event with the League of Conservation Voters to get out the vote in 2020. Endurance runner Clare Gallagher (44,500 Instagram followers) penned an op-ed in *UltraRunning* magazine in April 2021 on coping with climate anxiety.

In the U.S. Senate race in Montana in 2018, POW athletes rallied around Democratic candidate Jon Tester, a two-term senator with a proenvironment voting history.

Mountaineer Conrad Anker of Bozeman and fly-fisher Hilary Hutcheson of the greater Missoula area led the

No longer are skiers and snowboarders just people who like chasing powder for fun; they are citizens of the "Outdoor State," a body politic that demands their allegiance and fidelity.

charge. The two gave press interviews, wrote op-eds, and posted on social media in support of Tester, all of which POW shared with its followers through social media, email, and the web, said Auden. Tester won by nearly 18,000 votes.

Although it's unclear how much POW played a role in Tester's victory, athletes drawing in incremental votes is exactly the organization's mission, Schendler said.

Other organizations also target environmentally conscious voters. The nonprofit Environmental Voter Project (EVP) reaches out to people who consider the environment one of their main political issues but visit the polls only in presidential elections. This cohort could pack a punch: An EVP report from this year found that environmental voters could swing 2022 midterms in six purple states if they showed up. These voters are predominantly young, female, and disproportionately Hispanic, Asian American, and Pacific Islander.

Like POW, EVP wants to remake the model of a "good environmentalist" from someone who recycles or is a vegetarian into someone who votes in all elections, big or small.

Consumer preferences force businesses to adapt, too. A 2016 study of 83 Western ski resorts published in *Strategic Management Journal* found that "environmental institutional pressures"— defined as regulatory, normative, and cultural pressures—have led to increased adoption of climate change mitigation practices by resorts. These pressures were more successful at forcing resorts to adapt than were the adverse effects of climate change itself.

In June, four of the biggest North American ski resort companies (Vail Resorts, Alterra Mountain Company, POWDR, and Boyne Resorts) signed a charter to enforce, among other things, unity in climate advocacy.

On the retail side, 82 brands have now joined POW's brand alliance by giving $5,000 or more to the nonprofit. Burton and Patagonia have both contributed more than $150,000.

The recent events suggest that athletes, resorts, and brands agree that talking about climate change is now fair game. POW's Molina credits his organization for this shift in opinion. "I think we were able to actually nudge the entire industry into the realization that civic engagement is not a political activity," he said.

The next question is, What will the industry and its fans do with their newly found voice?

Downhill Emissions

Ski resorts are cutting emissions in creative ways.

- Aspen Skiing Company in Colorado partnered with a local mine operator to trap methane from one of its coal mines that would otherwise leak into the atmosphere. The methane powers the ski area, producing energy equivalent to what's needed to power roughly 2,400 homes.
- Berkshire East Mountain Resort in Massachusetts powers itself on 100% renewable energy using solar and wind on site.
- Jackson Hole Mountain Resort in Wyoming operates 100% on wind energy purchased from a wind farm in neighboring Idaho.

From the Statehouse to Capitol Hill

Fifty million Americans participate in outdoor sports, and the pandemic inspired many to visit parks for the first time. Although it's easy to think of a solo paddle or a hike through a reclusive forest as far from an economic activity, outdoor adventures leave a trail of money in their wake: The gear. The clothing. The transportation. The marathon registration. The cabin. The after-trip milkshake.

But climate change threatens that money train: U.S. downhill skiing, just one subset of the outdoor economy, lost $1.07 billion over a decade because of lower snow years between 1999 and 2010, according to a 2012 POW and Natural Resources Defense Council report. This downturn led to a loss of up to 27,000 jobs, a drop in unemployment of as much as 13%.

Since the release of that 2012 report, there's been a race to calculate just how much outdoor recreation is worth. POW releases estimates, the Outdoor Industry Association (OIA) has reported its own, and more estimates are in the works.

In 2016, Congress passed an order for a thorough assessment of how much money the outdoor sector contributes to the U.S. economy. The Bureau of Economic Analysis set up a special fund for this purpose and in 2020 published a tally: $459.8 billion of current-dollar gross domestic product came from outdoor recreation in 2019. (The amount is half of the current-dollar gross domestic product from all arts and cultural activity in the country in 2019.)

