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Eos

SCIENCE NEWS BY AGU

Engineering with Nature

Starry, Starry Nights

Gaming-Based Virtual Field Trips

DATABASE UPDATES

Scientists reassess dated data in the time of the Cloud.

AGU
ADVANCING EARTH AND SPACE SCIENCE

Your Databases Need a Reboot

We are awash in dated data: punch cards, 9-track tapes, Earth itself.

Well, "Welcome to a New Era in Geosciences Data Management"! In a mission to make such data findable, accessible, interoperable, and reusable (FAIR) in the time of the cloud, scientists are poring over and reevaluating reams of paper, film, CDs, VHS tapes, and, yes, punch cards. These records fill floor-to-ceiling shelves of entire archives and more than a few offices of retiring geoscientists. Being FAIR is not always easy, we learn in Saima Sidik's feature on page 24, but it's always fascinating. Bonus: Can you spot the binary Easter eggs in this feature? (Hint: 01000001 01000111 01010101.)

Those 9-track tapes? They're what astronomers used to store data in the 1980s. The waves of technology that have crested since then—from cassettes to DVDs to today's digital archives—are perhaps less of a sea change than what they represent: Scientists are no longer entirely tied to rarefied "telescope time" to access astronomical (and astronomical amounts of) data. Astronomer and science writer Katherine Kornei details how "Deluges of Data Are Changing Astronomical Science" (p. 30) and democratizing it as well.

No archives are more dated than the soil and sand of Earth, and yet none are less antiquated, say Krystyna Powell, Safra Altman, and James Marshall Shepherd in "Engineering with Nature to Face Down Hurricane Hazards" on page 36. More active hurricane seasons are requiring more aggressive engineering; natural and nature-based features such as dunes and berms provide flexible, resilient models for coastal communities to incorporate into disaster protection and mitigation plans. Engineering with nature, it turns out, benefits economies as well as ecosystems.

With oceans of data come seas of uncertainties. In their opinion "Overcoming the Challenges of Ocean Data Uncertainty," (p. 20) authors Shane Elipot, Kyla Drushka, Aneesh Subramanian, and Mike Patterson argue that the goal is not to eliminate uncertainty in data but, instead, to better communicate its size and nature.

Updated databases are redefining the Earth and space sciences. Stay tuned.

Caryl-Sue Micalizio, Editor in Chief

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Randy Fiser, Executive Director/CEO

Features

On the Cover

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Columns

UV Radiation Contributed to Earth's Biggest Mass Extinction

Researchers collect samples of rock formed on the Tibetan Plateau around the time of the end-Permian extinction event. Credit: Liu Feng, Nanjing Institute of Geology and Palaeontology

About 252 million years ago, the end-Permian extinction, or "Great Dying," killed more than 80% of sea life and 70% of terrestrial species. Basalt lava oozed and belched out of fissures in the Earth for hundreds of thousands of years during this fiery apocalypse, spewing methane, carbon dioxide, sulfur dioxide, and other greenhouse gases into the atmosphere over what is now Siberia.

Researchers think that sea life such as trilobites went extinct because of the resulting ocean acidification and anoxia, but experts still debate exactly what killed terrestrial plants and animals. A popular theory is that toxic volcanic chemicals weakened the ozone layer—similar to the effect of chlorofluorocarbons (CFCs) in the late 20th century—increasing harmful ultraviolet B (UVB) radiation at Earth's surface.

To test this idea, researchers turned to fossilized pollen grains from an ancient conifer. The plants increased their production of a sort of chemical sunscreen after the volcanoes began erupting, the scientists reported in *Science Advances* (bit.ly/pollen-radiation).

Pollen Provides the Key

The Permian period, which lasted for about 50 million years, was an eventful one for life on land. Plant and animal groups became better adapted to dry land, colonizing the vast supercontinent of Pangaea, and vertebrates grew larger and more agile. But the end-Permian forced a hard reset on terrestrial ecosystems that would rewrite the story of life on land. For decades, researchers have asked, What caused such dramatic devastation?

Pollen from a conifer that grew during the end-Permian mass extinction recorded compounds that absorbed ultraviolet B radiation. Credit: Liu Feng, Nanjing Institute of Geology and Palaeontology

A depleted ozone layer, compromised by volcanic activity, could have made Earth nearly inhospitable. The layer protects life from harmful UVB radiation, which hurts plant reproduction and development and causes cancer in animals, with repercussions that ripple across the entire food web.

