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SCIENCE NEWS BY AGU

A Volcanic Influence on Climate

Sea Ice Is Going, but When Will It Be Gone?

Ireland's Missing Earthquakes

An Eye on the Mediterranean

Scientists reevaluate regional risk and response

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Beyond the Wine-Dark Sea

The Mediterranean Basin is home to harvests and hailstorms, tourism and tectonics, windswept coasts and wavering water supplies. In this issue of *Eos*, we explore how a more thorough understanding of hazards in the region is helping scientists better inform stakeholders on risk assessment, food security, resource management, and energy production.

The benefits of more robust weather forecasting are outlined in "How Hail Hazards Are Changing Around the Mediterranean" by Sante Laviola, Giulio Monte, Elsa Cattani, and Vincenzo Levizzani (p. 34). In this feature, the scientists identify hot spots throughout the Mediterranean and describe the development of innovative modeling techniques that are "useful for both climatological studies of hail events and the operational needs of meteorologists." This new "climatology of hailstorms" clarifies links between climate change, hail, and damage to crops and infrastructure in the Mediterranean and beyond.

In "A Common Language for Reporting Earthquake Intensities" (p. 28), authors David J. Wald, Sabine Loos, Robin Spence, Tatiana Goded, and Ayse Hortacsu use the devastating impact of the 2023 Kahramanmaraş earthquake in Türkiye to make the case for a comprehensive macroseismic scale. Such a scale would cohere a jumble of crowded, crowdsourced Internet reports, as well as discordant scientific scales used in Europe, Asia, and the Americas.

A deep dive into the shallow earthquakes of the Kahramanmaraş sequence is also the focus of "The 2023 Türkiye-Syria Earthquakes Shifted Stress in the Crust" by Erin Martin-Jones (p. 22). Although the complex tectonic interplay underlying Anatolia is not new to scientists, these earthquakes allowed them to better identify seismic links between neighboring faults. A more nuanced understanding of stress transfer may help stakeholders in Türkiye, Syria, and the rest of the tectonically active Eastern Mediterranean prepare for future quakes with more targeted construction codes and awareness campaigns.

The evolving nature of society's ecocultural contract with water—particularly near Spain's mountainous Mediterranean coast—is the topic of this month's Opinion, "Protecting the Mountain Water Towers of Spain's Sierra Nevada" by Bopaiah A. Biddanda, Manuel Villar-Argaiz, and Juan Manuel Medina-Sánchez (p. 18). They stress the importance of holistic study and practical application to conserve these freshwater resources, from source to sea.

The integrated approaches pursued by scientists in this issue are applicable far beyond the Mediterranean: Consistent, systemic, and rigorous science contributes to healthier, safer communities.

Caryl-Sue Micalizio, Editor in Chief

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Janice Lachance, Interim Executive Director/CEO

This issue includes FSC-certified paper.

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This satellite image dramatically displays the depths and heights of the Mediterranean Basin. Credit: titoOnz/Alamy Stock Photo

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Where Does Fire Retardant Fall in a Forest? Ask a Satellite

A plane drops a red slurry of fire retardant onto the Taylor Fire in Coconino National Forest in Arizona, in 2009. The U.S. Forest Service applied more than 28 million gallons of fire retardant between 2010 and 2020, according to the Los Angeles Times. *Credit: Coconino National Forest, Ariz./Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0*

Here's an image that's all too familiar: A red cloud of fire retardant pours from the belly of a propeller plane onto a forest below. As climate change supercharges wildfires, fire crews are increasingly relying on fire retardants to create chemical breaks and contain fires. Knowing where the spray lands helps crews and scientists manage and study its effects.

A new remote sensing tool may help crews and scientists pinpoint the exact location of fire retardant by taking advantage of satellite images.

The tool "should be faster, cheaper, and better" than current methods, said Jerry Tagestad, a Pacific Northwest National Laboratory geographer who developed the technique.

Machine Learning in Action

The exact coordinates of where fire retardant lands depend on the wind and topography of the ground below. The red slurry loses its color within weeks under the Sun and washes away in the rain, making it difficult for scientists to study how it has affected the landscape.

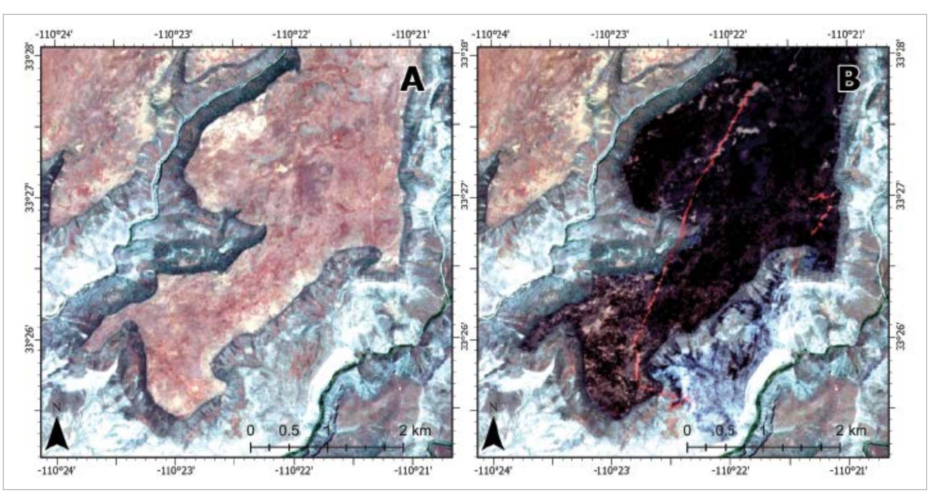
The U.S. Forest Service records a GPS location each time a plane releases fire retardant from its hatch. In some cases, fire crews fly a second plane to take photographs of the ground and trace drop locations by hand.

But restrictions to air space and other constraints make follow-up flights difficult during a fire.

To develop the tool, Tagestad and his colleagues trained a machine learning algorithm to locate retardant lines in images taken by the European Space Agency's Sentinel-2 satellite. They first sat down with satellite images and denoted areas with and without retardant. Using three machine learning classification models, the group then trained the computer to recognize those patterns in new images.

"We're taking the human out of the loop in terms of the mapping itself," Tagestad said.

The team tested the tool on images from seven fires in the southwestern United States that burned between 2020 and 2021. Five of



True color (a) before and (b) after images from the Sentinel 2 satellite reveal the red line of fire retardant dropped on the landscape during a fire in Blue River, Ariz., in 2020. Credit: Tagestad et al., 2023, https://doi.org/10.3390/rs15020342 the seven study sites were in scrub and shrubland—a more accessible landscape for remote sensing—and two were in conifer forests.

The three machine learning models successfully identified fire retardant lines at the seven sites—the best-performing model captured 62% of fire retardant with 99% precision. "Using this method, you may be able to report [the fire retardant location] within a week after the fire," Tagestad said. The team published the work in the journal *Remote Sensing* (bit.ly/remote-sensing-fire-retardant).

Previous research by the Forest Service found that fire retardant likely affects some threatened and endangered aquatic life.

Applications for Aquatic Habitats

"This work offers a novel and promising way to map fire retardant more effectively," said conservation ecologist Karen Hodges of the University of British Columbia, who was not involved in the research.

NOAA Fisheries expert Joseph Dietrich, who studies fire retardant toxicity in Chinook salmon, called the remote sensing technique a positive step forward. He said the tool could be designed to detect accidental fire retardant drops over water automatically by identifying breaks in fire retardant lines captured in the satellite images. Previous research by the Forest Service found that fire retardant likely affects some threatened and endangered aquatic life, and other studies have suggested that fire retardant enhances weeds and harms Chinook salmon (bit.ly/NSF-fire-retardant).

Dietrich is interested in future versions of the tool estimating the quantity and concentration of fire retardant across a landscape to understand better the amount entering salmon habitats. Tagestad said the team is excited to expand the tool's capabilities, including remotely sensing the thickness of fire retardant across the drop zone, which could be used to calculate the amount of fire retardant entering sensitive habitats.

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

New Forecasting Tool Could Help Indian Farmers Plan Irrigation

Tropical weather can be capricious, torrid one minute and drenching the next. Such mercurial meteorology poses challenges to farmers, who need to predict soil moisture to plan irrigation. In a new study, scientists developed a tool for Indian farmers in the region of Nashik that provides weather forecasts and irrigation suggestions at the scale of a single farm (bit.ly/Indian-farms). The authors said it could be used across the region's 6,000 hectares of farmland—and potentially beyond.

"It is an excellent initiative, and the objective to help farmers manage farm-level operations better is no doubt a good one," said Madhavan Rajeevan, a meteorologist and former secretary of the Ministry of Earth Sciences in India who was not involved in the study.

"Decision Tools in an Uncertain Environment"

The 4-year study encompassed two entire growing seasons, including two monsoon seasons (called kharif) and two winter seasons (called rabi).

The scientists enlisted the help of 10 grape farmers in the district of Nashik who had soil moisture sensors. Using data from just two of the 10 available sensors and estimates from satellites, they quantified current levels of soil moisture. The decision to use a small subset of available data demonstrated that the method could be successful despite limited field observations.

The researchers then gathered weather-related data such as rainfall, temperature, humidity, and wind from the India Meteorological Department's hindcasts and forecasts. Weather forecasts typically reach 10-kilometer scales at best, so they integrated these data into a machine learning model that yielded small-scale predictions useful to farmers. The new method forecasted rainfall 1–3 weeks in advance and at the scale of individual farms.

Given current soil moisture and predicted rainfall, the study's authors then developed a tool that translated forecasts into irrigation decisions. The tool saved water compared with the farmers' traditional approach, which relies on personal notes of past rainfall, daily weather conditions, and how dry the soil looks. The new forecasting tool reduced water usage by 20%–45% during the monsoon season and by 17%–35% during the winter season.

"The real contribution [of the study] is developing decision tools in an uncertain environment," said Subimal Ghosh, a coauthor and a hydroclimatologist at the Indian Institute of Technology Bombay. "The idea is to provide a simple tool to help farmers, especially poorer ones who cannot afford [soil moisture] sensors, decide how much water they should use."

Still, Rajeevan was skeptical. For starters, using large weather circulation patterns to make farm-level predictions introduces inaccuracies. In addition, it's not clear how easy it will be to scale up this small case study.

Ghosh, though, remained resolute. "No model predictions are perfect," and finer resolutions always add errors and uncertainties, he said.

"The real contribution is developing decision tools in an uncertain environment."

Weather Predictions with Climate Change

Early-warning systems like the new forecasting system could gain prominence as the climate changes. For example, the World Meteorological Organization recently announced a global initiative to build and scale early-warning systems, especially in vulnerable regions of Africa, Central and South America, South Asia, and small island states.

The new study is just one step in that direction. The next, the authors said, is to develop an app that broadcasts climate advisories in local languages. "This is very important for Global South countries with resource constraints," said coauthor Raghu Murtugudde, a climate scientist at the Indian Institute of Technology Bombay. "Adaptation is about learning how to manage the unavoidable."

By **Rishika Pardikar** (@rishpardikar), Science Writer

Soil Fungi May Be a Carbon Pool

Mycorrhizal fungi—soil-dwelling fungi that exchange nutrients with plant roots—are important players in plant and soil health. A new study published in *Current Biology* suggests that they are also significant carbon pools (bit.ly/fungi-carbon).

The researchers estimated that the fungi receive the equivalent of 13 billion tons of carbon dioxide (CO_2) annually from plants—an amount equal to 36% of current annual fossil fuel emissions.

"This confirms that the carbon flux to mycorrhizal fungi is globally significant," said Karina Clemmensen, a biologist at the Swedish University of Agricultural Sciences who was not involved in the research.

Exceeding Expectations

Mycorrhizal fungi absorb water and such mineral nutrients as nitrogen, sulfur, and phosphorus from the soil and deliver those nutrients to their plant partners. In return, plants provide the fungi with sugars and fats produced during photosynthesis.

This mutualism between plants and fungi has a long history: Mycorrhizae have been found in plant fossils more than 400 million years old. Today, most land plants form relationships with mycorrhizal fungi. (Notable exceptions include mosses and cabbages.) The fungi form a vast subterranean web that stabilizes soils, shuttles nutrients toward Earth's surface, and allows plants to grow and thrive.

Because plants supply mycorrhizal fungi with carbon-rich food, the fungal web can transport—and store—large amounts of carbon. But so far, this potential has been underappreciated, said Heidi-Jayne Hawkins, the study's lead author, an ecologist at the University of Cape Town and director of research at Conservation South Africa. "We have known for some time that these fungi are ubiquitous and vital across the planet," she said, but "soil fungi are more difficult to study than organisms aboveground, and progress tends to be slower."

To put a number on global mycorrhizal carbon cycling, Hawkins and her coauthors consulted 198 published data sets recording the percentage of plant-derived carbon that ends up in mycorrhizae. Some mycorrhizal fungi receive only 1% of a plant's carbon budget, with the rest going into plant biomass; other fungi receive far more.

The researchers combined this information with estimates of the total amount of atmospheric carbon taken in each year by various groups of plants. This enabled the authors to extrapolate how much carbon is allocated annually to mycorrhizal fungi.

The researchers compared their result with the total annual CO_2 emissions from fossil fuels. "We were surprised that the flux to the fungi amounted to 36% [of CO_2 from fossil fuel emissions]," Hawkins said. The high carbon flux implied that mycorrhizal fungi can influence atmospheric CO_2 concentrations and could amplify or reduce global warming.

Taking the Fungal Perspective

The result should be interpreted as a rough estimate that can guide future, more refined investigations, according to Clemmensen. To truly understand mycorrhizal fungi's role in carbon cycling, she said, scientists must first understand their life cycles and interactions with their surroundings: "[We need] to take the fungal perspective!"

Most of the source data were obtained from short-term laboratory studies, Clemmensen explained, so they may not reflect how mycorrhizal fungi store and transport carbon in nature or in the long term.

Not all the carbon accepted by mycorrhizal fungi remains in the soil. Fungi release CO_2 as they respire, or breathe, and can either promote or inhibit decomposition of organic matter, which reintroduces CO_2 to their surroundings. Some carbon is incorporated into fungal biomass underground, but the total size of that biomass, as well as the effects of respiration and decomposition, is still unclear.

"Mycorrhizal fungi certainly constitute a substantial carbon pool—and one we do not want to lose."

Hawkins said she hopes these questions will be addressed as mycorrhizal fungi receive more attention from researchers. "While there are uncertainties, mycorrhizal fungi certainly constitute a substantial carbon pool—and one we do not want to lose," she said.

Soil fungi are threatened by agriculture and development but are often neglected in environmental policy and conservation efforts. Agricultural practices such as preferring perennial to annual crops, not tilling the soil, and planting diverse crops can prevent damage to fungal webs, Hawkins said. In addition, protecting natural forests and grasslands helps to preserve fungi.

Clemmensen agreed that mycorrhizal fungi deserve environmental consideration. "Most plant species form symbioses with tens to hundreds of fungal species," she said. "In my opinion, the most important action would be to conserve the few pristine ecosystems that we have left to secure their biodiversity."

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

Boletus edulis *(also called porcini or penny bun) is a fungus that forms mycorrhizal relationships with trees. Credit: PalKarlsen/Pixabay*

On-Again, Off-Again Lake Cahuilla Likely Enhanced Earthquakes in Southern California

California's Salton Sea sits in the basin that once held mighty Lake Cahuilla, which stretched from Palm Springs to Mexico. Credit: Rman 348/Wikimedia Commons, Public Domain

In the arid expanse of what is today Southern California, a vast lake once waxed and waned. Lake Cahuilla spanned thousands of square kilometers before drying away to nothing and then reappearing in a decades-long cycle that repeated over millennia. When the lake was full, it served as a resting place for migratory waterfowl, and its ecosystem provided plentiful food and freshwater to communities of Indigenous Peoples.

Now, a new study published in *Nature* suggests that Lake Cahuilla had an effect not only on the surface but also underground (bit.ly/lake-filling). The filling of the lake may have caused major earthquakes along the southern reach of the San Andreas Fault, as the weight of the water increased pressure on the rocks underneath.

Today, with the lake gone and unlikely to return, those earthquakes have settled down—though the tectonic strain that caused them has continued to accumulate and will one day lead to another large earthquake in the region.

A Massive Lake Appears

Lake Cahuilla formed as the Colorado River periodically changed course, spilling into the low-lying Salton Trough instead of the Gulf of California. The trough typically would fill to a depth of around 100 meters (330 feet) before the Colorado returned to its normal course, and the lake would gradually evaporate.

"Lake Cahuilla extended from Palm Springs all the way down into Mexico," said Thomas Rockwell, a geologist at San Diego State University and a study coauthor. "It was a large, large lake."

Radiocarbon dates from sediments and charcoal found within Lake Cahuilla's one-time shoreline indicate that the lake had appeared and vanished six times over 1,100 years, with the last lake reaching its zenith around 1733.

That date and those of the five previous lake highstands match up nearly perfectly with the dates of major earthquakes in the region, Rockwell and his coauthors found. "Earthquakes can punch through layers of sediments, leaving a visible scar that scientists can use to date approximately when an earthquake happened," explained Ryley Hill, lead author of the study. Hill is a Ph.D. candidate at San Diego State University and the Scripps Institution of Oceanography at the University of California, San Diego.

Previous work pairing radiocarbon dating of Lake Cahuilla with paleoseismic data had already hinted at a connection between the lake's high points and prehistoric earthquakes. But with more data points and a more precise series of dates, the researchers were able to establish the relationship with greater certainty.

"The idea is not new, but the data is really amazing," said David Sandwell, a professor of geophysics at Scripps who was not involved with the research. "This matchup is so good that it's probably very likely the two are related."

The connection probably came down to what's known as induced seismicity, which describes earthquakes triggered by forces outside of the normal stress generated as Earth's tectonic plates interact with each other. It's been known to happen as large reservoirs are filled with water and explains why wastewater injection is often accompanied by swarms of earthquakes.

When it was full, Lake Cahuilla, which sat above a portion of the southern San Andreas Fault, exerted pressure on the fault equal to nearly 10 atmospheres, the researchers said. That's tiny compared with the pressure already inside the crust, but it could be enough to contribute to earthquakes.