According to a 2017 OIA report, American consumers spend about $887 billion on outdoor recreation annually. That is more than they spend directly on pharmaceuticals and fossil fuels combined.

These billions of dollars in market power form the backbone of lobbying by the outdoor industry. "It literally changed the conversation in Washington," said advocacy lead Chris Steinkamp at Snowsports Industries America (SIA), who led POW previously.

Before hard economic numbers appeared, the ski industry appealed to lawmakers by expressing a love of winter and a fear of its expiration date. Now advocates tout the sector's economic contribution to the U.S. economy. In Colorado alone, the ski industry generates $4.8 billion annually, according to a study by Colorado Ski Country USA and Vail Resorts.

Trade Organizations Band Together Amid Criticism

In 2019, SIA partnered with two other outdoor trade organizations to amplify their voices in Washington. Their goal is to use a jobs-first agenda to spur legislative climate wins.

Protect Our Winters founder Jeremy Jones, rock climber Tommy Caldwell, and ski mountaineer Caroline Gleich testify in front of the Senate Democrats' Special Committee on the Climate Crisis in Washington, D.C., in 2019. Credit: Jesse Dawson

The Outdoor Business Climate Partnership (OBCP) combines the power of SIA, which is a collection of winter recreation retailers, suppliers, resorts, and sales reps; the National Ski Areas Association (NSAA), which includes more than 300 alpine ski resorts and more than 400 suppliers; and OIA, an industry heavy hitter that represents 1,200 businesses in outdoor sports from big names like REI to small family shops.

The new partnership targets lawmakers in such states as Utah, Colorado, and New Mexico, where recreation is a major part of the state's economy. OBCP's priorities include putting a price on carbon, passing a clean energy standard, and supporting clean transportation.

Lawmakers on both sides of the aisle have aligned with OBCP. The partnership hosted Democratic Rep. Joe Neguse from Colorado and Republican Rep. John Curtis of Utah at a virtual event earlier this year, for instance.

Bipartisanship is at the heart of OBCP's mission. "We can't shame our elected officials into agreeing with us," said Steinkamp. "We have to be allies and not adversaries."

Steinkamp said that OBCP doesn't spend time talking to or supporting lawmakers who are climate skeptics, however. Instead, they home in on Republicans like Curtis, who recently launched a conservative climate caucus.

"We were very strategic with the name because we wanted to be very clear that we were embracing the science with climate, but that we were conservatives," Curtis said of the caucus in an interview with C-SPAN. "Today there are 65 members. It grows every day."

The industry's cross-party approach has attracted criticism, however.

The political contributions of ski resorts and their executives came under scrutiny following a 2016 article by Porter Fox in *Powder* magazine. Fox, a former *Powder* editor and author of *Deep: The Story of Skiing and the Future of Snow*, wrote that industry tycoons such as executives from Vail Resorts and Jackson Hole gave money to candidates or political action committees with a record of opposing climate legislation, according to records from the Center for Responsive Politics.

In a rebuttal, NSAA director of public policy Geraldine Link wrote, "The ski industry, like every other industry, is not 'single-issue' in its approach to advocacy." Republican candidates who were singled out in the article helped protect water rights and support year-round activities, she wrote. "We should be thanking these members of Congress, not attacking them."

"I think we were able to actually nudge the entire industry into the realization that civic engagement is not a political activity."

Three years later in an opinion piece in the *New York Times*, Fox responded. Supporting candidates who bolster year-round activities and water rights but not climate isn't enough, he wrote. "The time for soft-pedaling passed decades ago. At this very late stage in the game, the snow sports world needs decisive action."

To achieve the Paris Agreement target of limiting average global warming to 1.5°C, relative to pre-industrial temperatures, the world will need to phase out all carbon emissions by 2040. Humanity has made some progress: Before the Paris Agreement was reached, we were headed toward 3.6°C warming. Now we've got that down to 2.9°C.

But we have a long way to go: 2°C would still bring catastrophic climate impacts. And the world will need to make emissions cuts like those from the COVID-19 shutdowns every year for the next decade to keep warming below 1.5°C.