To see whether they could find direct evidence that plants suffered from increased radiation exposure coinciding with volcanic activity, researchers collected rock samples spanning a few hundred thousand years before and after the end-Permian extinction event. In all, they collected 32 rock samples, each corresponding to a different slice of geologic time. They processed the rocks with acids that removed mineral components, leaving behind only organic materials, including fossilized pollen grains.

After that, "the main challenge [was] to laboriously pick out individual pollen grains from the processed rock samples," said Phillip Jardine, a paleobotanist at the University of Münster and coauthor of the study.

The end-Permian extinction occurred more than 250 million years ago, but those who study it see parallels to modern human-caused environmental changes.

The grains, each half the width of a human hair, had to be identified under a microscope and individually tested for UVB-absorbing compounds. The researchers used a technique called Fourier transform infrared microspectroscopy, which allowed them to detect chemical signatures using infrared light. The team tested roughly 30 grains per rock sample, scanning more than a thousand pieces of pollen in total.

The analysis revealed a distinct spike in radiation-absorbing compounds produced during the extinction event. Over time, this radiation exposure would have impeded the growth of plants or even sterilized them, as well as affected animals directly with radiation poisoning.

"[This study] provides empirical evidence that UV levels were higher during the end-Permian extinction," said Vivi Vajda, a paleobiologist with the Swedish Museum of Natural History who was not involved with the research. "[Radiation exposure] has been proposed as a scenario for the extinction previously, but this is the first time that it could actually be proven."

"[Radiation exposure] has been proposed as a scenario for the extinction previously, but this is the first time that it could actually be proven."

In addition to helping solve a multimillion-year-old mystery, the research provided a powerful proof of concept for a technique to study ancient radiation levels. "I found it very interesting that the researchers identified a new molecular fingerprint revealing the substance that protects cell walls, in this case pollen grains, from UV light and solar damage," Vajda said. "This opens a new avenue for research in this area, and future researchers might apply this method to test other sites and other extinction events."

Parallels to the Present

The end-Permian extinction occurred more than 250 million years ago, but those who study it see parallels to modern human-caused environmental changes. Its impacts on land and sea life show how catastrophic the combined impacts of ozone depletion and a rapid increase in atmospheric greenhouse gases can be if left unchecked.

"While I'm not saying that without the Montreal Protocol we would have had another end-Permian mass extinction on our hands—the general context is obviously very different—the combination of climate change and ozone destabilization is clearly potentially very harmful for the biosphere," Jardine said. "For me, [the study] shows the importance of international agreements like the Montreal Protocol, and the necessity to keep to them in the long term."

By **Rachel Fritts** (@rachel_fritts), Science Writer

Starry Nights Are Disappearing

In the past decade, artificial lighting has decreased the number of stars visible to the human eye, especially in suburbs and cities. Credit: NOIRLab/NSF/AURA, P. Marenfeld, CC BY 4.0 (bit.ly/ccby4-0)

The Sun goes down. The stars come out. And so do the artificial lights. That's a huge problem for scientists, stargazers, and ecosystems that depend on a dark nighttime sky.

A new study evaluated how sky glow, the light that suffuses the night sky after sundown, has worsened over the past decade. Using more than 51,000 naked-eye observations from stargazers around the world, the team determined that the sky has brightened by an average of 9.6% per year, blinking out stars faster than anticipated from satellite measurements.

"Once you switch to LED lights, we see [cities] get darker in the satellite data. But when we look on large scales, most places are still getting brighter at night," said lead researcher Christopher Kyba, a scientist at GFZ Helmholtz Centre Potsdam in Germany who studies light pollution and sustainable lighting solutions.

Brighter and Brighter

Sky glow happens when artificial light scatters through the atmosphere and off of clouds at night, the same way that scattered light from the Sun makes the daytime sky blue and the dawn and dusk skies red. That nighttime illumination masks starlight. In recent decades, cities have expanded and installed new light fixtures, most of which use bright white light-emitting diodes (LEDs), which scatter light farther than older yellow-orange incandescent bulbs.

The switch has made measuring sky glow with satellites particularly challenging. Onboard technology that measures surface brightness dates back to the Cold War, before the advent of LEDs. Modern satellites were designed with similar technology to maintain continuity in the data.

Children born under a sky with 250 visible stars would be able to see only 100 of those stars on their eighteenth birthdays.