The weight of the lake's water increased the fluid pressure along the fault, pushing the sides away from each other and making the fault more prone to slipping. It's a phenomenon similar to how airflow on an air hockey table helps the puck glide along more easily by lifting its edges off the surface, Hill explained.

The slight depression in Earth's crust created by the lake played a role, too. Bending of the crust made earthquakes more likely at the edges.

"Earthquakes are more frequent when there's water," Rockwell said.

The Desert Returns

Today, the Colorado River is held back by Hoover Dam on the border of Arizona and Nevada, making any reappearance of Lake Cahuilla improbable at best. In its place is the Salton Sea, a shallow, briny lake about one sixth the size of Lake Cahuilla created when an irrigation canal burst in 1905. The Salton Sea isn't big enough to noticeably affect the odds of an earthquake happening on the San Andreas Fault, Rockwell said. It is also shrinking and, with agricultural fields lining its rim, unlikely ever to be allowed to grow significantly in size.

"Earthquakes are more frequent when there's water."

The disappearance of Lake Cahuilla makes it more difficult to predict when an earthquake might happen along the San Andreas Fault, said Debi Kilb, a project scientist at Scripps who wasn't involved with the research.

With the lake gone, the main force contributing to earthquakes along the fault today is the slowly building tectonic stress between the North American and Pacific plates.

Where once earthquakes happened in the region about every 180 years, now "the recurrence time has been reset," Kilb said.

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

Ambidextrous Microbes May Pump Out CO_2 as Temperatures Rise

Some tiny forms of life double-dip to sustain themselves: They're both photosynthetic and predatorial. But as the planet warms, such mixotrophic microbes are apt to shift away from being sunlight driven to being more predatory, researchers have found. And because photosynthesis consumes carbon dioxide (CO_2) and respiration expels the greenhouse gas, that transition has important implications for the climate. Furthermore, the early-warning signs that signal an impending shift from a carbon sink state to a carbon source state are muted in the presence of high levels of nutrients, the team reported in *Functional Ecology* (bit.ly/microbes-carbon).

Mixotrophy, which combines characteristics of both autotrophs and heterotrophs, is not common among macroscopic organisms. The Venus flytrap is one well-known example, said Dan Wieczynski, a biologist at Duke University in Durham, N.C. "It's sort of like a predator and a plant at the same time." However, such double-dipping is believed to be downright common among the smallest forms of life. "Mixotrophy is probably the dominant strategy in microbes," Wieczynski said.

Tiny but Mighty

The collective amount of all the CO_2 that mixotrophic microbes are capable of sequestering or releasing is likely to be substantial, Wieczynski said. That's because the combined biomass of Earth's microbes, including bacteria and plantlike organisms known as protists, exceeds that of animals by a factor of roughly 40, according to recent estimates. "They outweigh animals by a country mile," Wieczynski said.

To better understand how changes in ambient temperature and nutrient concentrations affect whether mixotrophs are more likely to practice photosynthesis or predation, Wieczynski and his colleagues focused on photosynthetic protozoa. These tiny lifeforms can photosynthesize or feed on bacteria.

"It's sort of like a predator and a plant at the same time."

"People have known about these organisms for centuries, but they've more or less been considered curiosities," said Aditee Mitra, a marine ecologist at Cardiff University in the United Kingdom, who was not involved in the research.

Sun Bathing or Hunting?

Wieczynski and his collaborators investigated how protozoa variably engaged in photosynthesis or predation at temperatures ranging from 19°C to 23°C and under different nutrient concentrations. The team used differential equations to model the temperature- and nutrient-dependent changes in mixotroph and prey biomass due to photosynthesis and predation. The reasearchers furthermore

Photosynthetic protozoa, such as Paramecium bursaria, *may be more apt to be carbon emitters as temperatures rise. Credit: iStock.com/NNehring* quantified how shifts in the balance of photosynthesis and predation translated into overall changes in CO_2 flux from the mixotroph system.

"We were interested in understanding how warming and nutrient loads, particularly high nutrient loads, would affect mixotrophic systems," Wieczynski said.

The researchers found that at low temperatures, their model consisted of very low densities of prey and that the protozoa relied primarily on photosynthesis: Only 17% of biomass production was derived from predation at 19.8°C, for example. As a result, the system was absorbing far more carbon than it was producing at lower temperatures, the team concluded.

> **"Warming may cause mixotrophs to pump more carbon dioxide into the atmosphere, which, in turn, causes more warming."**

At high temperatures the model was dominated by predation; at 22.2°C less than 1% of biomass production derived from photosynthesis. Because respiration was far more prevalent than photosynthesis, the system at higher temperatures was producing much more carbon than it was absorbing, the researchers surmised.

Flip-Flopping

But things got interesting at intermediate temperatures. Wieczynski and his collaborators found that at between 20.7°C and 21.1°C, the mixotrophs tended to fluctuate in abundance and to cycle rapidly between engaging in photosynthesis and predation. All that flip-flopping meant that the system variably functioned as a carbon sink and a carbon source. "You get these wildly fluctuating dynamics," Wieczynski said.

In a warming environment, such fluctuations could be viewed as early-warning signals that mixotrophic microbes are beginning to shift from a carbon-absorbing photosynthetic state to a carbon-emitting predatory state, the team proposed. But in the model, the temperature window over which that flip-flopping persisted—essentially the amount of warning time—tended to shrink as nutrient concentrations increased, Wieczynski and his collaborators found. "That early-warning signal shrinks and eventually disappears," Wieczynski said. That's a worrying observation, the researchers explained, given that nutrient levels have been increasing in natural environments, in part because of fertilizer runoff from agriculture.

A Vicious Cycle

These new findings are cause for concern given global temperature trends, the researchers suggested. The planet has already warmed by nearly 1°C from the 20th-century average, and up to 3°C of additional warming is predicted by the end of the century. "Warming may cause mixotrophs to pump more carbon dioxide into the atmosphere, which, in turn, causes more warming," Wieczynski said. "Because mixotrophs are so abundant globally, such a positive feedback loop may not be just a local phenomenon restricted to a small pond or a tiny region of the ocean but instead could affect carbon cycling and climate on a global scale."

Mixotrophic microbes no doubt play a role in the planet's carbon budget, Mitra said, but more sophisticated modeling is necessary to better understand the impact of these tiny organisms. The model that Wieczynski and his colleagues used is overly simplistic, she said, and some of their conclusions are at odds with the findings of other studies.

For instance, Mitra and other researchers recently found that communities of mixotrophic microbes don't rapidly toggle between photosynthesis- and predation-dominated states. Although capable of both trophic modes, they stick with one or the other. "There's no flip-flopping," Mitra said.

It's clear that more work is needed, she said. To that end, Mitra and her colleagues have begun compiling a database of mixotrophic plankton to better understand how these organisms grow, photosynthesize, and ingest prey.

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

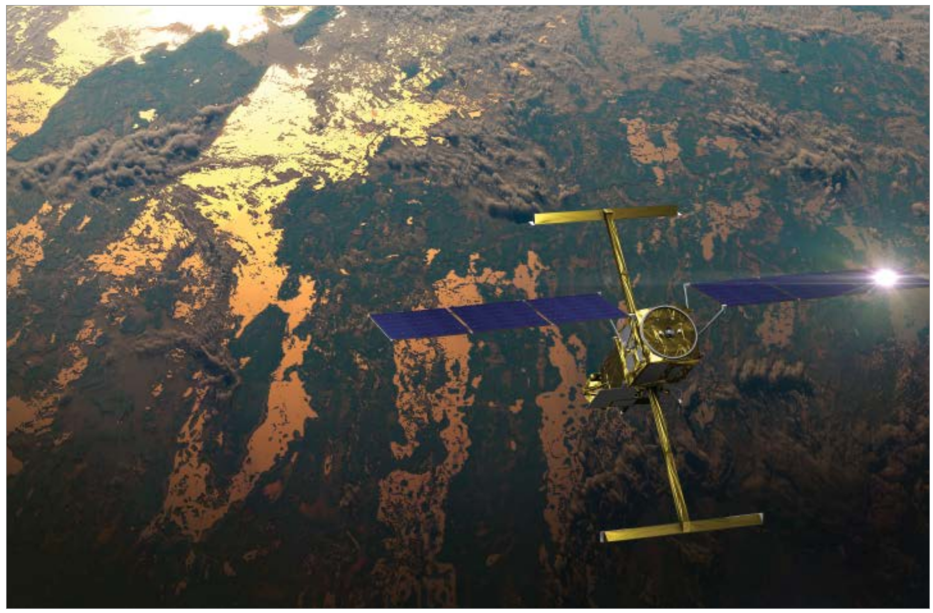
Major Lakes Have Suffered Major Water Losses over the Past Few Decades

Earth's lakes are drying up.

From 1992 to 2020, more than half of the world's largest lakes, which account for 95% of all the lake water storage on the planet, lost significant amounts of water, according to a recent study published in *Science* (bit.ly/lake-water-storage). The trend held for both natural lakes and human-created reservoirs and for both dry and wet regions. As a result, roughly one quarter of the human population now lives in a drying lake basin, a situation threatening water supplies, hydroelectric power, recreational opportunities, and more, the study suggests.

The study attributes the losses primarily to global climate change, which is increasing evaporation. It also identifies steadily growing human demand.

"I was surprised by this drying trend," said Fangfang Yao, a climate fellow at the University of Virginia and the study's lead author. "This had been seen locally in other studies, but we show that this pattern is global."



NASA's Surface Water and Ocean Topography mission, illustrated here in orbit, will scan lakes and reservoirs, providing new data for global lake water storage estimates. Credit: CNES

"Lake levels fluctuate annually and interannually, so you need these 30-year kinds of observations to estimate a trend."

Yao and colleagues obtained their estimates by combining almost 250,000 images from the Landsat satellite missions, altimetry from nine satellites, and lake-level measurements made from the ground. They obtained an average of six lake-level estimates per year for each of the studied lakes. The scientists then used climate and hydrological models to determine changes in both depth and areal coverage, from which they calculated the volume of the study's 1,972 lakes and reservoirs.

"Lake levels fluctuate annually and interannually, so you need these 30-year kinds of observations to estimate a trend," said Yao. "We started with 1992 because that's when Landsat 2 images became available. Before that, global coverage was spotty. But we really got good data."

"The results are robust, as they were able to use multiple data sources to compile the most complete and temporally dense time series of lake water storage globally," said Xiao Yang, an assistant professor of Earth sciences at Southern Methodist University who was not involved in the study.

The Dry Get Drier—And So Do the Wet

The researchers examined 1,051 natural lakes, each with a surface area of 100–377,000 square kilometers, and 921 reservoirs, with surface areas of 4–67,000 square kilometers, across all seven continents. They found that globally, 53% of the lakes and 64% of the reservoirs studied experienced significant losses. Combined, they lost an average of 21.5 gigatons (600 cubic kilometers) of water per year—the equivalent of all the water consumed in the United States in 2015.

Natural lakes lost an average of 26.4 gigatons per year, whereas reservoirs recorded an annual increase of 4.9 gigatons—the result of 183 new reservoirs impounded during the study period. About a quarter of the lakes saw large gains, usually in "dam-construction hotbeds," the *Science* paper noted, or in remote and underpopulated regions, such as the Inner Tibetan Plateau and the Great Plains of North America.

The researchers said that just 20 major lakes accounted for 80% of the total water loss, led by the Caspian Sea, the world's largest inland body of water, which lost half its volume. But major losses were recorded across the globe, including in the United States, led by substantial declines in California's Salton Sea and Utah's Great Salt Lake. And several lakes, such as Gowd-e-Zareh in Afghanistan, which contained 4 times as much water as Lake Mead when the study began, vanished almost completely.

The drying trend was prevalent across both arid and humid regions, the study reports. "Previous climate studies have indicated that the dry get drier and the wet get wetter," Yao said. "We found that the dry *do* get drier, but there are losses in wetter areas as well."

Losses Could Have Major Effects

The researchers identified three leading causes of the global decline in lake levels. The first is Earth's warming climate, which is significantly increasing both water and air temperatures, producing higher rates of evaporation. The team's models showed that global warming was the primary culprit in the disappearance of Lake Gowd-e-Zareh.

Second is overconsumption of water, driven by climate change, increasing populations around lakes and reservoirs, and inefficient water management plans, Yao said. Human activity got most of the blame for the massive water losses in the Great Salt Lake and the Salton Sea.

Third is increased sedimentation, especially in reservoirs, but "natural climate variability plays some role as well," Yao said.

Because such a large fraction of the population inhabits desiccating lake basins, continued water loss could have serious consequences, said Yang. "This is especially important if those water bodies are used as drinking water sources or sources for agriculture or industry," he noted. "In addition, declining storage in the reservoirs due to sedimentation can also compromise the designed functions of the reservoir to manage flood and drought. Recreationally, declining water storage, increasing water temperature, and a host of other climate warming–induced effects on lakes can all lead to a decline in water quality and damage the ecosystem services lakes provide to us."

Lower lake levels could exacerbate climate change by reducing the lakes' ability to store carbon, Yao said. "Lakes are hot spots for storing carbon, like the oceans," he said. "But if they warm up, their capacity to store carbon dioxide [CO_2] goes down. And in some highland regions, where we see higher degrees of warming in these bodies, we're seeing a big loss in protective ice cover. The ice-covered duration gets shorter, so the lakes lose more water, which means they can lose CO_2."

Yao said he plans to extend the research to include smaller lakes. Although they account for a tiny fraction of the planet's surface water, limiting their global significance, changes in storage can have big local impacts.

New satellite missions, such as NASA's Surface Water and Ocean Topography (SWOT), which was launched in December 2022, should provide the resolution and coverage needed to incorporate the smaller bodies.

"I'm very excited about SWOT," Yao said. "A single mission will provide estimates for large and small lakes, so we can extend to more water bodies. It may even make it possible to add river discharge, so we can really understand what's going on in terms of hydrology and what it means for water storage."

By **Damond Benningfield,** Science Writer

The Mysterious Case of Ireland's Missing Earthquakes

Ireland and Britain should be, seismologically speaking, equally boring. The two islands lie thousands of kilometers from the nearest plate boundary and are not volcanic hot spots. But though the ground rarely rumbles in Ireland, neighboring Britain experiences plenty of weak and moderate earthquakes.

The lithosphere—Earth's outermost rocky veneer, which includes the crust and the solid upper mantle—is thicker and cooler beneath Ireland than it is beneath Britain, new research has suggested. Cool, thick lithosphere is mechanically stronger than warm, thin lithosphere, which could explain the Emerald Isle's puzzling paucity of earthquakes. The new results, published in *Geophysical Journal International,* hinted that lithosphere thickness could underpin patterns in seismic activity in other places far from plate boundaries (bit.ly/Ireland-seismicity).

The Rarity of Intraplate Earthquakes

Around 90% of all earthquakes—including nearly all the most destructive ones—start at the boundaries between tectonic plates. Plate, or continental, interiors tend to be seismically quiet, though they're not dead. The New Madrid Seismic Zone in the Mississippi River Valley, for instance, released a series of magnitude 7.3–7.5 earthquakes in late 1811 and early 1812, despite sitting in the middle of the North American plate.

"We have a very good frame of understanding seismicity at plate margins," said geologist Mike Sandiford of the University of Melbourne, who wasn't involved in the new study. "The question is, What's controlling seismicity in continental interiors away from plate margins?"

The rarity of intraplate earthquakes has made it harder for scientists to understand them. And it's often unclear why some places deep within continents have more earthquakes than others.

That's the case in the British Isles, where the dramatic seismic contrast between Britain and Ireland is a centuries-old mystery.

Sergei Lebedev, a seismologist at the University of Cambridge and lead author of the

Ireland and Britain sit thousands of kilometers from the nearest tectonic plate boundary and just a few dozen from each other, yet Britain experiences far more earthquakes than Ireland does. Credit: NASA new study, described the situation by quoting British Geological Survey seismologist Roger M. W. Musson: "The quest for understanding how the distribution of seismicity [in Britain and Ireland] relates to geological structure has been a long and unfruitful one." The key question, Lebedev added, is why Ireland has so few earthquakes.

Faults are not the answer, Lebedev said, because many of Britain's major faults cut through Ireland, too. Nor is the type of crust present on the two islands. Britain and Ireland share a geological history, both having been assembled from bits of an ancient continent called Laurentia and a scrap of crust called Avalonia during the Caledonian Orogeny—one of the mountain-building events that stitched together the supercontinent Pangaea.

"The crustal blocks that make [up the islands] go from Britain to Ireland," Lebedev said, "and they have nothing to do with the distribution of seismicity."

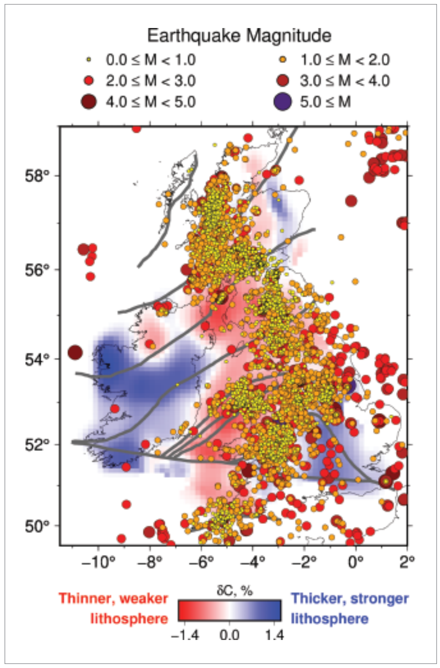
Seismic Scan

Until recently, Ireland's missing earthquakes were a mystery without clues. In 2008, Lebedev said, there was just one broadband station monitoring Ireland's apparently uninteresting seismology. But that's since changed dramatically.

The Irish National Seismic Network now runs six permanent broadband seismometers and is expanding its network. Between 2010 and 2012, Lebedev and his colleagues deployed an additional 20 temporary seismometers that operated continuously until 2021.

Until recently, Ireland's missing earthquakes were a mystery without clues.

With this beefed-up Irish seismic network and data from seismometers in Britain, Lebedev and his colleagues previously used surface wave tomography to map the thickness of the lithosphere in Britain and Ireland. The technique takes advantage of the fact that some seismic waves travel faster through colder lithosphere, which also tends to be thicker. With it, scientists can map subsurface structures in 3D. "It's akin to medical tomography where doctors shoot different



Earthquakes in Ireland and Great Britain according to the British Geological Survey catalog, superimposed on a map representing lithosphere thickness. Blue colors across much of Ireland and southeastern Great Britain indicate thicker, colder, stronger lithosphere. Gray lines are major faults. Credit: Raffaele Bonadio

kinds of rays through patients and find out what's inside them," Lebedev said.