Snowpack in the Sierra Nevada dropped sharply in 2015 (top) compared with 2010 (bottom). Credit: Jesse Allen/NASA

Charting a Line for Years to Come

Famed alpinist and POW athlete Graham Zimmerman spent much of his twenties chasing peaks around the world. Even though he studied glaciohydrology in college, he pushed climate change to the back of his mind. And when he did think of it, he felt guilty for all the plane flights, car rides, and gear he tore through as an international athlete.

But in the 20-minute documentary *An Imperfect Advocate* from Outside TV, Zimmerman argued that climate activism is for everyone—even those with large carbon footprints. We see Zimmerman calling his representatives and visiting statehouses, high schools, and universities to talk up climate change policy.

"Our goal with solving the climate crisis is not to stop traveling, or stop heating our homes," Zimmerman said. Instead, it's to continue to do the things that "inspire us and drive us" but with carbon-neutral or carbon-efficient technologies. "And that all comes from government."

An Imperfect Advocate represents a tension in climate activism that goes back decades. To halt carbon emissions and slow global warming, should individuals put their energy toward cutting their carbon footprint? Or should people focus on calling for top-down regulation from lawmakers? And what if the emitter isn't a person, but an industry? Must an industry walk the walk before sticking its neck out for systemic change?

"The outdoor industry and winter sports industry are not the largest carbon emitters, but we rely on those larger [emitting] sectors like transportation and electricity," said Amy Horton, senior director of sustainable business innovation at OIA. The dependence on these carbon-heavy activities is a catch-22: Carbon pollution is still needed to bring customers, but it's also slowly eroding away the sport's future.

A review of 119 research studies of climate change risk to ski tourism across 27 countries, shows clearly that the industry is in for a shake-up. Resorts can't depend on natural snow anymore. They'll need to pump more water and burn more power to make artificial snow, ski areas will close, ski seasons will shrink and shift, ski markets will bend and morph as skiers travel for snow or give up the sport altogether, and real estate values will shoot up or down accordingly.

The industry finds itself at a crossroads that environmental activists have long pondered: How can climate policy pass in the United States when the politics remain so divisive?

Steinkamp of OBCP doesn't think the discussions over the past 10 years demanding immediate action have spurred productive policy, however. Although bipartisanship "takes time," he said, "I think this is where we see the long-lasting change happening."

POW has put its bet with a strong voter base of outdoors people—a group that overwhelmingly believes in climate change but is politically diverse—who it says could sway elections. OBCP is betting on forging relationships with emerging Republicans who believe in climate change to adopt climate legislation.

"I think this ship is slowly moving in the right direction," Molina said of recent partnerships in the outdoor industry. "The next year or two will actually show us how many of the new coalitions and groups that have emerged are going to really put their weight behind the statements."

Author Information

Jenessa Duncombe (@jrdscience), Staff Writer

▶ **Read the article at bit.ly/Eos-ski-climate**

Modeling Volcanic Debris Clouds

The 1991 eruption of Mount Pinatubo in the Philippines ejected large amounts of ash and gases into the air. A new study examines how this debris evolved over time and how it might have entered the atmosphere. Credit: Dave Harlow, USGS

When a volcano violently erupts, a plume of ash and gases spews skyward. The hot slurry quickly rises into the atmosphere, where various atmospheric dynamics interact to shape the volcanic cloud's composition, height, and radiative properties. Volcanic clouds reflect solar radiation, cool Earth, cause weather extremes, and delay global warming, but scientists have long wondered exactly how volcanic material evolves and parses itself after eruption. To date, observations of the initial stage of strong eruptions have been sparse, and conventional climate models used to study the impact of volcanic eruptions cannot capture this initial stage in great detail.

In a new study, *Stenchikov et al.* modified a regional atmospheric chemistry model, WRF-Chem, to better capture the initial stage of volcanic cloud development. The researchers modeled the 1991 Pinatubo volcanic eruption in the Philippines for their study, assuming that along with the eruptive jet, a significant amount of volcanic debris was delivered into the lower stratosphere. They conducted simulations with 25-kilometer grid spacing considering simultaneous injections of sulfur dioxide (SO_2), ash, sulfate, and water vapor. In addition, they accounted for the radiative heating and cooling effects of all plume components including gaseous SO_2.