Because that technology was calibrated to measure light emitted by older-style yellow-orange bulbs, it's not very sensitive to the bluer light emitted by modern LEDs. Those sky glow measurements can therefore be inaccurate, explained Christian Luginbuhl, president of the Flagstaff Dark Skies Coalition in Arizona. LEDs emit more blue light than older bulbs do. Also, satellites look downward, measuring light reflected off the ground. A more accurate picture of sky glow's effects at Earth's surface comes from looking upward at the light scattering from molecules and aerosols, he said.

So Kyba and his colleagues turned to crowdsourced science to help them better measure changes in sky glow. For the Globe at Night project from the National Optical-Infrared Astronomy Research Laboratory (NOIRLab), people from 180 countries recorded how many stars they could see at night from their own backyards. From the 17-year database, the researchers mined more than 51,000 observations from 2011 to 2022, combining those from comparable locations, such as the centers of large cities or rural areas, to determine how night sky visibility has changed.

The researchers found that the decrease in visible stars is equivalent to the night sky brightening by an average of 9.6% annually during that period. At that rate, children born under a sky with 250 visible stars would be able to see only 100 of those stars on their eighteenth birthdays, according to the team. The researchers published their results in *Science* (bit.ly/sky-glow).

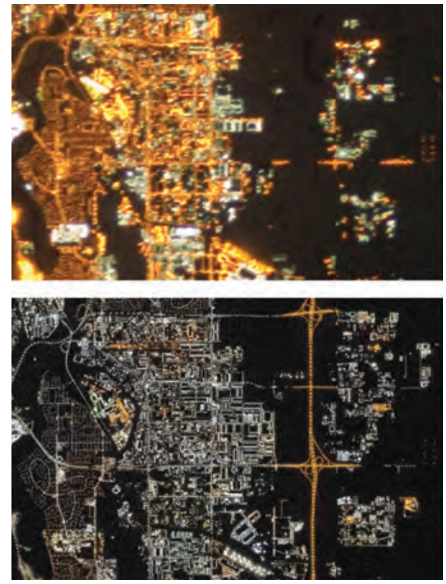
The increase in sky glow recorded by naked-eye observers around the world is roughly 6 times more than that measured by satellites. The discrepancy is partially due to the fact that most Globe at Night observations are recorded in residential areas, where development happens faster than under the darkest of rural skies.

"This study underscores and amplifies the alarm raised by light pollution researchers around the world in the last 10 years: Light pollution is increasing nearly everywhere, by substantial amounts," said Luginbuhl, who was not involved in the research. The work is "particularly important because of its reliance on human visual observations, which give a more accurate assessment of the impact to humans than the more commonly used satellite measurements."