Then, in the new study, the research team made a detailed map of seismic activity and compared it with their map of lithosphere thickness in Britain and Ireland. This comparison revealed a striking correlation: Earthquakes were scarce wherever the lithosphere was cold and therefore likely thick and strong.

"Ireland has low seismicity, and we see that it has thick, cold lithosphere," whereas Britain's lithosphere is warmer and thinner, Lebedev said. "Most Irish earthquakes are in the north of the island in County Donegal—more than 90% of them," he added, "and they happen to be where the lithosphere is thin."

Deep Structure

This isn't the first time scientists have linked lithosphere thickness to intraplate seismicity in general. For instance, geophysicist Walter Mooney of the U.S. Geological Survey showed in 2012 that large intraplate earthquakes are vanishingly rare in places where surface waves travel quickly at 175 kilometers deep—an indication of a thick "lithospheric root," he said.

However, it was long assumed that the lithosphere beneath Ireland and Britain was equally thick—there wasn't any evidence to the contrary, Lebedev said. "So we have a 150-year-old puzzle that has been unsolved until now."

There are still more puzzles—such as why Ireland's lithosphere is thicker than Britain's. Lebedev said his team hoped to solve that one soon. Lebedev also said he'd like to see whether surface wave tomography can uncover similar correlations between lithosphere thickness and seismicity elsewhere, beyond Britain.

"While lithosphere thickness tends to correlate with cooler temperatures, it doesn't necessarily have to."

However, "while lithosphere thickness tends to correlate with cooler temperatures, it doesn't necessarily have to," said Sandiford. This uncertainty can complicate simple generalizations associating lithosphere thickness with seismicity like those suggested in the new study, he said.

There are even places, such as western Australia, that are seismically active but have thick lithosphere. So, Sandiford added, "other factors are playing in. But it seems, as a first case, they make a reasonable assessment for Ireland and the British Isles."

Many questions still surround seismicity within continents, and the new result is a good reminder that the answers can be buried deeper than scientists would expect, Mooney said. Traditionally, he said, seismologists focused on the top 15 or so kilometers of Earth's crust because most earthquakes at plate boundaries are shallow.

Scientists assume "they don't need to think about the lithosphere because it's below their area of interest. That's not true," Mooney said. "Deeper structure has a big influence on shallow activity."

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

Mosses Play Key Roles in Ecosystems from Tropics to Tundra

Not having the vascular plumbing needed to move water and nutrients within themselves, mosses cling close to their supports—rocks, trees, or soil. With such a low profile, they are sometimes overlooked. Now researchers have taken a global survey of mosses, finding that they cover an area roughly the size of China and that they perform key roles across diverse ecosystems.

"Mosses have a bit of a bad rap. We think it's a slimy green thing that grows on rocks or grows around the swimming pool."

"Mosses have a bit of a bad rap," said David Eldridge, an ecologist at the University of New South Wales in Sydney and lead author of the study, which was published in *Nature Geoscience* (bit.ly/soil-mosses). "We think it's a slimy green thing that grows on rocks or grows around the swimming pool."

But Eldridge has always loved mosses. Put them under a microscope, he said, and you can glimpse something like a forest in miniature, complete with animals climbing around the vegetation. (In this case, the animals include microscopic invertebrates like mites, springtails, and tardigrades.)

Researchers previously have delved deep into the characteristics of some species, such as sphagnum moss, which grows in boreal forests, bogs, and swamps. And scientists have explored mosses' roles in particular ecosystems, such as hot deserts and polar environments. But "no one's ever really considered the importance of mosses across the globe," Eldridge said.

He and his colleagues cataloged moss coverage at sites around the world and correlated mosses' presence with soil attributes, ecosystem functions, and microbial habitats. As part of a global study comparing urban and natural green spaces, Eldridge and his team sampled 123 sites across all seven continents.

They collected soil samples from spots under moss to compare with bare soil and soil covered with vascular plants such as trees and ferns. They analyzed these soil samples for 24 attributes, ranging from soil biodiversity to nutrients, including carbon, nitrogen, and phosphorus.

Eldridge's team also noted environmental conditions at each site, including the climate and other vegetation. Then they extrapolated their moss coverage measurements to places with similar environmental conditions around the world.

Mosses in the Spotlight

Overall, the researchers estimated that mosses cover at least 9.4 million square kilometers (3.7 million square miles) of Earth's surface. And that figure is likely "a huge underestimate," Eldridge said. It doesn't include some of the planet's mossiest places, such as boreal forests, where mosses carpet the ground. Even where you find bare soil in the boreal forest, Eldridge said, "there's probably a 99.9% chance that it was dominated by mosses recently."

The soil sample analysis revealed some general trends that span a variety of ecosystems. First, mosses sequester far more carbon than bare soils do. Globally, the team estimated that mosses stash some 6 gigatons more than bare soils would. Soil under mosses also tended to have higher levels of certain nutrients, including magnesium, nitrogen, and phosphorus, than uncovered soils, suggesting that mosses play a role in moving these nutrients around. And measurements of enzymes hinted that the ground beneath mosses better supports the breakdown of organic matter than bare soils do. These ecosystem roles were similar to those found for vascular plants, the researchers reported.

Mosses aren't always as efficient at these tasks as vascular plants are, Eldridge said, but they're still "critically important" because of their global coverage, especially in places where vascular plants don't thrive. For instance, in the desert, mosses fortify soils by sucking in atmospheric carbon through photosynthesis and releasing it to the soil when they decay. Their structure also traps soil and keeps it from blowing away, he said.

Mosses, like this star moss in Belarus, thrive on every continent in a variety of ecosystems. Credit: ognevit, CC BY 4.0 (bit.ly/ccby4-0)

Underestimating Mosses

This was an "ambitious study," said Kirsten Fisher, a bryologist at California State University, Los Angeles who wasn't part of the work. It's notable that the researchers collected so many samples and used them to predict moss coverage, she said.

But the study's design—seeking comparisons between soils that were and were not moss covered—may have skewed the results, Fisher said. The study leaves out the "heavy hitters," she explained, places like arboreal forests and peatlands, where perhaps the most moss-driven carbon sequestration occurs.

So using the study's samples to extrapolate leads to "odd conclusions" about the types of ecosystems where mosses are the most important. Furthermore, about half of the environments sampled were urban, Fisher said, which may not provide broadly representative data for the global model.

"They're everywhere, so I'm hoping people look at them with a fresh eye."

The researchers also seemed to conflate mosses' ecosystem roles with those of the entire soil community, Fisher said. In the desert, for instance, it's unlikely that mosses would be found alone. They would be part of a community called a biocrust—a craggy living layer that tops the soil and contains algae, bacteria, fungi, and more. In such a community, she said, microbes are probably responsible for capturing more nitrogen than mosses are.

Even with the somewhat limited sampling, however, Fisher acknowledged that the team found that mosses make some pretty significant contributions to soil processes. "That's, in and of itself, a pretty impressive result," she said.

That result is part of Eldridge's aim: to place mosses in the limelight and prompt field ecologists to pay these unassuming plants more notice. "They're everywhere, so I'm hoping people look at them with a fresh eye," he said.

By **Carolyn Wilke** (@CarolynMWilke), Science Writer

Sea Ice Is Going, but When Will It Be Gone?

Scientists study the patchy ice of the Arctic's Chukchi Sea in 2010. Credit: NASA/Kathryn Hansen, Public Domain

Every September since 1979, the U.S. government has measured the extent of sea ice in the Arctic. And the picture is not pretty: More than 2 million square kilometers have been lost in that time, leaving only about 4.67 million square kilometers of sea ice intact.

Clearly, the Arctic is losing sea ice fast, but at what point the region will become seasonally sea ice free—a scenario that seems likely to occur before the end of the century—is still hotly debated. That's because climate models underestimate the melting that's been observed in recent years, leaving scientists uncertain whether they can use these models to make predictions.

Two new studies have added to this discussion. The first, published in *Nature Communications,* provided evidence that the Arctic will become seasonally sea ice free in the next few decades even under low-emissions scenarios (bit.ly/ice-free-Arctic). The second, published in *Nature Climate Change,* proposes that the extent of Arctic sea ice will decline more slowly than previously thought because the effect of wind has not been adequately incorporated into models (bit.ly/Arctic-projections).

"The take-home message for the two together is that we need a better understanding of what the models are missing," said physical oceanographer Erica Rosenblum of the University of Manitoba, who was not a part of either study. "If we don't resolve that, we're going to continue to have this very wide range" of possible scenarios.

"The take-home message for the two [studies] together is that we need a better understanding of what the models are missing."

Understanding Ice

Sea ice is complicated. It's brittle, it fractures, it forms large and small pieces that melt at different rates, and historically, its thickness has been tough to measure. All this heterogeneity and uncertainty have made it very difficult for scientists to create models that accurately reflect the melting that's been observed in reality.

To circumvent this difficulty, climate scientist Seung-Ki Min of Pohang University of Science and Technology in South Korea and his colleagues compared these imperfect models to observations of how sea ice has actually melted. They then adjusted the predictions made by models to be in line with historical differences between models and observations.

The results, published in *Nature Communications*, suggest that the Arctic will soon become seasonally sea ice free even under some low-emissions scenarios. "Even if we achieve [the] Paris Agreement goal—2° warming," Min said, summers will be ice-free in the Arctic within a quarter century.

The exact timeline will depend on how social and political systems adapt to our warming climate. Min and his colleagues examined four shared socioeconomic pathways—hypothetical descriptions of how the world may mitigate and adapt to climate change—each featuring different levels of international cooperation and attitudes toward fossil fuels.

If people around the world draw heavily on fossil fuels to continue elevating the global standard of living, the Arctic will see its first sea ice–free month around 2040, the researchers found. If the world prioritizes sustainable development, on the other hand, sea ice may persist year-round for an additional decade, and it may even recover after several seasonally ice-free decades.

The results illustrate the fragility of the Arctic and how close its ecosystem is to changing irrevocably, said climate scientist Christopher Horvat of the University of Auckland. "If we don't get on these high-reduction scenarios," added Horvat, who was not involved in the study, "ultimately, we're going to lose all the sea ice in summer very soon."

But What About the Wind?

Climate scientist Qinghua Ding of the University of California, Santa Barbara, on the other hand, thinks it's an open question when and if the Arctic will lose its summer sea ice. The reasons models fail to accurately describe observations are still opaque in his view, so "it's premature to do future projections."

"We really need to understand what the mechanism is—what are the dynamics behind historical melting?"

Part of the problem is that current models don't reflect the extent to which wind contributes to melting, Ding and his colleague Dániel Topál of the Université Catholique de Louvain put forth in their recent *Nature Climate Change* study.

Atmospheric circulation patterns can dramatically affect ground temperature by pushing warm air downward—the same process that caused a heat dome to form over the Pacific Northwest in 2021. Current climate models consider carbon dioxide levels to be the overwhelming cause of sea ice melting and attribute only about 1% to atmospheric circulation. Ding thinks circulation patterns may actually contribute around 30%.

The paper suggests that increased greenhouse gas emissions don't affect Arctic sea ice as strongly as researchers have assumed. "The ice-free summer will occur later, because right now, all the models are oversensitive," Ding said. If he and his coauthor are correct, ice-free summers in the Arctic may be delayed until as late as 2070, depending on how well societies mitigate climate change.

Reconciling Opposing Predictions

At first glance, the two studies seem to be at odds, but Rosenblum sees them as two sides of the same coin. First, Min and his colleagues clearly document that current models are flawed, and then Ding and Topál point to wind as a potential source of that flaw. "They're both interesting, in very different ways," Rosenblum said.

Min is not convinced that the effect of atmospheric circulation on sea ice has been studied enough to attribute a strong connection. Ding admitted that the whole situation is still shrouded in uncertainty. "We know very little," he said. "We really need to understand what the mechanism is—what are the dynamics behind historical melting?"

The take-home message is one of scientists' favorite phrases: "Further investigation is warranted," said Min.

By **Saima May Sidik** (@saimamaysidik), Science Writer

Spain's Seafaring Sports See Fewer Calm Days

Planning a vacation to the Spanish Mediterranean? A new study could help tourists home in on the best days to partake in their favorite recreational water activities using more than 60 years of weather and ocean data.

These data, available to the public and local businesses, revealed that conditions for active water sports are on the rise and that calm weather, suitable for more leisurely coastal activities, is becoming more infrequent. The changing seasonality of weather conditions will affect the local economy, which relies on tourism, and points to how climate change is affecting the region.

Climatologist Anna Boqué Ciurana surfs in Calafell, Spain. Credit: Toni Duran, courtesy Anna Boqué Ciurana

Wind, Sun, and Surf

Anna Boqué Ciurana is a climatologist at Universitat Rovira i Virgili in Spain. She also regularly surfs along Spain's Mediterranean coast, a popular destination for tourists and locals who enjoy seaside recreation. In recent years, climate change has made conditions less reliable in the summer months, threatening the existing tourist industry. Businesses want to expand their tourist season to better capitalize on sports such as surfing and sailing, a risky move if high-wind and high-surf days are unpredictable.

This new analysis pointed to changing conditions in Tarragona, but the trends might not be the same everywhere along the coast.

Partnering with the provincial government and businesses in Tarragona, Spain, Boqué Ciurana and her colleagues collected data on the state of the sea, including wave heights and wind speeds, from instruments installed on buoys along the coast. The records detail conditions for 1958–2022 near the coastal town of Calafell, just south of Barcelona.

The researchers used these data to tally "calm days," good for swimming, snorkeling, and stand-up paddleboarding; "brave days," with the high wind speeds ideal for sports such as parasailing, kitesurfing, and sailing; and "surf days," with tall waves. They tracked how the frequency and timing of each type of day have changed over 6 decades.

In 2022, Tarragona's shores experienced roughly 8 more brave days, 3 more surf days, and 5 fewer calm days per month than in 1958, though the trends are still preliminary, Boqué Ciurana said. The peak period for snorkeling and other gentle recreation, typically July and August, has gotten shorter, whereas periods good for more active sports such as surfing and sailing have grown longer. Boqué Ciurana presented these results at the European Geosciences Union General Assembly 2023 (bit.ly/Mediterranean-water-sports).

The researchers have partnered with the local government to make the climate and ocean data available to the public, "aligning the identity of the project with the identity of the territory," Boqué Ciurana said. Their goal in the future is to help the local economy grow, make the most out of seasonal weather trends, and guide tourists as they plan their travels by providing daily or weekly forecasts.

Local Versus Regional Trend

This new analysis pointed to changing conditions in Tarragona, but the trends might not be the same everywhere along the coast, cautioned Isidro Pérez, an applied physicist at the University of Valladolid in Spain, who was not involved with this research. Pérez has investigated the effects of climate change on weather across the Iberian Peninsula.

He and a colleague found that in contrast to the new study, the number of calm days increased by 7%–13% in the past 35 years, whereas brave and surf days remained steady. He pointed out, however, that his work was an average across the peninsula, whereas Boqué Ciurana's work was very location specific.

"At this point of the research," Pérez said, "both results may be compatible."

"With more detailed research, the contrasts among different sites would be visible," he said. "The trend of calm days could be increasing in some sites and decreasing in others, although the global trend would be increasing in the region."

Boqué Ciurana said her team hopes to expand the analysis to more towns beyond Calafell and to aid more tourists and businesses along the coast.

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

Protecting the Mountain Water Towers of Spain's Sierra Nevada

Throughout human history, the waterscape has transformed us, and in turn, we have altered it. The Mediterranean features some of the oldest humanized landscapes in the world. There, farming communities took shape in such areas as Spain's Sierra Nevada ("snowy mountains" in English). In these regions, scarce rainfall at low elevations supplemented by water flowing from mountain "water towers" (snowmelt and rainfall reserves stored in mountain ranges) supported a mix of farming and pastoral lifestyles. This working societal contract with water eventually diffused to societies across the world [*Boccaletti*, 2021].

Today, multiple stressors endanger this ecocultural contract with water. Such stressors, including rural exodus, urbanization, changing land use, and intensifying climate swings, make the waterscape the most altered of all of Earth's major biogeochemical cycles.

Around the world, freshwater resources, and the myriad ecosystem services they provide, are becoming increasingly threatened by the combined assaults of excessive land development and climate change. Such impacts are most visible for mountain water resources, which are the source of most of the world's streams, lakes, wetlands, and major rivers—the natural water towers of the world [*Viviroli et al.*, 2007; *Immerzeel et al.*, 2020].

Here we highlight the plight of Sierra Nevada water resources in Spain, along with education and conservation steps being taken to protect this vital peninsular resource.

A headwater stream flows downslope to feed the Río Poqueira, one of several rivers originating in the Spanish Sierra Nevada. Credit: María del Carmen Fajardo-Merlo, Agencia de Medio Ambiente y Agua de Andalucía

The World's Water Towers

About half of humanity depends on mountain water towers (MWTs) for everyday household consumption, farming, industry, and quality of life. However, because MWTs are particularly sensitive to intensifying anthropogenic impacts and ongoing climate change—high-altitude ecosystems are warming faster than the global average, for example [*Intergovernmental Panel on Climate Change* (*IPCC*), 2021]—both mountain ecosystems and downstream communities face increasing water-related uncertainties.

Mountains cover some 27% of Earth's surface and provide more than 50% of the world's freshwater resources.

MWTs play a vital role in society because of their worldwide distribution, coupled with an immense capacity for intercepting, capturing, and storing precipitation and distributing it to lowlands.

Water from MWTs is even more critical in dry regions such as the Mediterranean [*Viviroli et al.*, 2007; *Food and Agriculture Organization of the United Nations* (*FAO*), 2012]. Mountain lakes, streams, and rivers also sustain numerous fragile ecosystems such as riparian forests and biodiverse wetlands in their watersheds [*FAO*, 2012].