The researchers found that differential heating played an essential role in the initial evolution of a volcanic cloud and its separation into layers, which then dispersed or fell to the ground. Their new model showed that during the first week after eruption, the volcanic cloud rose into the atmosphere 1 kilometer per day, driven initially by ash solar absorption and later by sulfate aerosol absorption of solar and terrestrial radiation.

The researchers note that their findings could be helpful in many applications, from aviation safety to understanding climate and geoengineering technologies. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2020JD033829, 2021) **—Sarah Derouin,** *Science Writer*

A New Method Produces Improved Surface Strain Rate Maps

Earthquakes occur when tectonic strain that has gradually accumulated along a fault is suddenly released. Measurements of how much Earth's surface deforms over time, or the strain rate, can be used in seismic hazard models to predict where earthquakes might occur. One way that scientists estimate strain rate is via orbiting satellites and detailed measurements of how much GPS stations on Earth's surface move.

There are challenges, however, to using such geodetic data. The stations provide measurements only at specific locations and aren't evenly distributed—constructing a continuous strain rate map requires that scientists make estimates to fill in data gaps. These interpolated data add uncertainty to resulting mathematical models.

To tackle these issues, *Pagani et al.* developed a transdimensional Bayesian method to estimate surface strain rates in the southwestern United States, with a focus on the San Andreas Fault. Their method essentially divided the study area into nonoverlapping triangles and then calculated velocities within each triangle by incorporating measurements from the GPS stations located inside.

The team didn't rely on just one such model. They used a reversible-jump Markov chain Monte Carlo algorithm to produce up to hundreds of thousands of such models, with slightly tweaked coordinates for those 2D triangles. In fact, across these models, even the number of triangles could change—because the method is transdimensional, the authors didn't predetermine any parameters. Finally, they stacked all these models together to generate a final continuous strain rate map.

Using test data, the authors found that their approach handled data errors and uneven data distribution better than a standard B spline interpolation scheme. In addition, because the approach included information from many models, it produced a range of strain rate estimates at each point and probabilities for those values.

When the team used the new approach to calculate strain rates around the San Andreas Fault system, they found that their map agreed with past studies. It even successfully differentiated creeping sections of the fault system from locked segments. The newly described technique could potentially be used by researchers to develop other strain rate maps and may generally have application to other interpolation problems in the geosciences. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2021JB021905, 2021) **—Jack Lee,** *Science Writer*

Improving Weather Simulations Through Increased Generality

Modern weather forecasts and climate studies rely heavily on computer simulations implementing physical models. These models need to make cohesive large-scale predictions but also include enough small-scale detail to be relevant and actionable. Given the enormous physical complexity of weather systems and the climate, realistic stochastic simulation of hydroenvironmental events in space and time, such as rainfall, is a significant challenge.

A statistical approach is a natural alternative to describe the huge variability of weather systems and the climate. Statistical models are easier to use and do not require massive computational resources and thus provide scientists and decisionmakers with operational, easy-to-use tools to study pressing climate-related problems. Nonetheless, statistical models often make simplifying assumptions.

Although these assumptions can make the modeling task more tractable, they also lead to additional divergence from the physical systems they are intended to represent. *Papalexiou et al.* describe improvements to the Complete Stochastic Modelling Solution (CoSMoS) framework that introduce significantly increased generality for a wide range of hydroenvironmental simulations.

One important addition is support for spatially varying velocity fields. These velocity fields govern the movement of packets of fluid, such as air or water, across the simulated region. Such gradients are extremely common in nature; the expansion of air as it warms, for example, creates an outwardly diverging velocity pattern. Similarly, the rotation of a hurricane or tornado requires a velocity field that curves in space.

The authors also describe the handling of anisotropy, in which the properties of the physical process can vary with not just distance from a reference point but also direction. By combining anisotropy with spatially varying velocity fields, a simulation can reproduce complex meteorological phenomena, such as storms or the rotating *and* spiraling structure of a hurricane.