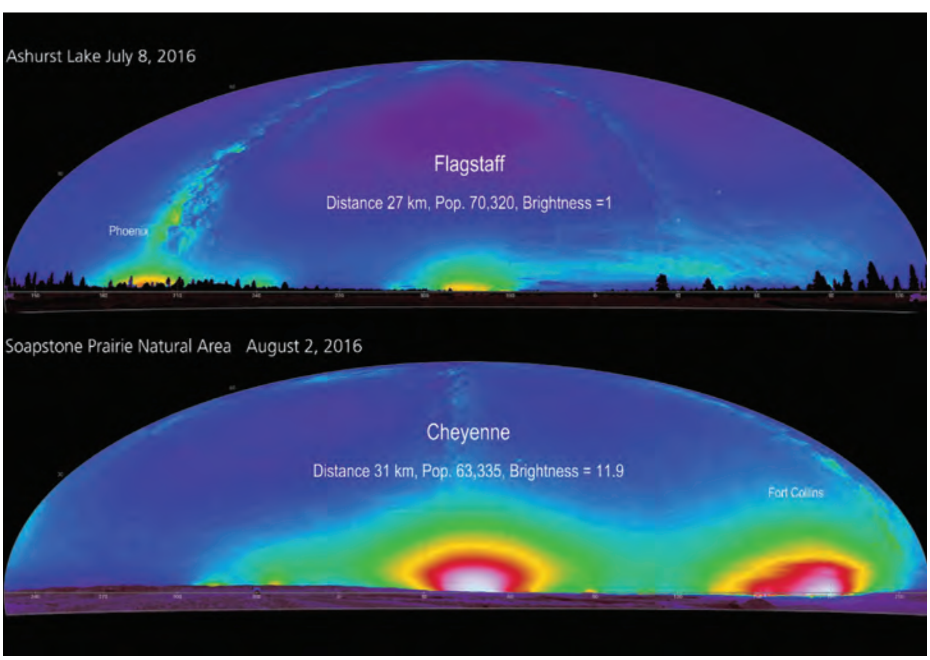
Impacts of Light Pollution

This research was "highly credible as a measure of decreasing visibility of the dark night sky," said Richard Green, an astronomer at University of Arizona's Steward Observatory in Tucson who was not involved with the research. "The rate of decrease is truly alarming. It is likely indicative of increasing disruption of natural processes, not to mention wasted energy."

Nearly half of species are nocturnal. The increasing loss of dark, starry nights has put many species at risk, including insects, sea turtles, and birds. "It's hard to overstate how big of an environmental change this is," Kyba said. "Life evolved for hundreds of millions of years under fairly constant conditions of a bright day and a relatively dark night.... Now, in a 100-year period, the natural signals of daytime and nighttime are gone over huge stretches of North America, Europe, and parts of Asia."



Astronaut photographs of East Calgary, Alta., Canada, show how city lighting changed from 2010 (top) to 2021 (bottom). Many streetlights switched from warm yellow-orange sodium lights to white LEDs, and new lighting was installed in residential areas and along highways. Credit: Earth Science and Remote Sensing Unit, NASA Johnson Space Center; georeferencing by GFZ Potsdam

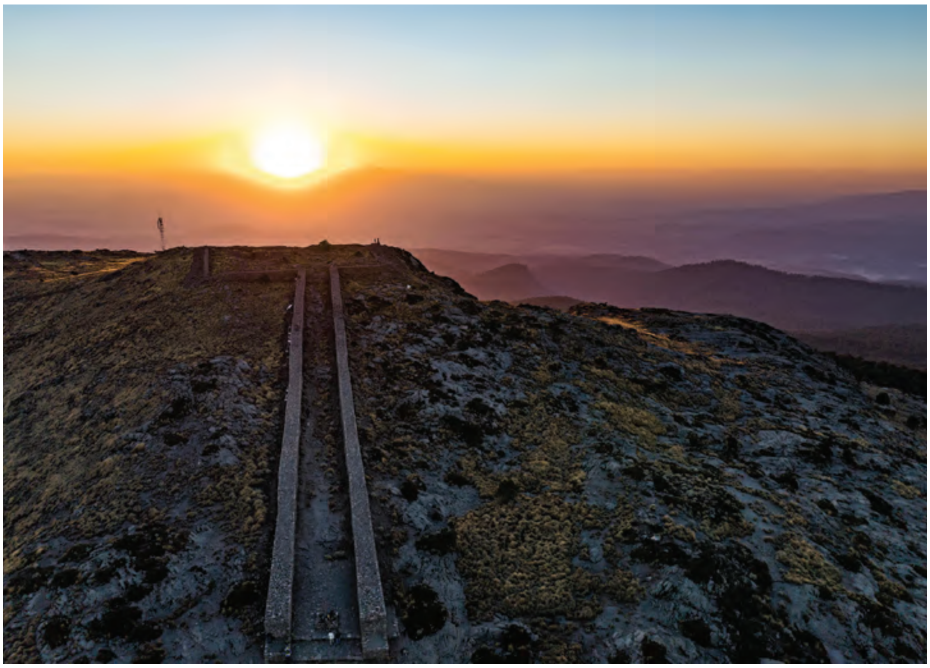


These all-sky images from the U.S. National Park Service show sky glow from about 30 kilometers outside Flagstaff, Ariz., and Cheyenne, Wyo., in 2016. Warm colors (red and white) indicate areas with brighter nighttime skies, and cooler colors (blue and purple) show darker sky areas. The two cities have similar populations, but Flagstaff's regulatory efforts to control light pollution reduced the impact of light on the night sky. Credit: Green et al., 2022, https://doi.org/10.1007/s00159-021-00138-3, CC BY 4.0 (bit.ly/ccby4-0)

Some regions, especially those near observatories or with endangered species, enforce ordinances to reduce light pollution, but individuals and communities also can make simple, low-tech changes to reduce sky glow and save on energy costs, Green said. "Such changes do not involve removing lights that are needed but, rather, using the right amount of light, in the right place, and at the right time." Shield lights so they shine downward, use yellow lights instead of white ones, and have lights on timers or motion sensors so they shine only when needed, he suggested. With these changes, said Green, "sky brightness reductions of 90% are realistic."