However, both the quantity and quality of mountain waters, the ecosystems they sustain, and the services they provide are increasingly threatened by climate change (e.g., warming; extreme droughts and floods;reduced rain, snow, and ice or their increasing loss), unsustainable land use and water extraction, and ongoing pollution. All these factors endanger the attainment of the U.N. Sustainable Development Goal of Clean Water and Sanitation [*United Nations*, 2021], which aims to provide universal and equitable access to safe and affordable drinking water, sanitation, and hygiene by 2030.

Fig. 1. The Sierra Nevada, Europe's southernmost glacial mountain range, is located just east of Granada in southern Spain. Credit: Base map: Google; map data ©2022 Inst. Geogr. Nacional

Sierra Nevada Mountain Water Resources

The Sierra Nevada is Europe's southernmost glacial mountain range (Figure 1), with 15 peaks higher than 3,000 meters. It stretches across some 2,273 square kilometers in Andalucía in southern Spain, and its watershed encompasses multiple Mediterranean bioclimates. The Sierra Nevada contains 74 glacial lakes, and it is the source of hundreds of streams and several major rivers, including the Rio Genil, which terminates in the Atlantic Ocean, and the Rio Poqueira, which terminates in the Mediterranean.

Today, parts of the Sierra Nevada are included in the Sierra Nevada National Park system, and the entire range is a U.N. Educational, Scientific and Cultural Organization biosphere reserve. These mountains, located across the Mediterranean Sea from Africa, experience pronounced interannual variability in climate, including moderate winter conditions and frequent, severe droughts.

In 2022, a mid-March event turned the skies over Europe red, parts of southern Spain were drenched in mud rain, and the snow on the Sierra Nevada turned brown.

Although the last permanent glaciers of the Sierra Nevada melted away at the turn of the 20th century, ice and snow cover still occur in the highest reaches for much of the year, and substantial reserves of periglacial ice persist, enabling the Sierra Nevada to sustain a diverse array of ecosystems [*Zamora and Oliva*, 2022].

The Sierra Nevada receives Saharan dust on a regular as well as episodic basis. The dust fertilizes the water and soil of this Mediterranean ecosystem with such key nutrients as iron, calcium, and phosphorus. Some transcontinental dust events can be massive: In 2022, a mid-March event turned the skies over Europe red, parts of southern Spain were drenched in mud rain, and the snow on the Sierra Nevada turned brown.

Just as mountains intercept rain clouds from moving air masses, they disproportionately intercept dust circulating in the free troposphere, relative to flatlands in the landscape. (The free troposphere is above the planetary boundary layer, about 1,700 ± 500 meters above sea level.) Further, dust lowers the albedo of snow, ice, and water. This change in albedo warms snow and ice and enhances their melting, which affects the water cycle of the Sierra Nevada and its watershed [*Zamora and Oliva*, 2022].

Even though different mountain ranges of the world experience climate change and anthropogenic impacts differently, there are common effects, such as depleting MWTs and degrading mountain and downstream ecosystems. We have observed long-term (decadal) trends in changing conditions (decreasing annual precipitation; increasing warming, snow loss, pollution, etc.) in time series observations from the Sierra Nevada Global Change Observatory.

These trends are in step with increasing ice loss in lakes across the Northern Hemisphere and reduced winter ice that lead to increased interannual variability in water flow. In recent years, southern Spain has been experiencing increasingly mild winters, hot springs, and summers that include heat waves.

In addition, water quality in the Sierra Nevada watershed has deteriorated over the past few decades, in sync with increased human appropriation of water and recurring drought events. Many of these watershed observations, made on the mountains and in downstream locations, mimic those taking place in mountain ecosystems globally (the Andes, Rockies, Himalayas, etc.). Concurrent loss of glacial and periglacial ice is a looming problem across the world, and it affects water availability, water quality, and biodiversity [*IPCC*, 2021].

On 12 July 2018, the water in the 150-meter-wide Laguna de la Caldera (left), a mountain lake near Mulhacén peak in the Sierra Nevada, appeared clear and blue amid conditions of average snowfall and low dust deposition. On 31 May 2022, the lake appeared muddy and brown (right) following lower-than-average snowfall and intensive dust deposition. Areas around the lake underwent an unusually early spring thaw in 2022 after massive dust deposition events in late winter decreased the albedo of accumulated snow and ice and rapidly warmed the landscape. Credit: Mani Villar-Argaiz

Education and Conservation in the Sierra Nevada

Currently, researchers at the University of Granada coordinate two innovative programs covering high mountain lakes, streams, and rivers in the Sierra Nevada watershed. These projects, which involve students and community members, broaden youth participation and inform the public about the intrinsic value of water in their everyday lives and the need for its protection and conservation [*Zamora and Oliva*, 2022].

In one program, Ríos de Vida (Rivers of Life), high school students who live in different parts of the Río Genil basin work in partnership with the university. The students chronicle changes in the ecology and health in the stretches of the river closest to them as it runs from the mountains through Granada, a city of 300,000 people, and other communities on its way to the sea. At the end of the school year, they all gather for a conference to share data and discuss their observations.

All together, 13 active river renaturalization projects are underway in Spain that aim to restore biodiversity and natural hydraulic flows in the watershed. However, these efforts are mostly focused on downstream and urban stretches of the rivers, where strong environmental consciousness prevails among urban communities.

The other program coordinated through the University of Granada, 74 High Mountain Glacial-Lake Oases, focuses on the headwater regions of the Sierra Nevada's rivers. This community science campaign has made a good start by involving all segments of the public and stakeholders. It focuses on extending environmental protections and restoration practices to the mountain headwater ecosystems, which have received less attention than regions farther downstream.

The headwaters are where the water towers primarily recharge and sustain sensitive mountain biodiversity (high-altitude wetlands and other flora and fauna endemic to mountain ecosystems) and provide numerous downstream ecosystem services. Project participants—everyone from hikers and scientists to farmers and city managers—keep their eyes on the 74 glacial lakes of the Sierra Nevada by sharing images of and notes about the lakes.

Because the ways in which people use and misuse water are closely tied to how they value it, such community science projects can spur wider engagement and implementation of sustainable water policies. This engagement is becoming increasingly important because many parts of the world with Mediterranean climates, including California, Chile, southern Africa, and southern Australia, are experiencing critical water shortages

High school students participating in the Ríos de Vida project sample aquatic macroinvertebrates in the Río Genil in February 2022. Credit: Mani Villar-Argaiz

Students and instructors in the Ríos de Vida project discuss their observations of and samples collected from the Río Genil to determine water quality in February 2022. Credit: Mani Villar-Argaiz

and deterioration of water quality. These problems are attributed to a succession of episodic and intensifying droughts and exponentially rising water demands, along with the resulting concentration of existing pollutants. The situation is particularly critical in the southwestern United States and Chile (regions undergoing megadroughts) and in the Spanish Sierra Nevada region, which is experiencing its worst drought on record.

The Future of Mountain Water Towers

The world's MWTs are rarely valued as strategic water reserves. These water reserves even out changes in water supplies by capturing and freezing vast quantities of water during the winter months and releasing it during warmer summer months [*Huss and Hock*, 2018; *Immerzeel et al.*, 2020].

Periglacial water represents one important gap in our knowledge. The combined action of glacial and periglacial water is fundamental to the provision of water to streams, rivers, and water tables in the watershed. Knowledge of periglacial water pools and fluxes is key to adapting to a world where all continental glaciers are fast disappearing. We hope that the recently operational Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellite, which takes sensitive measurements of belowground gravity anomalies, will shed light on the size and turnover of this hidden component of the world's MWTs.

As groundwater depletion continues unabated around the world, the value of mountain water towers to the water balance of downstream societies and ecosystems can only increase.

As groundwater depletion continues unabated around the world, the value of MWTs to the water balance of downstream societies and ecosystems can only increase. It is time that MWTs receive their due protection at both watershed and global scales. In this context, news that the Spanish government is preparing to extend protection to 41 aquifers in the Iberian Peninsula is encouraging. Seven of these aquifers are located in the province of Granada, which includes the 74 glacial lakes of the Sierra Nevada. Preserving mountain water towers is our best policy for ensuring a steadier water supply and damping the growing tendency for floods and droughts as the climate increasingly warms and the water cycle wobbles ever more.

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THE 2023 TÜRKIYE-SYRIA EARTHQUAKES SHIFTED STRESS IN THE CRUST

BY ERIN MARTIN-JONES

A fault segment offset an agricultural field during the Kahramanmaraş earthquake sequence. Credit: Emirali Kokal/500Px Plus via Getty Images

In February, a devastating magnitude 7.8 earthquake struck the eastern Mediterranean, triggering a second major jolt and a cascade of aftershocks.

In the early hours of 6 February 2023, a magnitude 7.8 earthquake struck southern Türkiye. Just 9 hours later, a magnitude 7.5 earthquake hit 90 kilometers (60 miles) to the north. For weeks afterward, thousands of smaller aftershocks rattled already frail buildings and disrupted relief work.

Before 2023, seismologists had warned that large earthquakes were likely in this area, but the scale of damage caused by the event was unforeseen. The quakes were among the most devastating the world has witnessed this century, inflicting terrible loss of life in Türkiye and neighboring Syria.

Scientists are now trying to understand how the earthquakes in this cascade were seismically linked by exploring how the initial main shock triggered a chain of further shocks by offloading stress onto neighboring faults. The research points to where future aftershocks are likely to occur.

"Although we can't predict earthquakes, we can identify faults that might be more likely to break," said seismologist Ross Stein, CEO of the earthquake hazard modeling company Temblor, who is involved in the investigations.

Warnings from History

Eastern Türkiye sits at a seismically active crossroad, with two major strike-slip faults marking the junction between the Anatolian, Arabian, and Eurasian plates. The two major 6 February earthquakes (together referred to as the Kahramanmaraş earthquake sequence) occurred on separate faults branching off the 600-kilometer-long (380-mile-long) East Anatolian Fault, which runs through eastern Türkiye and south into Syria, separating the Anatolian and Arabian tectonic plates. Another major fault—the North Anatolian Fault—runs along the length of northern Türkiye.

> "The scale of the ruptures meant that damage was widespread."

"These two faults effectively hold Türkiye in a huge tectonic vise," Stein said. The Anatolian plate, on which Türkiye sits, is slowly escaping from that grip, moving westward at about 20 millimeters (0.8 inch) per year. But this motion isn't smooth, because fault surfaces aren't smooth; as the plates slide past each other they get stuck, sometimes for centuries. When enough stress builds, the plates suddenly slip, releasing that stress and causing a large earthquake.

Türkiye's national hazard map, published in 2018, highlights the North and East Anatolian Faults, signaling the high likelihood of seismic activity along them. The hazard was known, said Karin Şeşetyan, an earthquake engineer at the Kandilli Observatory and Earthquake Research Institute (KOERI) in Türkiye, but the recent double earthquake exceeded expectations.

The country's last magnitude 7.8 (*M*7.8) earthquake happened in 1939, on the North Anatolian Fault. "That earthquake initiated a striking falling-domino sequence of earthquakes," Stein said. Twelve very large quakes happened over the next 60 years, sequentially unzipping more than 1,000 kilometers (620 miles) of the North Anatolian Fault.

Southeastern Türkiye has been quieter over the past century. But "the East Anatolian Fault is still familiar with very large earthquakes," Şeşetyan said. "You just have to look back through history to find them."

Historic evidence from the past thousand years shows that this stretch of fault has hosted six very large temblors, with reconstructions placing their magnitudes between 7.0 and 7.5. The cities of Antakya in southeastern Türkiye and Aleppo in northern Syria were razed by several earthquakes over this period, including one of *M*7.0 in 1822 that caused more than 20,000 fatalities.

Damage of Staggering Proportions

The recent *M*7.8 earthquake struck just after 4:00 a.m. local time on the previously unrecognized Narli Fault, a minor branch of the East Anatolian Fault. Once an earthquake begins at an initial rupture point, it grows as a larger section of fault slips. The longer the stretch of fault that ruptures is, the greater the magnitude of the earthquake.

The initial rupture grew mostly northeastward, toward the East Anatolian Fault itself. "It could have been a much smaller earthquake," said Jean-Paul Ampuero, a geophysicist from the Géoazur Laboratory, Université Côte d'Azur in Nice, France. If the rupture had stopped when it got to the East Anatolian Fault, he estimated that would have resulted in a roughly *M*6.7 earthquake, which is about 45 times smaller than *M*7.8. "Instead," he said, "it became huge." When the rupture reached the junction, it took off in opposite directions, growing to a staggering 350-kilometer-long (220-mile-long) span.

Hours later, the *M*7.5 shock hit directly to the north of the *M*7.8 epicenter, on a larger fault known as the Çardak-Sürgü fault zone, which branches off the East Anatolian Fault. That rupture spread for 150 kilometers (90 miles).

"The scale of the ruptures meant that damage was widespread," said Luca Dal Zilio, a geophysicist from ETH Zürich.

Estimates from the U.S. Geological Survey (USGS) indicate that roughly 32 million people experienced a shaking intensity of "strong" or above as a result of the main and secondary shocks. Severe to violent shaking occurred along the length of both ruptures, but light shaking was felt even in Istanbul, roughly 800 kilometers (500 miles) away. In Türkiye, the provinces of Kahramanmaraş and Gaziantep suffered the most damage; in Syria the provinces of Idlib and Aleppo were the most affected.

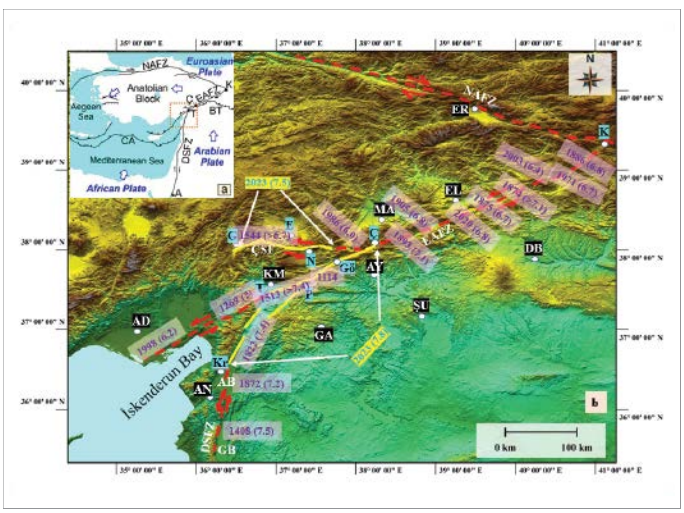
> **“The quick turnaround between these two earthquakes of this scale would have been hard to foresee.”**

Dal Zilio said that the *M*7.8 rupture was particularly unusual because it released three long segments of the East Anatolian Fault in one go. “Past earthquakes on the East Anatolian Fault have generally broken just one section,” Şeşetyan said.

Satellites observed roughly 6 meters of ground displacement along the East Anatolian and Çardak-Sürgü Faults, which ripped roads, buildings, and railways in two.

Reconstructions of how the faults slipped showed that the *M*7.5 earthquake ruptured extremely fast in one direction along the Çardak-Sürgü Fault. Previous observations of these so-called supershear earthquakes have suggested that they might be more destructive, said seismologist Diego Melgar of the University of Oregon. “The rupture speed could explain why ground shaking was so strong.”

Shaking was also magnified by the shallow depth of the earthquakes. Vertical ground motions were unusually strong close to the faults, according to Eser Çaktı, an earthquake engineer at KOERI. “This kind of shaking could be particularly damaging for high-rise constructions,” she said.



The inset map (a) provides the geologic setting of the eastern Mediterranean region with the movement of Africa, Arabia, and Anatolia relative to Eurasia. (NAFZ, North Anatolian fault zone; EAFZ, East Anatolian fault zone; BT, Bitlis Thrust; CA, Cyprus Arc, K, Karlıova; Ç, Çelikhan; T, Türkoğlu, A, Aqaba). The large map (b) illustrates the East Anatolian fault zone. Red dashed lines indicate major active fault segments, annotated in the list below. Yellow dashed lines indicate segments reactivated during the seismic events of 6 February 2023. The numbers in pale rectangles show the year and approximate magnitude of the last major historical earthquake that occurred at that fault segment. AB, Amik Basin; AD, Adana; AN, Antakya; AY, Adıyaman; Ç, Çelikhan; CA, Cyprus Arc; ÇSF, Çardak-Sürgü Fault; DB, Diyarbakır; DSFZ, Dead Sea fault zone; E, Elbistan; EAFZ, East Anatolian fault zone; EL, Elazığ; ER, Erzincan; G, Göksun; GA, Gaziantep; GB, Ghab Basin; Gö, Gölbaşı; K, Karlıova; KM, Kahramanmaraş; Kr, Kırıkhan; MA, Malatya; N, Nurhak; NAFZ, North Anatolian fault zone; P, Pazarcık; ŞU, Şanlıurfa; T, Türkoğlu. Credit: Erdik, Tümsa, Pınar, Altunel, and Zülfikar. Map produced from SRTM Worldwide Elevation Data (1-arc-second resolution).

The many staggering dimensions of this earthquake sequence were all the more devastating because they played out over the course of just a few hours. For Şeşetyan, that’s what made the Kahramanmaraş earthquake sequence scientifically unique. “The quick turnaround between these two earthquakes of this scale would have been hard to foresee,” she said.

Identifying how these two events were connected could add to scientists’ understanding of cascading aftershock sequences, which can worsen the damage done by the initial main shock and hamper rescue and relief efforts.

Earthquake Communication

Scientists have known for some time that earthquakes, particularly large ones, can trigger or inhibit additional tremors on neighboring faults. “Stress relieved during an earthquake doesn’t just fade away into Earth’s crust,” Stein said. It can get transferred to other faults in the area; even a subtle increase in stress can trigger another tremor. In this way, “earthquakes are effectively in communication with one another,” Stein said.

By mapping out patterns of stress change during the Kahramanmaraş earthquake sequence, scientists tested whether the first shock caused the *M*7.5 event.

“We could see that the one-two punch of earthquakes in close succession was pretty unusual,” said Matthew Herman, an earthquake modeler at California State University, Bakersfield and one of the authors of a stress model developed by the USGS. “Stress transfer helps us explain that sequence.”

Two groups developed independent stress transfer models in the days after the earthquake sequence: One was published by Temblor, and the other was published by the USGS 2 weeks later. Both models treat

> **“That little fault gave a kick to the East Anatolian Fault, which was already primed to go. Then it just kept unraveling.”**

Earth’s crust as if it were a stiff block of rubber with faults scored through it. Running the models, the researchers simulated how the rocks grated past each other to identify patterns of stress change. To check their models, they compared the locations of forecast stress changes against those of actual recorded aftershocks.