After introducing these advancements, the authors demonstrate their potential through a series of numerical experiments. These simulations illustrate the wide variety of fluid structures and evolution patterns that such a platform can deliver. Nevertheless, challenges remain, including the high computational costs of simulating large structures at high resolution and the need for additional model development with the aim of global-scale simulations. (*Water Resources Research*, https://doi.org/10.1029/2020WR029466, 2021) **—Morgan Rehnberg,** *Science Writer*

Scientists Uncover the Seasonality of COVID-19

Much like the flu, COVID-19 fluctuates with the seasons, spiking in the winter and abating as the weather warms in temperate climates. Credit: Kristoffer Trolle, CC BY 2.0 (bit .ly/ccby2-0)

As the novel coronavirus has raced around the world, experts have wondered whether it would behave like influenza and other respiratory viruses, spiking in the winter and abating in the summer. Now, more than a year into the pandemic, researchers have enough data to confirm the seasonality of COVID-19 and determine which environmental factors may be driving it.

Of course, environmental factors alone cannot fully explain the spread of COVID-19; social and biological factors, such as population density and social distancing policies, also play a role. To isolate the impact of the environment, *Choi et al.* examined data on COVID-19 prevalence and environmental variables between 1 March 2020 and 13 March 2021 across five countries—Canada, Germany, India, Ethiopia, and Chile—that had relatively consistent social controls throughout the study period.

Previous studies have linked seasonal spikes of viruses like influenza, which spread by virus-laden droplets, to low humidity. But Choi and colleagues note that this pattern holds only in temperate regions; in the tropics, influenza peaks during the wet season. To account for this disparity, the team also looked at air drying capacity (ADC), defined as the rate of decrease with time of droplet surface area, given ambient temperature and humidity. Essentially, it predicts the fate of droplets under specific temperature and humidity conditions.

The team compared COVID-19 rates with the daily mean temperature, specific humidity, ultraviolet radiation, and ADC across a wide range of climate zones. Much like influenza, COVID-19 peaked in the winter months in the countries with temperate climates—Canada, Germany, and Chile—when temperature and humidity were at a low. But in the tropical countries, cases peaked during the summer monsoons, when humidity was at a high, suggesting that temperature and humidity considered separately can't explain the seasonality of respiratory viruses like influenza and COVID-19. The seasonal values of ultraviolet (UV) radiation and ADC, however, were consistent with fluctuations in COVID-19 prevalence across all five countries, with high ADC and UV linked to low prevalence, and vice versa.

Understanding the seasonality of the virus will be critical for future efforts to combat its spread, as experts have cautioned that people may need annual booster shots to protect against the virus and its emerging variants. (*GeoHealth*, https://doi.org/10.1029/2021GH000413, 2021) **—Kate Wheeling,** *Science Writer*

Crustal Motion and Strain Rates in the Southern Basin and Range Province

The Eagletail Mountains in southwestern Arizona are characteristic of the southern Basin and Range Province: rugged but with sinuous mountain fronts consistent with minimal young normal faulting. Credit: P. A. Pearthree, Arizona Geological Survey

North America's Basin and Range Province is home to some of the most extreme environments on the continent, including Death Valley. Stretching from the Wasatch Mountains in Utah to the Sierra Nevada in California and into northwestern Mexico, the area experiences near-constant drought and extreme summer heat.

The Basin and Range Province is also seismically active. For example, the 1887 Sonoran earthquake in the southern Basin and Range caused extensive damage and dozens of deaths. However, deformation rates in the southern Basin and Range are hard to quantify because there are young faults and infrequent seismic events. Furthermore, the adjacent San Andreas and Gulf of California fault systems of the Pacific–North American plate boundary can mask strain rates in the southern Basin and Range.

In a new paper, *Broermann et al.* explored deformation in a large area including Arizona, New Mexico, and southern portions of Utah and Colorado, within the southern Basin and Range and the Colorado Plateau. The authors observed crustal motion using the EarthScope Plate Boundary Observatory. The array of GPS sensors, seismometers, and other instruments monitor seismology and the tectonic plates underlying North America. The authors used the data to develop models of crustal surface velocity and strain rates in the study area. They concluded that accumulated strain in the crust is the primary driver of future continental earthquakes.