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

Agriculture Is at the Center of the Aztec Horizon Calendar



Mount Tlaloc in Mexico is the highest archaeological site in Mesoamerica. When observed from the hill of Tepeyac on 23 and 24 February, the Sun rises in alignment with Tlaloc, marking the beginning of the Aztec year. Credit: Ben Meissner

On 24 February 2022, Exequiel Ezcurra and a group of colleagues climbed to the top of Mount Tlaloc in Mexico, the highest archaeological site in Mesoamerica.

Trekking 4,120 meters above sea level was not just another adventure for Ezcurra, an ecologist at the University of California, Riverside. He was trying to confirm his latest hypothesis.

Between 1428 and 1521, Aztecs used the site to pay tribute to Tlaloc, the god of rain, but Ezcurra believes that Mount Tlaloc was more than a ceremonial center for the ancient civilization. He thinks it was a calendrical solar marker that allowed them to efficiently manage agricultural cycles.

Before the Spanish arrived in 1519, the Basin of Mexico was home to about 3 million inhabitants. Feeding so many mouths required extraordinary knowledge of the land and climate, said Ezcurra.

During the early morning, Ezcurra's group waited patiently at the base of the causeway structure that leads to the mount's peak. At 7:20 a.m., the Sun rose right at the center of the top edge of the road, as if it had been built with that exact intention.

The sight was "the most mystical thing my eyes have ever seen," Ezcurra said.

The Horizon Calendar

Seasonal change in Mexico differs from much of North America and Europe. Spring is dry and dusty, whereas torrential rains—caused by the absorption of moisture coming from the Pacific Ocean, the Gulf of California, and the Gulf of Mexico—strike during the summer, a phenomenon widely known as the Mexican monsoon.

"In that scenario, any advance rainfall could have confused farmers, which would have caused severe consequences for the harvest."

Vegetation has adapted to these patterns. Several of the most common seeds found in the region, such as those of beans and teosintes (one variety of which was eventually domesticated as corn), have a hard outer layer and need several showers of rain to germinate.

Ezcurra wondered how ancient civilizations successfully mastered agriculture in the region without using modern tools. "In that scenario," Ezcurra explained, "any advance rainfall could have confused farmers, which would have caused severe consequences for the harvest."

Through astronomical computer models, the researcher and his team began to calculate where the sunrise was observed from the perspective of someone standing in the Templo Mayor—the absolute center of ancient religious life in the region, which also was used to make astronomical observations.

The concept of a horizon calendar is widely known to archaeoastronomers; it refers to use of the landscape, such as mountains and hills, to mark sunrise, and keep track of the changing seasons. It was used by civilizations across Latin America, explained Daniel Flores, an astronomer at the National Autonomous University of Mexico's (UNAM) Institute of Astronomy, who was not involved in the new research.

The results from Ezcurra's team showed a clear association between sunrise and seasonal Aztec festivals and celebrations. The arid spring equinox, when the Sun rises behind Mount Tlaloc, was associated with the god of water and rain; the summer solstice, when the Sun rises behind the shores of Lake Texcoco, was associated with salt and corn; and the winter equinox, when the Sun rises beside the Iztaccíhuatl volcano, was associated with fertility.

But among all the dates and events on the ancient calendar was one that did not coincide: 23 and 24 February, the dates marked as the beginning of the Aztec year by Rafael Tena Martínez, one of Mexico's most prominent historians.

Ezcurra thought that previous civilizations must have used a horizon calendar before the Templo Mayor was built. The hill of Tepeyac, where Tonantzin (the Aztec mother of all gods) was celebrated and which peaks above the clouds, "was the obvious place to observe the sunrise," Ezcurra said.

By calculating where ancient sunrises occurred from the top of Tepeyac, the scientists noted that sunrise can be observed precisely at the top of Mount Tlaloc between 23 and 24 February, coinciding with what Tena Martínez had identified as the Aztec new year.

Ezcurra and his coauthors published their results in the *Proceedings of the National Academy of Sciences of the United States of America* in December 2022 (bit.ly/solar-observatory).