Both models showed that the *M*7.8 quake likely triggered the *M*7.5 quake by shifting stress from one fault to another. “That stress transfer unclamped a section of the Çardak-Sürgü—the same section where the second quake nucleated,” Stein said.

The stress transfer calculations can explain other elements of the sequence, such as why the *M*7.8 quake started on an unmapped minor fault and propagated along the larger fault, Herman said. “That little fault gave a kick to the East Anatolian Fault, which was already primed to go. Then it just kept unraveling.”

Some aspects of the Kahramanmaraş sequence can’t be explained by stress transfer alone. One peculiarity is that the *M*7.5 earthquake nucleated on a fault that was oriented almost perpendicular to the East Anatolian Fault. Stein explained that the odd arrangement of the Çardak-Sürgü Fault should make it harder for tectonic forces to get it moving.

“Even if I’d known that section was unclamped, I wouldn’t have foreseen that fault going next,” Stein said. Herman agreed: “Why didn’t the East Anatolian Fault take all of the deformation?” He added, “Other factors must also influence which faults end up rupturing.”

Though stress transfer from the *M*7.8 earthquake seems to have triggered the *M*7.5 shock, the short time between the two events still puzzles scientists. Investigations by Ampuero and his colleagues have so far yielded no smoking gun indicating that seismic activity was building along the Çardak-Sürgü Fault during the intervening hours.

Aftershocks in the Shadows

By overlaying patterns of stress released by the *M*7.8 and *M*7.5 quakes, the researchers developed an idea of where future aftershocks might strike. According to both models, zones of high stress now radiate from both ends of the East Anatolian Fault and the Çardak-Sürgü Fault.

Seismologists generally agree that once a fault has ruptured, the chance of another large quake along the same stretch is lessened. That’s because earthquakes tend to release nearly all their pent-up stress, and as such, there is promise of calm to follow. “Some people might say that the immediate area is out of the woods for a couple of centuries,” Stein said, “but it’s important to remember that other faults in the vicinity will have been stressed, and aftershocks will occur.”

More than 10,000 aftershocks struck the region in the 3 weeks following 6 February. Most of them were too small to be felt, but roughly 2,000 registered at *M*3 or greater. The aftershocks dot the faults that ruptured in the main event and reach farther into the zones of calculated stress increase.

Several larger aftershocks occurred at either end of the East Anatolian Fault, within these high-stress zones. An *M*6.4 quake on 20 February in Antakya, Türkiye, struck at the fault’s southwestern limit. At least three *M*5.2–M5.7 quakes have so far occurred at the ruptured section’s northeastern limit, near Malatya, Türkiye. Aftershocks will continue for several years, Stein said, becoming less frequent but not necessarily smaller.

Stress transfer calculations could help delineate areas where seismic risk might be higher, Herman said, but “as with any earthquake forecast, we can’t say what magnitude that earthquake will be or when it will happen.”

The Kahramanmaraş earthquake sequence is a potent reminder of the challenges to earthquake forecasting. Stress transfer can cause earthquakes to happen more frequently in some locations for a time or even inhibit them in others. These interactions are difficult to build into earthquake forecasts, which often assume that quakes will follow the same tempo they kept in the past.

The Kahramanmaraş earthquake sequence broke the mold in terms of scientists’ expectations, but the hazard was known nonetheless. Social and economic factors, including poor management of building quality, conspired to make this a human tragedy.

Ampuero and Dal Zilio have several ideas to help build resilience to future earthquakes in this region. They suggested that beyond improved regulation of construction practices and enforcement of building codes, awareness campaigns could help empower citizens to verify the quality of buildings they rent or buy.

Çaktı agreed that the priority should now be on building design and the control of construction. “If you can get all of that right, then your structure is still standing, and you can save lives.”

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A COMMON LANGUAGE FOR REPORTING EARTHQUAKE INTENSITIES

Scientists are working together to establish a standardized international scale for measuring and reporting the intensities and impacts of earthquake shaking.

By David J. Wald, Sabine Loos, Robin Spence, Tatiana Goded, and Ayse Hortacsu

Search and rescue efforts continued in Hatay Province in Türkiye, on 12 February 2023 amid the damage caused by intense shaking from two earthquakes on 6 February. Credit: Anadolu Agency via Getty Images

Crossing Europe by train used to be far more challenging. Travelers were required to pass through sometimes complicated and confusing passport checks at each international border and carry cash in various currencies (or—ugh—traveler's checks). The expansion of the European Union (specifically, the Schengen Area) and the creation of the Eurozone largely resolved these challenges by eliminating barriers to travel across borders and adopting the euro as a common currency among many countries.

In 1998, European nations accomplished another feat of harmonization by developing and adopting the European Macroseismic Scale (EMS-98) [*Grünthal*, 1998]. This scale established a common basis for assigning intensities to seismic events across Europe, overcoming differences among existing intensity scales and producing more consistent and useful assessments of earthquake shaking and damage.

An important challenge now for the seismological and earthquake engineering communities is to eliminate barriers to sharing earthquake intensity data around the world and develop a globally accepted macroseismic scale to further extend the value of macroseismic observations. By combining the standardization of such a scale with the benefits of innovations in global Internet availability, artificial intelligence, and other technologies, we have an opportunity to gain a far more comprehensive understanding of seismic risks and safety around the world.

What Is Macroseismology?

Macroseismology involves determining the intensity of earthquake shaking on the basis of human perceptions and observed effects to structures, primarily buildings. Systematic approaches for assigning seismic intensities connect analyses of our collective seismological past with the present and the present with the future. They also provide a means of sharing and archiving assigned intensities in a reproducible form and of effectively communicating the effects of shaking to different audiences.

Intensity observers include members of the public who self-report their perceptions of shaking, as well as seismologists and civil engineers sent out on traditional surveys to interview individuals and record building damage after an earthquake. The use of such macroseismic intensity data in research and operational settings has grown with time, as is illustrated by the millions of community observers who have participated in reporting their experiences and observations to the U.S. Geological Survey's (USGS) Internet-based Did You Feel It? (DYFI) system [*Quitoriano and Wald*, 2020] (Figure 1) and to analogous systems worldwide [e.g., *Bossu et al.*, 2017; *Tosi et al.*, 2015; *Goded et al.*, 2018].

Applications of intensity assignments from both approaches are far-reaching. For example, traditional macroseismic surveys illuminate critical aspects of earthquakes, such as the extents and intensities of shaking needed to constrain the locations and magnitudes of historical events, and their impacts on society. Internet-based macroseismic data, meanwhile, are extremely important for constraining real-time shaking estimates, which afford increased situational awareness to many affected populations and emergency managers and help prioritize postearthquake responses. In combination, traditional and crowdsourced macroseismic intensity data contribute to scientific analyses of earthquake behavior as well as to earthquake engineers' loss and risk analyses related to built structures (see *Quitoriano and Wald* [2020] for many such examples).

Maintaining these essential applications of macroseismic observations requires that we revisit whether traditional macroseismic surveys remain well suited to modern environments and standardize Internet-based collection strategies. We must also ensure compatibility between traditional and Internet-based approaches to macroseismic data collection and intensity assignments.

An important challenge now for the seismological and earthquake engineering communities is to develop a globally accepted macroseismic scale.

Shortcomings of Modern Practices

Even when observers follow best practices, there are several limitations to modern macroseismic data collection approaches. For example, although crowdsourced Internet intensity reports are rapid and abundant, they are insufficient for describing higher, damaging intensity levels because accurate assignments require expert knowledge of buildings' structural systems and damage characteristics. In addition, limited access to Internet and mobile phones in some countries and communities hampers equitable access to Internet-based intensity reporting systems and data [e.g., *Hough and Martin*, 2021]. So despite being costly in terms of time and finances, traditional field approaches to assigning shaking intensities are still required to assign higher intensities and fill gaps in Internet reporting.

Because traditional approaches vary worldwide, though, they can produce inconsistent results. This situation necessitates a truly

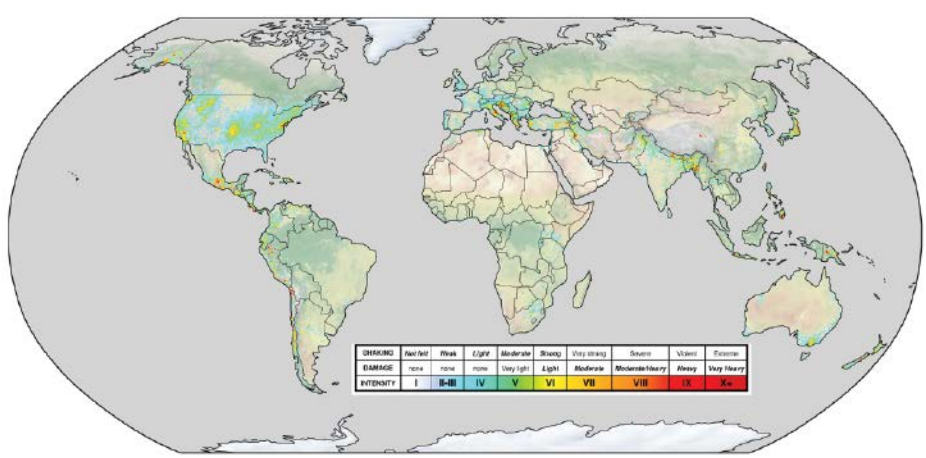

Fig. 1. Shown here are the highest earthquake shaking intensities reported from locations around the world to the U.S. Geological Survey's Did You Feel It? system over more than 20 years (2000–2021). The color scale corresponds to shaking categories defined according to the Modified Mercalli Intensity Scale. Credit: USGS, 2023, https://doi.org/10.5066/F7J101C8

international macroseismic scale (IMS) that standardizes procedures and accounts for regional differences in, for example, how building damage from similar seismic shaking can vary starkly because of different conditions and construction practices. Several macroseismic scales in use have been implemented independently, and intensity values from these cannot be directly compared. Scales used in highly seismically active nations like Japan, China, and India are particularly at odds. Informal adaptations of EMS-98 outside Europe, especially in Central and South America, present additional inconsistencies that could be improved. Furthermore, the United States, New Zealand, and many other countries still use the Modified Mercalli Intensity (MMI) Scale, which was developed in 1931. The MMI Scale is consistent with—yet inferior to—the more recent EMS-98 because the latter requires detailed building vulnerability assignments, well-specified damage grades, and statistical analyses of building damage.

Collecting postearthquake shaking and damage data is critical to archiving and documenting earthquake experiences and impacts. Incompatibilities in collection approaches and among the data themselves become limiting factors for many seismological and earthquake engineering analyses. The development and implementation of EMS-98 provide several lessons and guidelines for developing a worldwide standard to overcome these limitations.

Raising the Bar for Intensity Assignments

The rollout of EMS-98 was an important innovation that substantially raised the standards of traditional intensity assignments. To assign higher intensities, EMS-98 requires detailed field reconnaissance observations gathered using strict data collection protocols. The EMS-98 methodology characterizes the seismic vulnerability of individual buildings and assigns each to an established vulnerability class (A–F, with A indicating most vulnerable), and it describes damage to structures using predefined damage grades (1–5, with 5 indicating the most severe damage; Figure 2).

Several macroseismic scales in use have been implemented independently, and intensity values from these cannot be directly compared.

With sufficient postearthquake observations in a town or neighborhood, one can assign the intensity level at a particular location on the basis of the fraction of buildings in each damage state at that location. For example, intensity VIII on the EMS-98 scale is defined as "many buildings of vulnerability class B suffer damage of grade 3; a

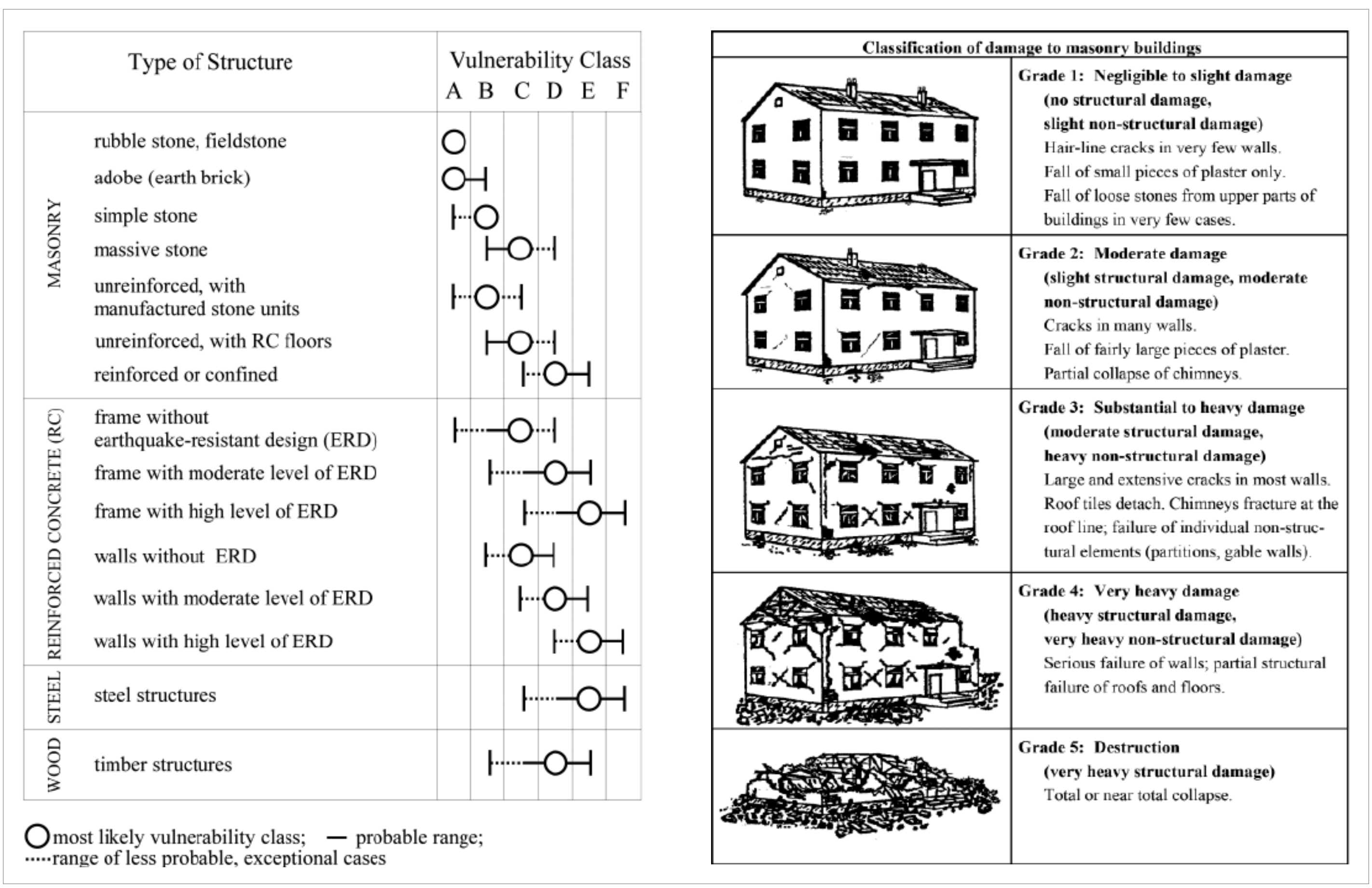

Fig. 2. The European Macroseismic Scale defines vulnerability classes for different building types (left) as well as damage grades for building types, including masonry buildings (right). Credit: Grünthal *[1998]*

few of grade 4" [*Grünthal*, 1998, p. 19], with "many" meaning 15%–55% and "a few" meaning 0%–15%. Intensity IX requires that "many buildings of vulnerability class A sustain damage of grade 5" or "many buildings of vulnerability class B suffer damage of grade 4; a few of grade 5" and so on [*Grünthal*, 1998, p. 19].

EMS-98's stringent requirements ensure that quality building damage data are collected and archived, allowing shaking intensities at different locations to be assigned statistically and objectively. Indeed, EMS-98 raised the bar for the expected quality of data used in macroseismology. In doing so, it brought to light limitations of earlier practices. Earlier macroseismic intensity scales—most of which were developed 50–150 years ago—are often ambiguous in how they define the essential EMS-98 ingredients: structural vulnerabilities, damage grades, and damage level fractions.

Moreover, building vulnerability classes of the past were, in some cases, quite different than they are now. At the same time, many scales have not been sufficiently updated to account for today's broader range of structures and the presence of buildings with earthquake-resistant designs. For example, most older brick chimneys—damage to which was a key indicator for assigning intensities in California—have been either replaced or retrofitted, confounding assignments that would have been straightforward in the past.

When properly recognized, such limitations can, in principle, be accommodated by providing uncertainty estimates or by weighting data accordingly. These approaches are particularly helpful for characterizing historical earthquakes that occurred before EMS-98 standards existed and for which archival observations are less detailed.

Still, what is needed is a worldwide standardization of intensity assignment practices and associated data collection for both Internet-based and traditional, ground survey–based observations, especially for high-intensity, damaging levels of shaking. With the rapid development of new crowdsourcing technologies, vast improvements in damage data collection practices are already here or on the horizon. So how can we ensure that professional damage data assessors in the field have the mandate and tools they need to collect sufficient observations (including of building types and damage percentages) for assigning EMS-98-like intensities?

The Benefits of Building an IMS

In October 2022, we and the other experts making up the International Macroseismic Scale Working Group (IMSWG) gathered at the USGS John Wesley Powell Center for Analysis and Synthesis in Fort Collins, Colo., to address these issues. Attendees focused on how to revise the MMI Scale in countries where it is in use, such as New Zealand and the United States, to be compatible with EMS-98, with the idea that these revisions will add momentum toward creating a global IMS. They also focused on improving strategies for rapid macroseismic assignments, especially for higher intensities, and producing recommendations for updating EMS-98 into a global IMS.

Our current effort can, fortunately, benefit from past efforts, and several of the luminaries behind the development of EMS-98 who participated in the October workshop had already begun devising strategies to move toward an IMS [e.g., *Spence and Foulser-Piggott*, 2014, 2015; *Abrahamczyk et al.*, 2017]. These strategies involve adapting building vulnerability classes and illustrating damage grades so they comprehensively reflect the wide, heterogeneous array of structures and building practices outside Europe that were not considered in the original EMS-98 (Figure 2).