The authors separated the effects of the plate boundary and fluctuating impacts of coseismic and postseismic deformation on strain rates in the region. The results revealed three distinct regions with unique characteristics: a western region, an eastern region, and the Colorado Plateau interior block. Each area differs in the strain rate and motion it experiences, which can affect the probability of future earthquakes. For example, the western region features higher strain rates and an approximately east–west principal axis. In contrast, the eastern region has lower strain rates and a more west–southwest trending axis.

The region with the highest strain rate in the study area includes southwestern Arizona, an expanse with sparse faults and low seismicity. The high strain rate in the region may indicate a potential for future large-magnitude earthquakes, although strain accumulation may be reduced through other processes. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2020JB021355, 2021) **—Aaron Sidder,** *Science Writer*

Improved Algorithms Help Scientists Monitor Wildfires from Space

Raging wildfires pump tiny pollutants into the air, degrading air quality across vast areas. These pollutants, or aerosols, can soar high into the atmosphere at the tops of smoke plumes or creep close to the ground where they pose a health risk to humans. To track these pollutants and their spread, scientists need accurate monitoring systems that can see the whole picture.

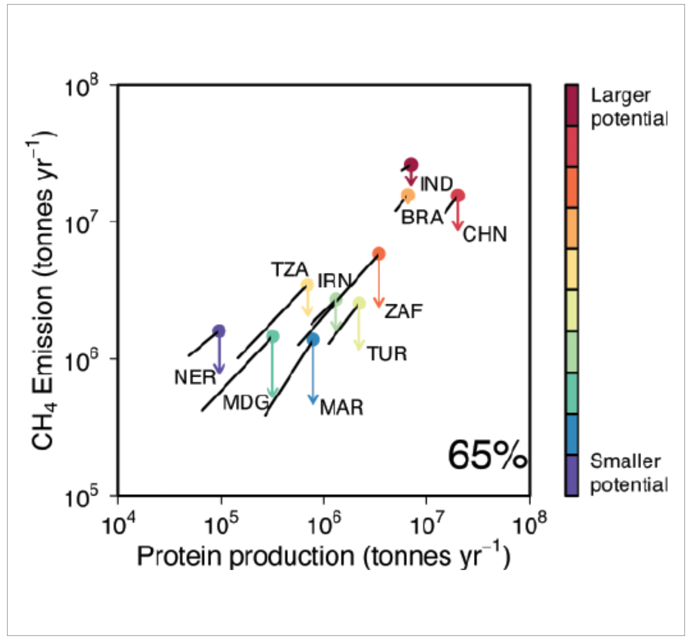
In the past, satellite monitoring, while providing a huge visual scope, fell short in on-the-ground measurements. In a new study, *Loría-Salazar et al.* evaluated improved algorithms using imagery from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) instruments. They tracked the spread of aerosols outward from the fire source and upward into the atmosphere, focusing on August 2013 fires in the western United States.

The researchers found that the new algorithms are much more accurate, aligning well with on-the-ground measurements. Research into their plume heights also revealed that whether aerosols from wildfires will remain within the planetary boundary layer—the lowest layer of the atmosphere (where people live, breathe, and are exposed to smoke), which is heavily influenced by Earth's surface—depends on local geography and daily weather conditions. In addition, the researchers argue that it is necessary to continue investigating the role of aerosols in local and regional weather when smoke penetrates different layers of the atmosphere.

The new research suggests that satellites may fill observation gaps in areas without ground-based monitoring or by providing additional data in areas with complex weather patterns. The accurate algorithms used to track aerosol distribution can also inform models of future aerosol conditions, especially to predict impacts to human health. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2020JD034180, 2021) **—Elizabeth Thompson,** *Science Writer*

What's the Beef About Methane?