This causeway on Mount Tlaloc could have been used as a solar marker that let Aztecs know when the year started, helping them to pinpoint their planting and harvesting cycles. Credit: Ben Meissner

An Ancient Technology

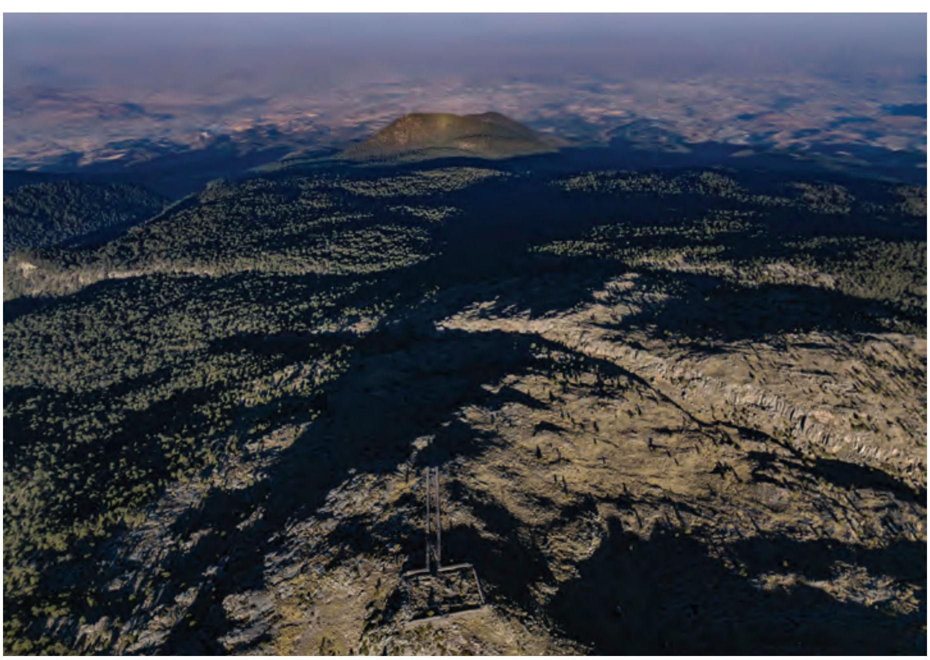
Ezcurra's team was also interested in the slope of the 150-meter causeway leading to the top of Mount Tlaloc, which deviates from the ceremonial center but aligns perfectly with Tepeyac.

From the base of the causeway in the early morning of 24 February, the group observed that the structure was aligned not only with Tepeyac, but also with the rising Sun.

This perfect alignment, according to Ezcurra, could have helped the Aztecs master the concept of leap years, a feat that is still debated among archaeoastronomers. "A calendar system that ignores leap years would accumulate an error of weeks in two or three generations, which would [have been] catastrophic for the beginning of agriculture," Ezcurra said.

Medieval European historians such as Motolinía argued that the Aztecs did not have the complex mathematical procedures needed to assess such precise time correction. But Ezcurra argued that through their own measuring technology, such as using Mount Tlaloc as a solar marker, Aztecs were perfectly capable of maintaining a sophisticated calendar, including adding or subtracting days to account for leap years.

Colgate University astronomer and archaeologist Anthony Aveni agreed with Ezcurra that the Aztecs were proficient in keeping track of time in a sophisticated manner. In fact, the entire concept of a leap year "didn't exist for [Aztecs] because it is a Western contrivance," Aveni explained. "People often think that they couldn't do anything precise without technology…. It's a presentist, ethnocentric view." For Aveni, the problem is that "we've just become so dependent on [our technology] that we don't realize what you can do with the naked eye."



This drone's-eye view offers a look at the ceremonial compound at Mount Tlaloc. In the distance is Mount Tepeyac. Credit: Ben Meissner

The new research, however, has been criticized by other experts. Flores, for his part, said he thinks that the study is a "compilation of previous contributions." (Aveni, for instance, published similar conclusions about the alignment of Mount Tlaloc in 1988.) Even so, Flores said, it is crucial to recognize that "the disregard and nonrecognition of the advances of ancient science are the legacy of the conquering imperialist mentality."

For Ezcurra, the central argument of the study is, indeed, a critique of a historical approach that continues to center European worldviews. In the 15th century, "Tenochtitlan was one of the most populated areas on the planet," he said, "which demonstrates a monumental agricultural capacity and an extraordinary food supply system, something that Europeans could not even remotely dream of having."