However, challenges to updating EMS-98 remain. In particular, structural engineering experts from around the world must be consulted to guide vulnerability class assignments for missing endemic building types and validate these assignments with damage data from past earthquakes in the region. New approaches for evaluating evolving earthquake-resistant building designs must also be taken into consideration.

The benefits of moving to an IMS would be considerable. It would require and motivate collection of more dependable and accessible postearthquake building damage data sets. Consistent building damage data would facilitate a wide range of modeling and scientific studies by seismologists and engineers looking to better understand earthquake behaviors, hazards, and risks. These data would also facilitate more uniform messaging and communication of earthquake effects worldwide, and they would illuminate trends globally in building damage and losses caused by seismic activity, serving broader policymaking related to urban planning and community resilience, for example. Furthermore, they would serve other decisionmakers, such as the U.S. Federal Emergency Management Agency and other such agencies that depend on this impact information as a basis for equitable allocations of resources and financial adjudications during earthquake response and recovery.

Roughly 80% of an earthquake's DYFI responses are received within an hour of the event [*Quitoriano and Wald*, 2020], making them timely enough to constrain and improve the accuracy of ShakeMaps. Rapid, consistent shaking intensity assignments across the globe would be especially beneficial in areas that face substantial seismic hazards but lack real-time monitoring instrumentation. More accurate maps, in turn, would enable more detailed examinations of geotechnical forensics and the design of more resilient structures, as well as improved loss and risk estimates. These capabilities would also improve correlations between assigned macroseismic intensities and instrumentally recorded ground shaking measurements, which would inform relationships between shaking levels and earthquake effects.

The use of macroseismic intensity data is expanding widely as the metric by which shaking hazards and risks are depicted within essential real-time earthquake information products, including earthquake early warning systems (e.g., ShakeAlert), ShakeMaps, DYFI, and the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) system [e.g., *Quitoriano and Wald*, 2020]. Seismologists even use them for presenting long-term probabilistic seismic hazard maps in a friendlier format to nontechnical users.

Moving to an international macroseismic scale would require and motivate collection of more dependable and accessible postearthquake data sets.

Taking Steps to Tackle Challenges

With the adoption of standardized damage and intensity scales, new approaches and technologies could prove valuable for macroseismology. Community science–based observations reported online already account for 95% of the macroseismic data now collected, in part because lower intensities of shaking are much more common than higher intensities, which currently require field observations to be assigned properly. What if a portion of the building damage data

Artificial intelligence could greatly augment and accelerate traditional intensity assignments while collecting valuable damage data that could be used for other humanitarian and scientific purposes.

needed to assign higher intensities could also be gathered through crowdsourced or automated image recognition of photos collected on the ground or from satellite imagery? With proper training, artificial intelligence (AI) and other nontraditional methods could greatly augment and accelerate traditional intensity assignments while collecting valuable damage data that could be used for other humanitarian and scientific purposes.

Promising machine learning approaches for rapidly updating modeled loss estimates with satellite imagery analysis will benefit from any immediate on-the-ground damage observations that are available [e.g., *Xu et al.*, 2022]. And AI-assisted intensity assignments will improve ShakeMaps and help constrain overall impact assessments for disaster response and recovery.

While those advances are still on the horizon, we are considering strategies for addressing challenges to integrating traditional and Internet-based intensity assignments by standardizing building damage data collection. As long as accurate assignments of higher intensities require more expertise than is available via community-based reports, we must ensure that professional damage assessors and building inspectors collect data that provide a statistically sufficient sampling of buildings in a given area.

During a second IMSWG workshop at the Powell Center on 2–6 October, we plan to bring in experts on postearthquake building damage data collection. Working with these experts, we can facilitate modifications to their inspection protocols to ensure that they provide the needed sampling of buildings, along with accurate information about building types and damage. Such modifications will provide the standardization required by an EMS-98-like IMS. We will also facilitate standardization of Internet-based intensity data collection practices.

Integrating traditional field-based assignments with crowdsourced assignments (e.g., from DYFI and similar systems), as well as with those for past events based on historical sources like newspaper accounts and diaries, also requires accounting for the different uncertainties among these approaches. It is important to note that these uncertainties vary with intensity: Assignments of higher intensity are more uncertain than lower ones, particularly when assigned via crowdsourcing [*Quitoriano and Wald*, 2022].

Improving default approaches for estimating uncertainties—particularly when they are used quantitatively such as in ShakeMaps and downstream earthquake loss models like the PAGER system—is essential. Recognizing variations in uncertainties in crowdsourced assignments and ensuring that traditional assignments are based on adequate samplings of building damage are steps that will help. For assignments of shaking intensity during past earthquakes from historical observations, we anticipate that experts—informed by knowledge of data sources, the scale used, and even the expertise of assigners—will help provide accurate uncertainties.

Tackling the challenges of improving access to the DYFI system and to more systematic shaking and damage reconnaissance protocols worldwide should help address problems of inequitable access to reporting systems. Improved access also will be on the agenda at the upcoming second workshop, along with the challenges mentioned above. Initial strategies include adding more language options to DYFI (beyond the currently provided English and Spanish), expanding regional efforts similar to DYFI in countries where participation in global systems is lower, and improving outreach to remote locales by working with local experts and media to publicize the availability of DYFI immediately after significant earthquakes.

Moving in the Right Direction

Developing a global IMS will not fully solve the challenges of collecting and analyzing macroseismic data after earthquakes. However, it will lead to more orderly macroseismic data collection across much of the planet. It also will help harmonize Internet-based crowdsourced observations with traditional damage data gathered in the field, leading to more systematic cross-border analyses of seismic activity and thus a better understanding of the hazards and risks that populations face.

Acknowledgments

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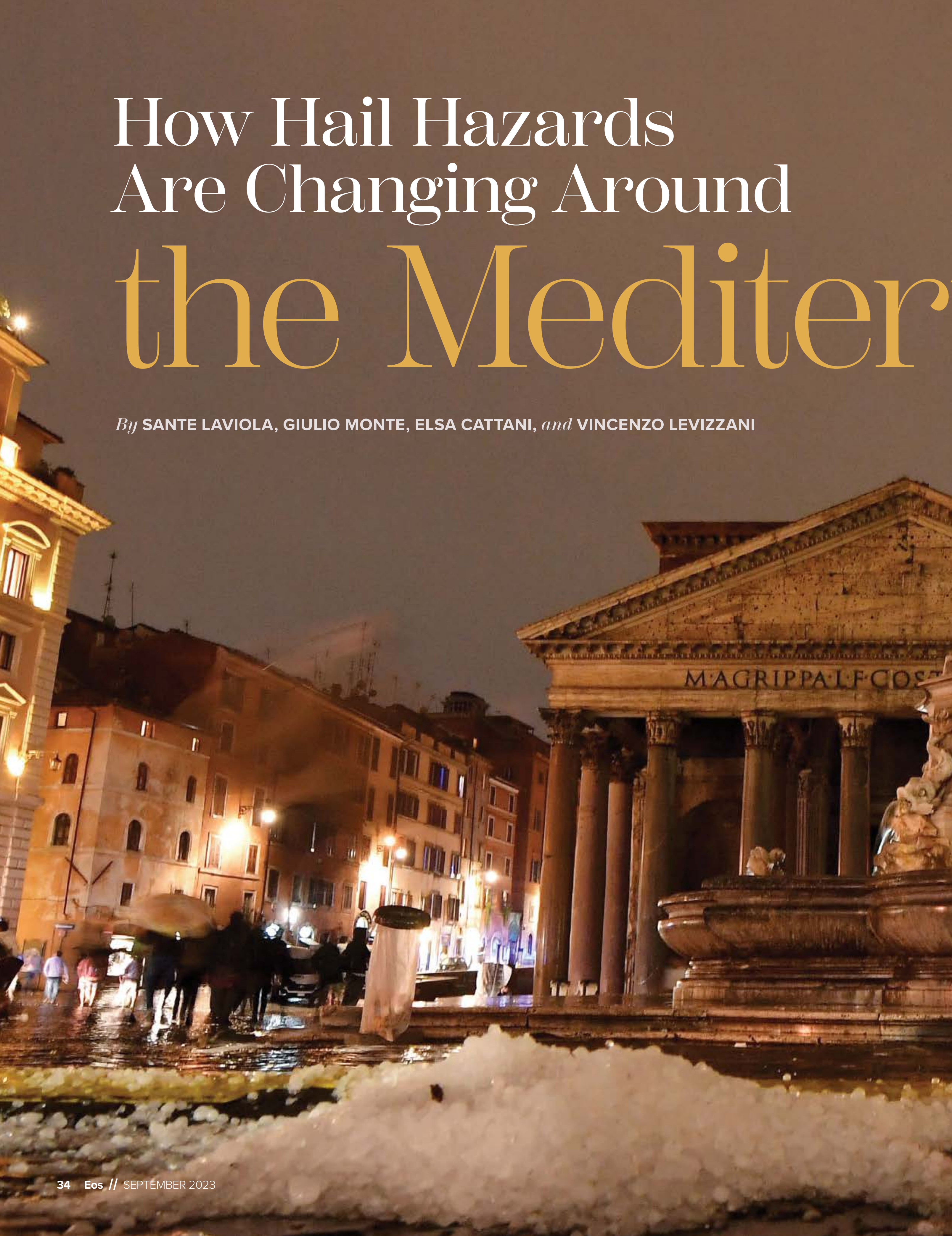
How Hail Hazards Are Changing Around the Mediter

By **SANTE LAVIOLA, GIULIO MONTE, ELSA CATTANI,** *and* **VINCENZO LEVIZZANI**



A new method for studying hailstorms from space offers more consistent and more complete views of how and where hail forms, as well as how climate change might influence hail's impacts in the future.

ranean

Piles of hail sit in the Piazza della Rotonda, facing the Pantheon in Rome in October 2018. Credit: Tiziana Fabi/AFP via Getty Images

The Mediterranean Basin is one of the areas on Earth most vulnerable to the effects of rapid climate change. Observed rates of temperature rise indicate that the region is warming 20% faster than the global average, inducing a trend toward drier conditions and changing precipitation regimes. Average temperatures today are 1.4°C higher than in the late 19th century [*Cramer et al.*, 2018].

The steep temperature rise increases the vulnerability of the Mediterranean Basin to several hazards that affect ecosystems and human health and security, such as heat waves, droughts, and fires. Along with such events, the frequency and intensity of storm-related hazards also may be amplified around the Mediterranean in a warming climate.

The links between regional climate change and hail occurrence and damage around the Mediterranean remain unclear, in part because of a shortage of historical data.

Hail is one hazard of interest because of its dangerous and destructive nature, especially when hail particles grow to large sizes.

During summer 2021, for example, a series of hailstreaks heavily damaged crops, vehicles, and infrastructure in northern Italy. One of the most severe events occurred on 26 July 2021 near Fidenza, when a storm produced hailstones larger than 8 centimeters in diameter that caused vehicle crashes and other damage on the A1 highway. A similar synoptic pattern affected northeastern Italy, including the city of Pordenone, on 1 August 2021, with very rapid and localized deep convection creating damaging hailstones upward of 5–6 centimeters in diameter.

The links between regional climate change, hail occurrence, and damage around the Mediterranean remain unclear, however, in part because of a shortage of historical data documenting hail events and in part because of the complex and varied topography and conditions around the region that affect hail production. This uncertainty complicates efforts to model and forecast hail generation accurately.

Recently, we have been working to improve scientific understanding of hail in the Mediterranean using satellite remote sensing. After developing a new satellite-based method for detecting hail-bearing storms [*Laviola et al.*, 2020a], we have comprehensively quantified the occurrence of hail events around the region during the past 22 years (1999–2021) [*Laviola et al.*, 2022].

Our goal is to explore the distribution, seasonality, and frequency of events to identify "sub-hot-spot" areas within the Mediterranean that are most susceptible to hail events. This work has extended and updated the historical record of Mediterranean hail events, and it should help advance understanding of hail-generating processes, produce a global hail climatology, and illuminate possible ties between hail trends and ongoing climate change.

Detecting Hail from Space

Hail forms when strong updraft winds in storm clouds keep raindrops and ice particles aloft at high altitudes, where temperatures are below freezing, and where these particles can collide and freeze into larger pieces. When hailstones become too heavy to be supported by the updrafts, they fall to the ground. Hailstorms are typically short-lived (<30 minutes) and affect limited geographic areas (<10 kilometers), factors that significantly complicate their observation where ground-based instruments are not available.

Satellite sensors, with their wide range of sounding frequencies, high spatial resolution, and increasing abundance in low Earth orbits, offer substantial promise for hail detection and investigation on regional to global scales.

The Global Precipitation Measurement Constellation (GPM-C) is an international mission designed to measure precipitation using microwave sensors aboard about a dozen satellites. Satellite microwave instruments probe precipitating clouds by sensing perturbations in Earth's natural microwave radiation field caused by liquid or frozen water droplets (hydrometeors). High-frequency (>60 gigahertz) microwave channels on these instruments mostly capture the signal produced by ice

Table 1. Categories and Traits of Hail Considered in the MicroWave Cloud Classification–Hail (MWCC-H) and associated potential severity[a]

Category description	Probability of hail	Diameter range, cm	Kinetic energy, J	Terminal velocity, m s-1	Potential severity
Hail potential (HP)	0.20–0.36	—	—	—	absent to low
Graupel/hail initiation (HI)	0.36–0.45	<2	<33.84 × 10-2	<19.09	low to moderate
Large hail (H)	0.45–0.60	2–10	33.84 × 10-2 – 423	19.09–42.69	high to severe
Super hail (SH)	>0.60	>10	>423	>42.69	severe to extreme

[a] Adapted from Laviola et al. [2022], CC BY 4.0 (bit.ly/ccby4-0)

hydrometeors, namely, graupels or hailstones, in the upper part of storm clouds. These large ice aggregates scatter microwaves, typically reducing the upwelling radiation field measured by satellites.

The hail detection method we developed, called MicroWave Cloud Classification–Hail (MWCC-H), is based on the inverse proportionality between the amount of upwelling radiation and hail cross sections [*Laviola et al.*, 2020a, 2020b]. Through a probability-based model of growth, the MWCC-H interprets the signature from ice aggregates at 150–170 gigahertz to identify and isolate hail-bearing clouds in storm systems. For each detected hail cloud, the method calculates the probability of hail occurrence—and its potential severity—as a function of diameter (Table 1).

By applying our new detection method to the high-frequency microwave sensor observations acquired by orbiting GPM-C satellites between 1999 and 2021, we investigated the susceptibility of different areas of the Mediterranean Basin to hail events over that time period [*Laviola et al.*, 2022]. The data set included observations of hail in all four size-severity categories described in Table 1, although we considered only the most severe events—that is, those with large (2- to 10-centimeter-diameter) or super (>10-centimeter-diameter) hail—in identifying Mediterranean sub-hot-spots of hail activity.

We divided the Mediterranean Basin into nine subregions and counted the number of occurrences of large or super hail during the April–November hail season from 1999 to 2021. Our analysis showed that parts of southern Europe, especially southern Italy, and central Europe experienced the most severe hail events over this period (Figure 1) and that the peak timing of these events varied somewhat by subregion, delineating their broader seasonality (Figure 2).

Different climatic and topographic factors influence convective activity, and thus the frequency and seasonality of hail formation, in different areas of the Mediterranean Basin. Western and central Europe (S1.3 and S2.3 in Figure 1), for example, are highly exposed to hail hazard in the summertime. Hail occurrence in these regions mostly relates to how the land surface morphology (e.g., the Alps or the Po Valley lowlands in northern Italy) interacts with atmospheric factors like moisture content and wind shear. In central to eastern Europe (S3.3), convective activity is often forced by local orographic influences of the Balkan and Carpathian mountains.

The climate of southern Europe (S1.2, S2.2), including southern Italy and the eastern Iberian Peninsula, is dominated by high solar insolation and effects of the Mediterranean Sea. Across these areas, warm and moist air masses formed over the sea are primarily responsible for convection and the formation of severe hailstorms that peak during late summer and autumn.

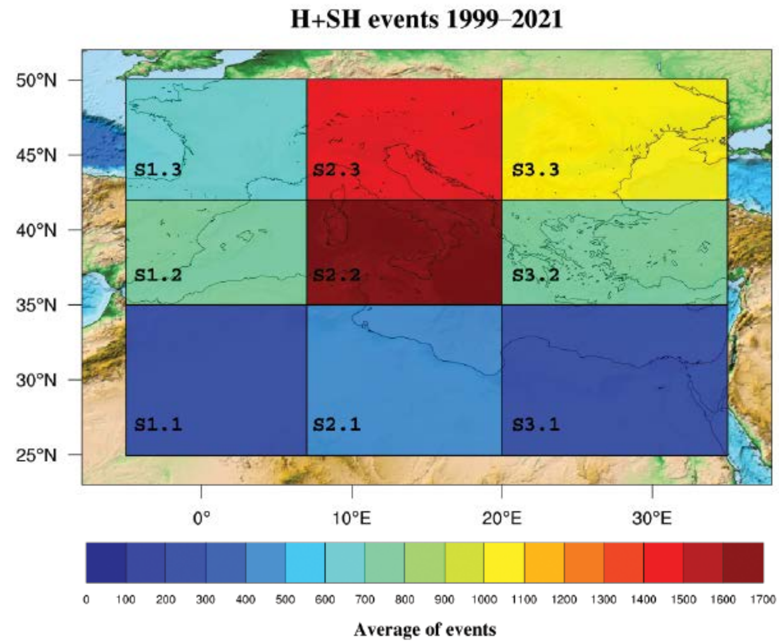


Fig. 1. The average annual number of large and super hail events (H and SH as defined in Table 1) from 1991 to 2021 varied greatly across nine subregions of the Mediterranean Basin. Regions S2.2 and S2.3, including Italy and other parts of southern and central Europe, experienced the highest occurrence of hail events over this period. Credit: Adapted from Laviola et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

In southeastern Europe (S3.2), the climate is influenced by complex local conditions. The Mediterranean and Black seas combined with numerous islands, several gulfs, and large mountain chains (e.g., in the Balkans and Anatolia) create local instabilities that can trigger vigorous convective activity and may play a role in hailstorm formation.