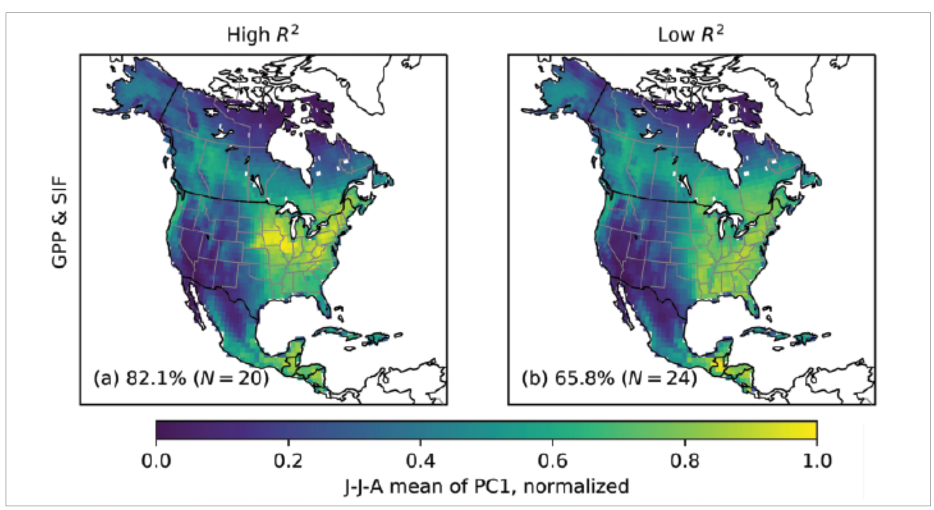
Methane is the second most important greenhouse gas, and livestock produce one third of anthropogenic methane emissions. *Chang et al*. quantify the potential to mitigate methane emissions through continued improvements in livestock management practices that reduce the amount of methane emitted per kilogram of livestock protein produced. This increased production efficiency is shown to offer the greatest potential to reduce methane emissions as worldwide demand for livestock products grows. Some of the largest mitigation opportunities are in developing countries where livestock production is expected to grow but efficiency is currently low. (https://doi.org/10.1029/2021AV000391, 2021) **—Eric Davidson**



Projections from the accounting method used by Chang et al. *for increases in protein production and methane emissions for all livestock under business-as-usual scenarios (black lines)—and for the livestock emissions reduction potential from improved production efficiency (arrows)—in selected countries from 2012 to 2050 are shown here. There is considerable opportunity to reduce emissions in the 10 countries plotted: Brazil (BRA), China (CHN), India (IND), Iran (IRN), Morocco (MAR), Madagascar (MDG), Niger (NER), South Africa (ZAF), Tanzania (TZA), and Turkey (TUR). The color bar represents the relative scale of mitigation potential. The number at lower right, 65%, indicates the contribution of these 10 countries in global total mitigation potential from improved livestock management. Credit: Chang et al., 2021*

Croplands Reduce Carbon Dioxide During the Growing Season

The land-atmosphere carbon balance has long been one of the most uncertain components in the global carbon cycle. However, data from carbon dioxide (CO_2) observation networks and from global satellites are increasingly providing constraints on this balance, especially for the seasonal uptake of CO_2 in the temperate growing season. *Sun et al*. evaluate seasonal land carbon uptake from a range of prognostic and diagnostic land models. They compare the atmospheric CO_2 pattern derived from coupling modeled fluxes to atmospheric transport models with actual patterns observed by a network of tall tower stations in continental North America. Models that best reproduced the observed spatial and temporal variability in atmospheric CO_2 were those that showed the strongest growing season uptake in croplands. This runs counter to the common view that this uptake is dominated by forests. (https://doi.org/10.1029/2020AV000310, 2021) **—Susan Trumbore**



Major patterns of CO_2 uptake by photosynthesis (as indicated by gross primary production, GPP) during the June–July–August growing season (in arbitrary units) resulting from the combination of satellite solar induced fluorescence (SIF) data with models are seen here. Shown are (left) the mean pattern from models that best reproduced observed atmospheric CO_2 variations during 2007–2010 and (right) the mean pattern from models that showed less correspondence with observed variations. Models with higher explanatory power (left) indicate greater seasonal uptake in croplands and forests compared with those with less explanatory power (right). Credit: Sun et al., 2021

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Expedition 397: Iberian Margin Paleoclimate

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The Iberian Margin has rapidly accumulating sediment that contains a high-fidelity record of millennial climate variability. Sir Nickolas Shackleton demonstrated that piston cores from this region can be correlated precisely to polar ice cores from both hemispheres. Moreover, the narrow continental shelf off Portugal results in the rapid delivery of terrestrial material to the deep-sea environment, thereby allowing correlation of marine and ice core records to European terrestrial sequences. Few places exist in the world where such detailed marine-ice-terrestrial linkages are possible. The continuity, high sedimentation rates, and fidelity of climate signals preserved in sediments make this region a prime target for ocean drilling. On Expedition 339, Site U1385 was drilled and recovered a complete record of hemipelagic sedimentation for the last 1.43 Ma with a mean sedimentation rate of 11 cm/kyr. Expedition 397 will extend this remarkable sediment archive through the Pliocene and recover a complete depth transect of five sites that will provide a suite of downhole records with which to study past variability in the major subsurface water masses of the North Atlantic.