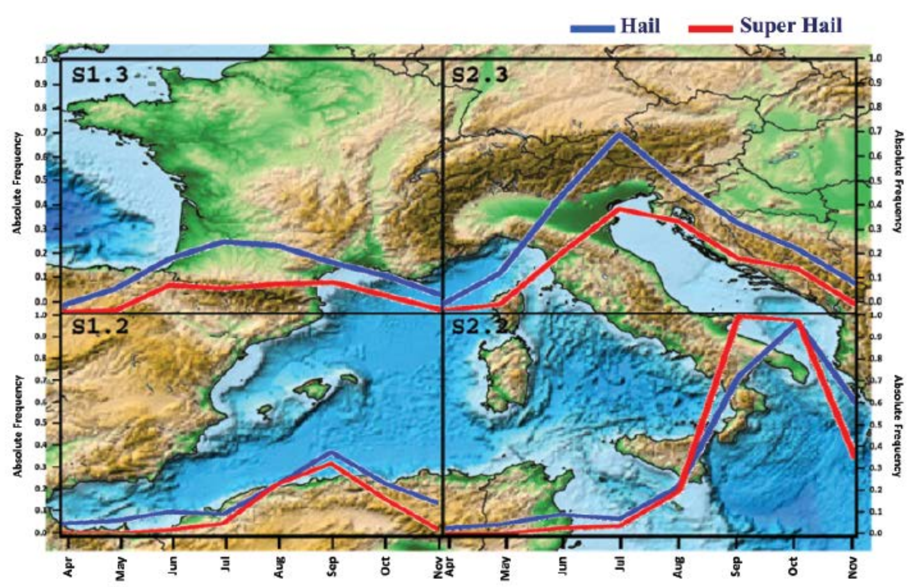


Fig. 2. The seasonality of large hail (blue) and super hail (red) events within the April–November "hail season" also varies across Mediterranean regions. The absolute frequency of events increases in midsummer for regions S1.3 and S2.3 while for regions S1.2 and S2.2 hail events are more frequent in late summer and autumn. Credit: Adapted from Laviola et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

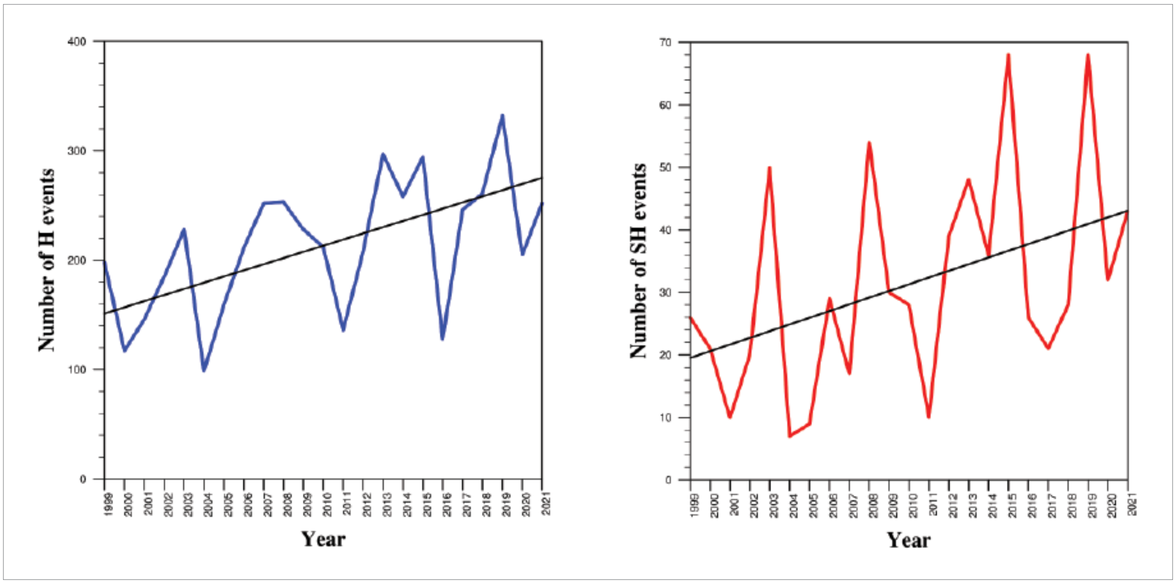


Fig. 3. The temporal evolution from 1999 to 2021 of the annual numbers of H and SH events for the entire Mediterranean Basin considering combined measurements from the NOAA 15, MetOp-A, and MetOp-C satellites. Black lines indicate the linearized trends of the data. Credit: Adapted from Laviola et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

In the southern sectors of the study domain (S1.1, S2.1, S3.1), comprising much of North Africa and the Middle East, far fewer large or super hail events occurred than in other subregions because of the proximity of the arid Sahara desert. Where hail events do sometimes occur in North Africa, however, such as in Tunisia (lower left of S2.2) and Libya (S2.1), the late spring to summer seasonality is similar to that in other Mediterranean sectors.

Considering the high stakes for public safety of worsening hail hazards, we are investigating what conditions or factors are most favorable for hail production and how those conditions are changing with climate warming.

The Unknown Contribution of Climate Change

Our analysis of the 22-year data set demonstrates, despite high interannual variability, that there are statistically significant (significance > 90%) increasing trends in the number of large hail and super hail events across the entire Mediterranean Basin (Figure 3). For both types of events, the incidence of the phenomena in the past decade (2010–2021) increased from that of the preceding 1999–2010 period by roughly 30%.

These rising trends raise questions about whether climate change is accelerating the occurrence or severity of hailstorms in the Mediterranean Basin. Such causal attribution is challenging, and these questions are far from answered. However, considering the high stakes for public safety of worsening hail hazards, we are investigating what conditions or factors are most favorable for hail production and how those conditions are changing with climate warming.

The steep increase in hail events during the past 2 decades motivated us to explore trends around the Mediterranean in atmospheric variables generally thought to be precursors of the deep convective activity that can produce hailstones. These variables include the convective available potential energy (CAPE), which relates to atmospheric instability; the zero degree level (ZDEGL), or the altitude where the temperature is 0°C, which affects melting of ice hydrometeors; the temperature at 850 hectopascals (T850), which occurs at an altitude of roughly 1.5 kilometers, typically just above the boundary layer; and the sea surface temperature (SST).

Applying the Mann-Kendall test, which assesses monotonic trends in variables over time, to annually averaged data on these four variables from the European Centre for Medium-Range Weather Forecasts' Reanalysis Version 5 (ERA5) for the period 1959–2021 indicates that amid high variability, each of these key variables has increased during the past 62 years (Figure 4).

The approximate doubling of CAPE in the Mediterranean reflects enhanced atmospheric instability and, in turn, the tendency of the environment to form hail-bearing convective systems. The ZDEGL has risen by about 400 meters, on average, meaning that hail has a longer distance over which to melt. Although this may allow smaller hailstones to melt into raindrops on their way to the ground, large and super hailstones that do not melt fully accrue more kinetic energy due to the longer path of their fall, thus making them more dangerous. Finally, warming of T850 and SST can alter dynamics at the air-sea interface that trigger and intensify vigorous convections in the central basin of the Mediterranean Sea, thereby also potentially influencing hail formation.

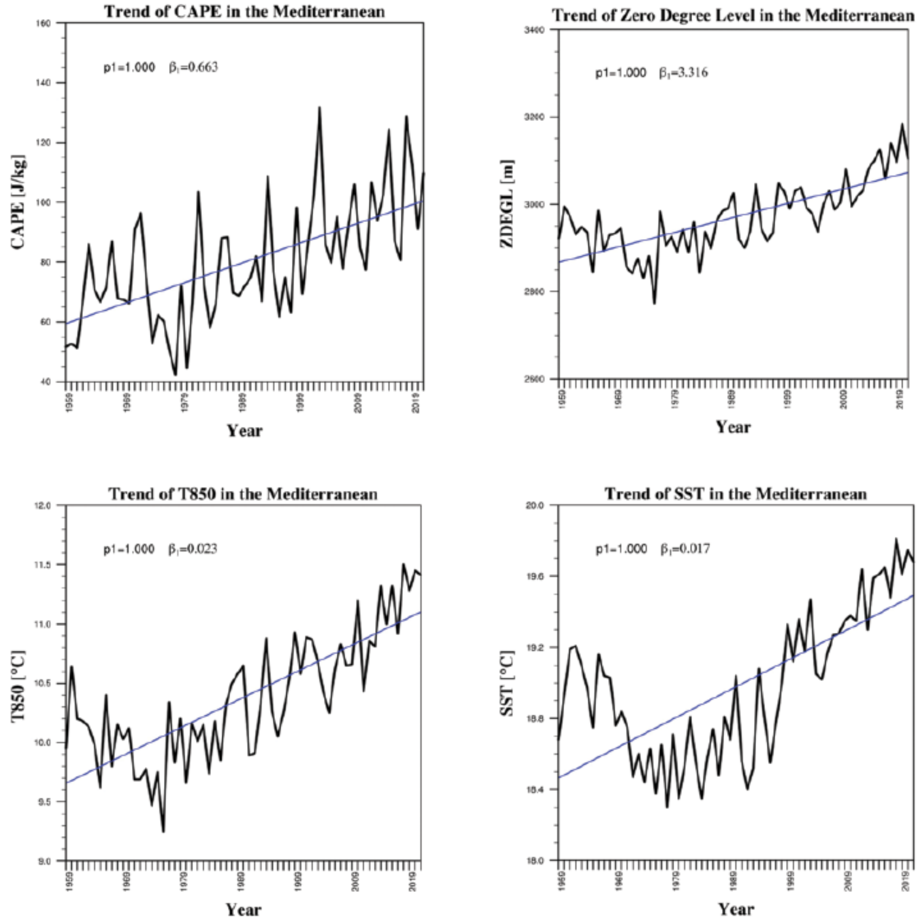


Fig. 4. Annual trends from 1959 to 2021 in the Convective Available Potential Energy (CAPE) in joules per kilogram, zero degree level (ZDEGL) in meters of altitude, temperature at 850 hectopascals (T850), and sea surface temperature (SST) calculated for the entire Mediterranean Sea. Blue lines indicate the linearized trends of the data. Credit: Laviola et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

The upward trends in these factors do not prove their roles, or a role of climate change more broadly, in increased hail formation, but they suggest an atmosphere that has become increasingly primed to produce more and bigger hail. And it is widely understood that continuing warming will both amplify the intensity of extreme weather events and influence the probability of their occurrence, quite possibly including the locations and severity of hail impacts. Thus, it is vital that we rapidly improve our scientific understanding of the drivers of hail formation by integrating all available information from ground, air, and space.

Toward a Global Climatology of Hailstorms

Hailstorms are brief and localized events, but they can pose a hazard almost everywhere in the world. Investigations of the phenomenon usually focus on hailstorms over land, where the effects of hail are associated with or often derived from damages to agriculture or infrastructure, whereas no information is provided on hail events over the sea. The result is that we have an inconsistent, patchwork understanding of hail events and their effects.

Applying our hail detection method to the worldwide observations from GPM-C is the basis of a new approach to producing more complete and uniform hail data sets and thus more consistent hail maps, not just for the Mediterranean but also globally. After initially producing monthly global hail distribution maps with MWCC-H [*Laviola et al.*, 2020b], further advancements have allowed us to experiment with generating such maps at higher temporal resolutions (e.g., daily or even every 3 hours).

Figure 5 presents an experimental daily global map at a grid resolution of 1° × 1° showing the likelihood of hail events having occurred around the world on 10 July 2019. Probabilities for hail potential and hail initiation are used to better define hailstorm dynamics, as these categories are usually associated with the first stages of hail-producing convection. As expected, most large and super hail activity occurred in the tropics, and there were elevated probabilities in parts of the Mediterranean Basin (e.g., the Adriatic Sea and the Balkans) and the central United States, in agreement with the midlatitude seasonality of hail events. Meanwhile, few events were identified in the Southern Hemisphere (winter season).

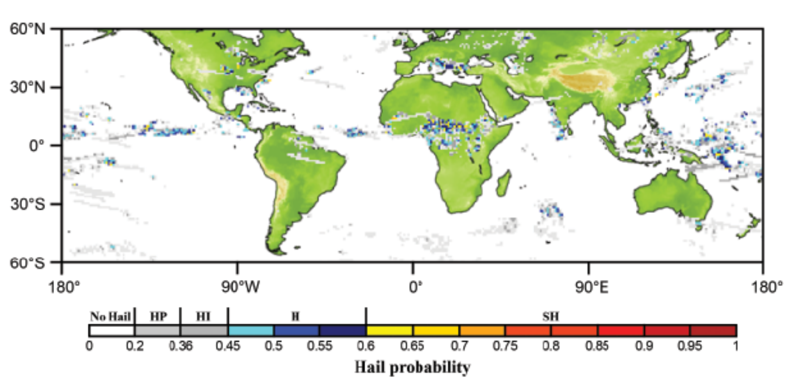


Fig. 5. Daily hail probability map showing the MicroWave Cloud Classification–Hail (MWCC-H) categories (HP, hail potential; HI, hail initiation; H, large hail; SH, super hail) calculated through the Global Precipitation Measurement Constellation (GPM-C) on 10 July 2019. The data set was retrieved using the daily orbits of nine platforms equipped with microwave radiometers.

These data sets and global maps may be useful for both climatological studies of hail events and the operational

Hailstones can vary in diameter from a few millimeters to more than 10 centimeters. The pieces shown here are roughly 8–9 centimeters across. Credit: iStock.com/spxChrome

needs of meteorologists. With frequent, recursive observations of worldwide hail distribution and severities affecting different regions, researchers can significantly improve predictive climate and weather models. Observation of hail events at a global scale over land and ocean also may open new paths to understanding severe phenomena and their connections to climate change.

Further, global hail maps can support risk management with respect to civil protection, insurance, food security, resource management, and energy production, thus mitigating the impacts of hail on human safety and activities.

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Volcanoes' Future Climate Effects May Exceed Standard Estimates

Astronauts aboard the International Space Station photographed this large eruption of Sarychev volcano in the Kuril Islands of Russia in June 2009. Credit: NASA

When volcanoes erupt, they often spew large amounts of sulfur dioxide into the atmosphere. This toxic, foul-smelling gas may then form tiny sulfate particles that can influence Earth's climate for months to decades.

In modeling future climate change, scientists have therefore incorporated the effects of volcanic eruptions. However, *Chim et al.* now show that there is a 95% chance that volcanic eruptions between 2015 and 2100 will release more sulfur dioxide into the atmosphere than standard climate models currently assume.

The challenge of predicting future sulfur dioxide release arises because eruptions cannot be precisely forecasted. So standard climate models have typically relied on averaged historical sulfur dioxide release data from 1850 to 2014, under the assumption that future releases will be similar. However, this approach does not account for large variations in releases that can occur from century to century, nor does it account for small-magnitude but frequent eruptions that are not captured in historical records.

To address these shortcomings, the researchers used updated data sets from satellites and ice cores, which provide a glimpse into eruptions over the past 11,500 years, to simulate the effects of future volcanic sulfur dioxide releases. They also applied a mathematical modeling method that more adequately represents eruptions of all magnitudes, and they developed a new modeling framework that better simulates plumes of gases and other materials ejected in eruptions.

The researchers' analysis suggests that existing climate projections most likely underestimate the effects of volcanic sulfur dioxide on Earth's climate, including on global surface temperature, sea level, and sea ice extent. It also indicates that existing models appear to inadequately account for the effects of smaller-scale eruptions that add up over time to influence climate significantly.

The researchers recommend that standard climate models—in particular, those produced as part of the Coupled Model Intercomparison Project—be updated accordingly. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL103743, 2023) **—Sarah Stanley,** *Science Writer*

Enhancing Earthquake Detection from Orbit

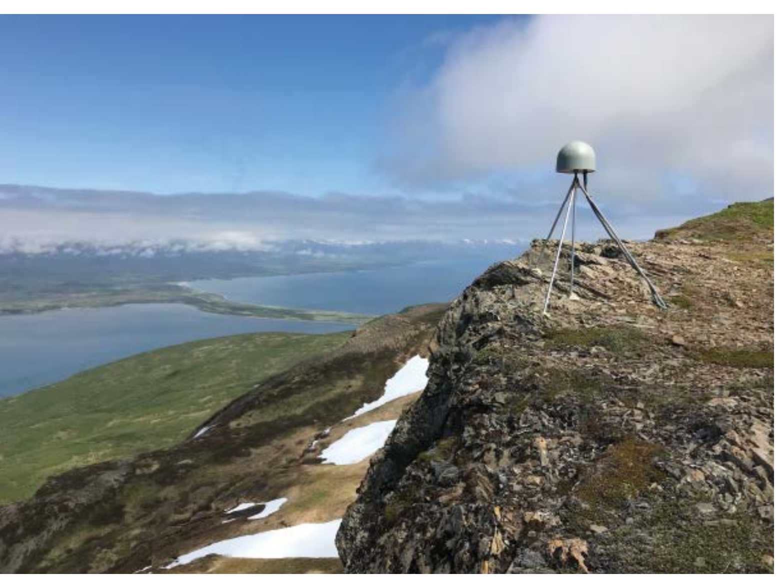
When a major earthquake strikes, nearby seismometers can provide rapid alerts to residents and emergency services that potentially hazardous phenomena may be headed their way. However, local seismometer measurements are not sufficient to determine in real time just how big the largest earthquakes are.

Scientists have harnessed high-precision measurements of ground displacement from Global Navigation Satellite Systems (GNSS), such as GPS, to complement seismometer observations. GNSS data can differentiate between the largest earthquakes but are noisier than data from conventional seismometers, which has limited their contributions in natural hazards applications.

To address the noisy data, *Dittmann et al.* made two experimental choices predicated on previous GNSS seismology research and machine learning development: They adopted an alternative method for processing geodetic measurements, and they trained a machine learning model to use GNSS sensor data to detect earthquakes. The team trained, validated, and tested the model using data from the National Science Foundation's Geodetic Facility for the Advancement of Geoscience archive from 77 earthquakes greater than magnitude 4.5 that occurred over 20 years.

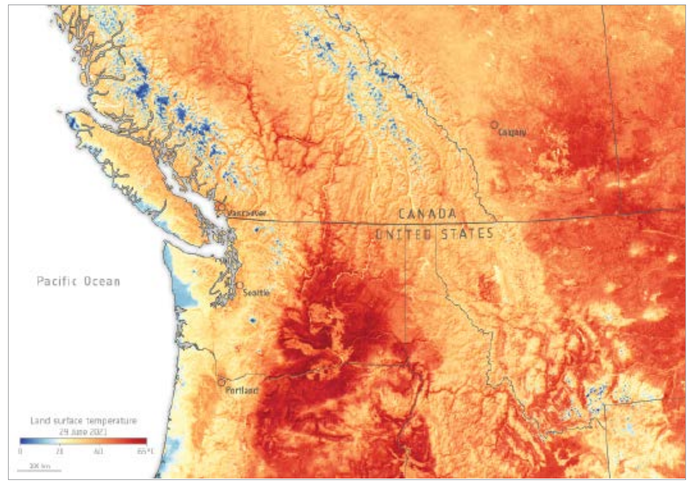
When pitted against existing GNSS earthquake detection methods, the new model detected more true seismic signals and triggered fewer false alarms. In addition, unlike previous methods, the new model relies on computationally lightweight processing and does not rely on additional corrections to account for false signals.

The researchers suggest that the new model can be widely applied to enhance the role of GNSS sensors in earthquake detection. They also outline opportunities for future refinement, such as applying more extensive data sets to train and validate the model. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2022JB024854, 2022)
—Sarah Stanley, *Science Writer*



A new algorithm was shown to improve the use of data for earthquake sensing from Global Navigation Satellite System sensors, like this one on the Aleutian Peninsula of Alaska. Credit: Ellie Boyce/UNAVCO, CC BY 4.0 (bit.ly/ccby4-0)

Far-Flung Forces Caused the 2021 Pacific Northwest Heat Wave



The 2021 heat wave in the Pacific Northwest brought record-setting temperatures to the region from Oregon to British Columbia. Temperatures are displayed for 29 June 2021. Credit: European Space Agency/Copernicus Sentinel, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

An extreme heat wave struck the Pacific Northwest in June 2021. Temperatures soared to above 40°C across Oregon, Washington, and British Columbia, and sometimes approached 50°C. Experts estimate that at least several hundred people died as a result.

In a recent paper, *Schumacher et al.* identify earthly factors that caused the heat wave. The researchers teased apart potential causes using the Community Earth System Model, an atmospheric model developed by the National Center for Atmospheric Research and made freely available for the climate community to use.

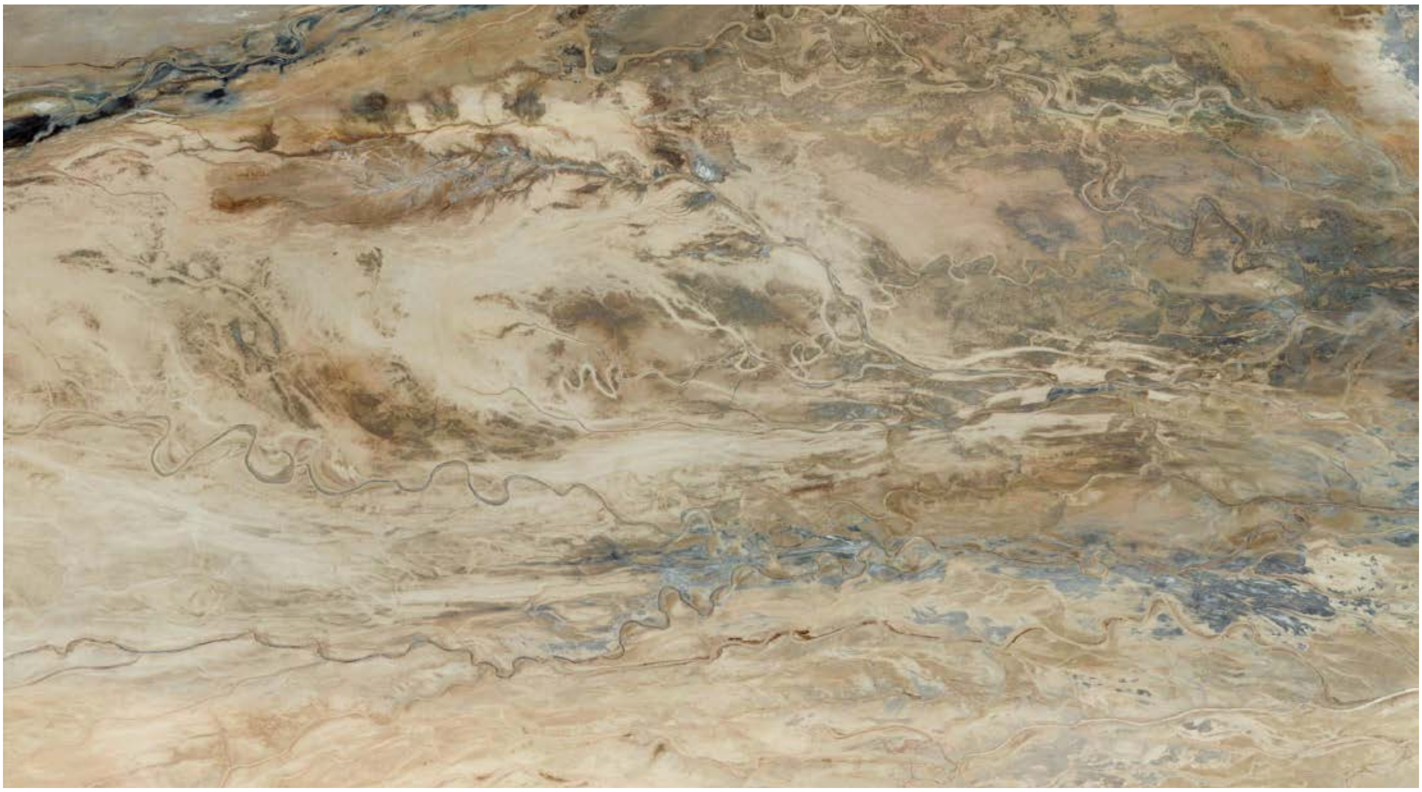
The heat wave started thousands of kilometers away from the Pacific Northwest in the air above the northern Pacific Ocean, the researchers found. Above the open sea, high humidity charged potential energy in the air. This amped-up air traveled thousands of kilometers on airstreams known as "conveyor belts" to reach western North America.

From there, the air spiraled down toward the ground, where the potential energy was converted into heat. This hot air went on to spread both vertically and horizontally. The vertical spread funneled additional heat down from higher in the atmosphere, and the horizontal spread brought dangerously high temperatures to a broad geographic area.

Extremely low soil moisture also contributed to the heat wave. Wet soils buffer extreme heat, and had the land been moister, temperatures might have been 5°C cooler.

As bad as the heat wave was, it could have been worse, the researchers say. The soil could have been even drier, the region upwind could have been warmer, and the air above the Pacific Ocean could have been more moist. As the planet heats in the future, the authors expect these trends to bear out. (*Earth's Future*, https://doi.org/10.1029/2022EF002967, 2022) **—Saima May Sidik,** *Science Writer*

Mud Could Have Made Meandering Rivers Long Before Plants Arrived



Seen in this satellite view are meandering channels in Badwater Basin in California's Death Valley National Park. Similar single-thread channels can be found around the world in barren environments that are dominated by fine-grained sediments and virtually free of vegetation. Credit: Google Earth, 2023

Geologists have long thought that meandering rivers, with their gently swooping banks, are a geologically recent feature. According to the rock record, these rivers began proliferating around 450 million years ago in the Silurian period, coinciding with the spread of plants on land. The prevailing idea was that plants would have stabilized riverbanks, leading water to flow in concentrated, meandering channels rather than forming chaotic braided river systems in loose sediments.

But a growing body of literature is challenging this idea. Meandering-style rivers have been found in barren landscapes on Earth, and similar features have been spotted on Mars. Physical modeling has shown that single-channel rivers can form in fine sediments alone. And some studies have found Proterozoic fluvial deposits with low slopes, dunes, and deep channels similar to modern meandering rivers.

Now, *Valenza et al.* present the oldest evidence yet that plants may not be necessary for meandering rivers to form. The researchers studied 1.2-billion-year-old river deposits preserved in rocks of the Stoer Group in northwestern Scotland, analyzing sediment composition, riverbed features such as dunes and ripples, and channel geometry.

The researchers found that the river sediments were likely deposited in sinuous 4- to 7-meter-deep channels with gentle downslope gradients like those of modern meandering rivers. The presence of dunes at the river's bottom suggested that channelized water flowed relatively quickly over the sediments. The team's analyses of small-scale mud physics showed that a mix of sand and mud like that seen in the Stoer Group sediments could have been cohesive enough to hold a riverbank together without the help of plants.

The seeming increase in the presence of meandering rivers in the Silurian could be explained by a drop in the average speed of river migration thanks to bank-stabilizing plants rather than by the sudden introduction of a new river shape, the authors posit. If rivers prior to this time migrated quickly, the sediment deposits they left behind could look similar in the rock record to those left by braided rivers, potentially leading scientists to misinterpret them as signs of braided systems.

As evidence of similar river geometries in other Proterozoic deposits builds, further understanding of how these rivers formed is increasingly important, according to the authors. They are planning flume experiments to explore how a meandering river can leave deposits that mimic those of a braided river. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL104379, 2023) **—Rebecca Dzombak,** *Science Writer*

Neural Networks Map the Ebb and Flow of Tiny Ponds

Researchers used satellite data and machine learning to map small ponds like these in Alaska. Credit: Andrew Mullen

Small ponds emit a surprisingly large amount of methane compared with larger water bodies. Because ponds are so tiny, they have been difficult to track, and their contributions to terrestrial greenhouse gas emissions are largely unaccounted for. In a new study, *Mullen et al.* use deep learning to construct a fine-grained map of ponds in Alaska.

The counterintuitive relationship between pond size and carbon emissions has to do with the ratio of perimeter to surface area. The smaller a pond is, the greater the ratio. A large perimeter accumulates more decaying leaf litter, sediment, and other terrestrial carbon. Smaller ponds also are shallower, so their carbon loads are more concentrated, and gases generated at the bottom are not far from the surface.

Because ponds are so small (<0.01 square kilometer), their size can fluctuate drastically in response to environmental factors like precipitation and permafrost. In the new study, the team used Planet Labs' PlanetScope satellites to census ponds in Alaskan boreal and tundra landscapes and tracked them over several years.

These satellites provide daily imagery at 3- to 5-meter resolutions, but even these resolutions are too coarse to fully delineate small ponds with traditional methods. To reach a greater resolution, the researchers turned to machine learning.

They used convolutional neural networks—a type of machine learning that specializes in classifying complex imagery. The technique has been successful in monitoring large lakes in the past but until now has not been used to monitor ponds.

The authors looked at four areas in Alaska that included a number of different ecosystem gradients. Using data from 2019 to 2021, they mapped ponds down to 0.0001 square kilometer and tracked them over time.

The surface area of ponds varied by 20%–40% in a single season. In addition, on the basis of an existing data set, the team found that ponds can contribute a broad range of methane emissions, depending on the local environment—anywhere from 8% to 37% of the total methane stemming from freshwater lakes and ponds.

The findings, the team says, demonstrate a new and improved way to monitor small water bodies and highlight the importance of fine-scale tracking for habitat assessment, land cover change, and biogeochemical modeling. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL102327, 2023) **—Sarah Derouin,** *Science Writer*

Dissecting Ocean Dynamics in Greenland's Fjords

Greenland's deep fjords are the interface between the world's second-largest ice sheet and the Atlantic Ocean, catching tremendous volumes of frigid freshwater from melting ice and calving glaciers and facilitating water exchange, heat transport, and other processes important in the global climate system. However, ocean dynamics in fjords are relatively unknown because observational studies of the features are costly and technically challenging.

In a recent study, *Gelderloos et al.* modeled ocean currents in four fjords along Greenland's southeastern coast using three high-resolution numerical simulations, checking the modeled results against in situ observations to validate the simulations.

The authors specifically looked at changes in ocean dynamics over several-day periods, known as subinertial changes. Subinertial variability is distinct from tidal, or daily, variability and long-term seasonal to annual variability. Previous work identified subinertial variability as being critical to Greenland's fjord dynamics, contributing to its hydrological properties and regulating the flux of water to and from the continental shelf.

The new research indicates that ocean currents in the studied fjords result mainly from the action of coastal trapped waves, a class of ocean waves that form in shallow ocean regions above continental shelves. The patterns and variability of volume and heat transport in the four fjords were found to cycle in either 2- to 4-day or 10-day frequencies depending on the size of the fjord. The widths of the fjords as well as temperature- and salinity-driven density stratification within them further shape wave patterns. Both cycles are associated with coastal trapped waves, suggesting that the continental shelf is more influential in shaping currents and variability in the fjords than alongshore winds are, though the latter appear to play a role too.

Documenting variability in Greenland's glacial fjords is vital for understanding their role in changing climate and ocean dynamics, according to the authors. The new research will help scientists predict fjord dynamics and variability, they say, and it indicates that these characteristics can vary from one fjord to the next. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2022JC018820, 2022) **—Aaron Sidder,** *Science Writer*

High-Frequency Monitoring Reveals Riverine Nitrogen Removal

Humans tend to make messes, and when it comes to the excess nitrogen we contribute to waterways, aquatic plants get stuck cleaning it up. Nutrients such as nitrogen in wastewater and agricultural runoff often escape into rivers, where they can overstimulate the growth of plankton, resulting in excessive algal blooms and oxygen-depleted conditions as the blooms decompose. Submerged riverine plants can partially mitigate this effect by taking up nitrogen-containing compounds from the water.

Botrel et al. bring a new level of temporal resolution to this long-observed phenomenon, reporting on observations of nitrogen retention at a site where two agricultural tributaries join Lake Saint-Pierre on the St. Lawrence River in Quebec, Canada. At the junction, a submerged plant meadow absorbs nitrogen and prevents much of it from reaching the St. Lawrence Estuary.

From June to November between 2012 and 2017, the researchers estimated the daily biomass of plants in the meadow by calculating changes in the slope of the water level caused by the vegetation using measurements from upstream and downstream of the study site. This was done using a model they developed through detailed plant biomass collection in

Researchers studied nitrogen removal by a submerged meadow of aquatic plants situated near where the Saint-François and Yamaska rivers enter Lake Saint-Pierre on the St. Lawrence River in Quebec, Canada, seen here from the air and in detail (inset). Credit: Christiane Hudon

the meadow across very different climatic years. Then they estimated the amount of nitrate entering the site from the tributaries and calculated the amount the plants processed by placing a high-resolution nitrate sensor at the edge of the meadow to measure the amount exiting.

By analyzing biomass levels, the authors related plant abundance to nitrogen retention, calculating the amount assimilated by plants and lost to the atmosphere through denitrification. On average, each square meter of the aquatic meadow removed about half a gram of nitrogen per day, the researchers estimated, resulting in up to 0.8 kiloton of nitrogen retained per year, or the amount generated by a city of a half million people annually—among the highest values reported so far in rivers. In years when biomass was low, only 47%–62% of the nitrogen put into the system was removed, whereas 63%–87% was removed in years when biomass was high.

Although the meadow is always performing this important ecosystem service, the researchers found that moderate rainfall and temperatures were optimal for denitrification because of high plant biomass, whereas extreme conditions reduced the fraction of nitrogen retained by the plant meadow. With climate change likely to increase the frequency of extreme weather, the future could see more nitrogen getting to the St. Lawrence Estuary, which could cause a higher incidence of blooms and oxygen depletion. Management actions should thus aim to preserve or restore this meadow and similar sites, the researchers write. (*Water Resources Research*, https://doi.org/10.1029/2022WR032678, 2022) **—Saima May Sidik,** *Science Writer*

JEFFERSON SCIENCE FELLOWSHIPS

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PRINCETON UNIVERSITY

MODEL EXPLORATION OF IRON FERTILIZATION AT PRINCETON UNIVERSITY

The Atmospheric and Oceanic Sciences Program at Princeton University in cooperation with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) seeks a **postdoctoral or more senior research associates** to enlist global earth system models to assess the effectiveness and risks of ocean iron fertilization as a carbon dioxide removal strategy to slow the pace of climate change. The work will be conducted as part of a recently funded collaborative project with Woods Hole Oceanographic Institution and the National Center for Atmospheric Research on assessment of potential marine Carbon Dioxide Removal strategies. The incumbent will leverage GFDL's existing 1/2 degree fully-coupled Earth System Model (ESM4.1) and high-resolution coupled physical-biological ocean configurations. The incumbent will assess the effectiveness, implications, and observational requirements for both small- and Petagram- scale fertilization. Personnel will join an active group at Princeton and GFDL studying the connections between biogeochemistry, ecosystems, and climate (**https://www.gfdl.noaa.gov/marine-ecosystems/**).

This is a one-year position with the possibility of renewal for a second year (contingent upon satisfactory performance and funding) based at GFDL in Princeton, New Jersey. Complete applications, including a cover letter, CV, publication list, a one to two-page statement of research interests and names of at least 3 references in order to solicit letters of recommendation, should be submitted online at **https://www.princeton.edu/acad-positions/position/30561** by **August 31, 2023 11:59 p.m. EST** for full consideration, though evaluation will be ongoing. Princeton is interested in candidates who, through their research, will contribute to the diversity and excellence of the academic community.

Essential Qualifications: PhD is required. Candidates with quantitative, interdisciplinary knowledge from subsets of fields including climate dynamics, ocean and coastal biogeochemistry, marine ecosystem dynamics, and fisheries science and management are particularly encouraged to apply. Experience analyzing large data sets and/or model output is also critical, as is model development experience for those positions.

This position is subject to Princeton University's background check policy. Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

Dear Readers:

A 20-minute drive north from Barstow, Calif., on a mostly washboard dirt road brings you out of a monochromatic desert into an oasis of color in Rainbow Basin. Layers of sediment and volcanic tuff streak through the bathtub-shaped depression in a 3D chevron of yellows, greens, and reds known as the Barstow Syncline. Deposited between 25 and 13 million years ago, the layers were subsequently folded and faulted.

—Jennifer Schmidt, Managing Editor, *Eos*

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