Expedition 398: Hellenic Arc Volcanic Field

6 December 2022 to 5 February 2023

The Hellenic Arc Christiana-Santorini-Kolumbo (CSK) volcanic field, which includes Santorini caldera and its Late Bronze Age eruption, provides a unique opportunity to address how subduction-related volcanism impacts life. Better understanding of island-arc volcanism requires study of the processes that drive such volcanism, and how the volcanoes interact with the marine environment. What are the links between crustal tectonics, volcanic activity, and magma genesis? What are the dynamics and impacts of submarine explosive volcanism and caldera-forming eruptions? What are the reactions of marine ecosystems to volcanic eruptions? The rift basins around the CSK field, as well as Santorini caldera, contain volcano-sedimentary fills up to several hundreds of meters thick. We propose to drill six sites, four in the rifts basins and two in Santorini caldera. Deep drilling is essential to characterize and interpret the depositional packages visible on seismic images, to chemically correlate primary volcaniclastic layers in the rift fills with their source volcanoes, to fill in gaps in onland volcanic records, to provide a precise chronostratigraphic framework for rift tectonic and sedimentary histories, and to characterize the subsurface microbial life.

For more information on the expedition science objectives and the *JOIDES Resolution* schedule see http://iodp.tamu.edu/scienceops/. This page includes links to the individual expedition web pages with the original IODP proposals and expedition planning information.

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Dear *Eos*:

Laguna Bacalar in the Yucatán Peninsula of Mexico—called "the lake of seven colors" by the Maya for its varying shades of turquoise and blue—is home to one of the largest freshwater microbialite reefs ("living rocks") in the world.

Here, a near-contiguous microbialite reef runs for over 15 kilometers along its southern shoreline edged by cenotes (sinkholes). These modern-day reef structures are formed, like those of the fossil stromatolites, by a millimeters-thin layer of subsurface cyanobacteria growing in the carbonate-rich karstic waters of the lagoon. Therein, micrometer-sized filamentous cyanobacteria precipitate calcium carbonate during photosynthesis and keep rising as the reef builds up around them, to stay within the sunlit zone.

Life in the microbialite ecosystem appears to hide just millimeters beneath the limestone surface in a thin "Goldilocks zone"—neither on the very surface, where filaments might suffer UV photodamage, nor too far below the surface, where it may receive too little sunlight and waterborne nutrients for photosynthesis and growth.

So much of life on Earth is found hidden from our senses below the surface and remains understudied in terms of its evolution, physiology, biogeochemistry, and biodiversity. We should be probing, imaging, and studying all forms of extant subsurface life for a fuller understanding of Earth's closely interconnected biosphere.

—**Bopi Biddanda,** Robert B. Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich.; and **Scott Kendall,** Life Sciences Department, Muskegon Community College, Muskegon, Mich.

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Father of American hydrology and founder of AGU's Legacy Society

Robert E. Horton, often called the father of American hydrology, is remembered most as a scientist of great vision, curiosity, and originality. Horton was very active in several professional societies, allowing him to think and work with colleagues across disciplinary lines. The ultimate emergence of his seminal ideas was the result of his innate ability to think across disciplines and his continual interplay between engineering practice and scientific curiosity.

In keeping with his legacy of curiosity and collaboration, the Robert E. Horton estate and AGU's Hydrology section established the Horton Research Grant. Since 1983, the grant has been awarded to up to three Ph.D. candidates annually in support of research projects in hydrology (including its physical, chemical, or biological aspects) or in water resources policy sciences (including economics, systems analysis, sociology, and law). Each winner receives $10,000 in support of his or her work as well as travel to the AGU Fall Meeting to advance his or her project and network.

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