By **Humberto Basilio** (@HumbertoBasilio), Science Writer

Wind Could Power Future Settlements on Mars

A crewed expedition to Mars has been a century-long subject of fascination and, for now, fantasy. The basic engineering challenges are enormous: To start with, there's the question of where to find a viable and steady source of energy, which would be required for any human mission to Mars. The answer to that question may be blowing in the Martian wind, according to a new study.

Solar and nuclear energy have traditionally powered robotic missions. But nighttime shutdowns and dust storms disrupt solar energy generation, and waste disposal is a huge concern for nuclear power.

Wind power has been explored in the past, but with the atmospheric density of Mars being 1% that of Earth, much larger turbine blades would be needed to generate sufficient energy from comparable wind speeds. In addition, the Viking and InSight lander instruments recorded low wind readings, although these sites were, by design, quiet wind zones. Wind was dismissed as not viable.

Now, a study published in *Nature Astronomy* has suggested that wind energy could, indeed, be harnessed to power human settlements on Mars (bit.ly/Mars-winds).

"We were excited to find that there are many locations across the planet where winds are strong enough to provide a really stable power resource" and compensate for a shortfall in solar power using wind turbines, said Victoria Hartwick, lead author of the study and a postdoctoral fellow at NASA Ames Research Center. She and her team tailored a climate model designed for Earth to simulate Martian climatic conditions and assess winds on the Red Planet.

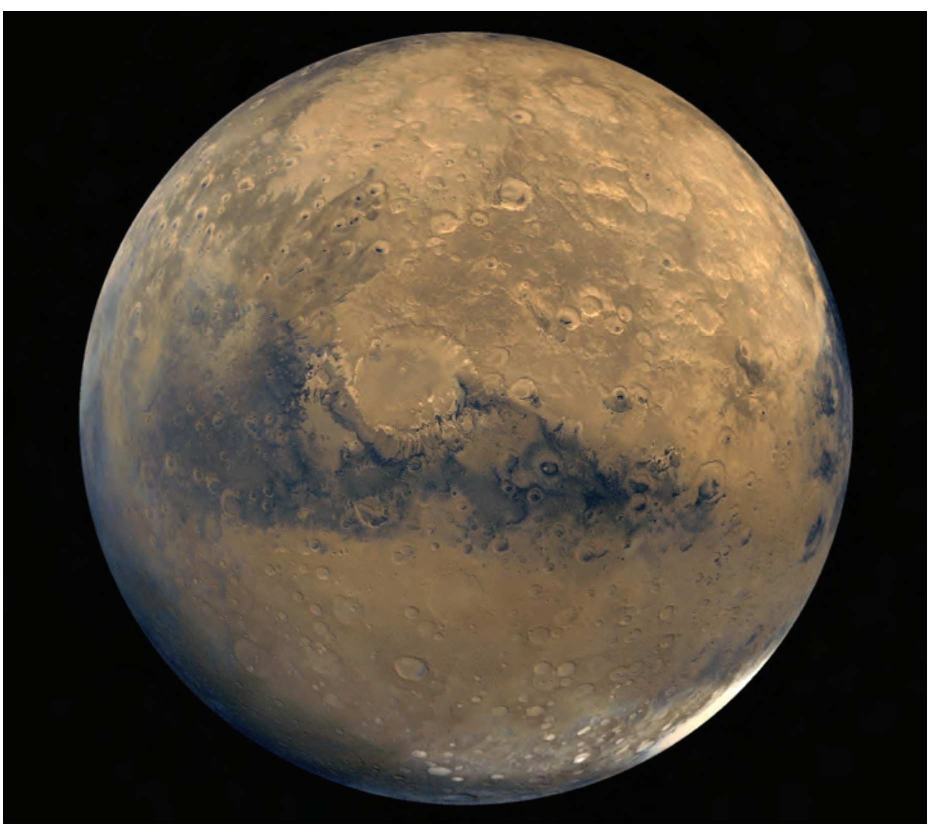
Tools for the Job

A new NASA Ames Mars global climate model factors in not only standard fluid flow but also elements specific to Mars, such as how the atmosphere interacts with the surface.

The new model uses topographic, heat storage, and albedo and dust maps from prior Mars observations. It simulates wind patterns and strengths across the entire surface and their variation with time of day and season, and during years with and without dust storms.

The researchers measured a potential turbine's maximum and actual power production and compared the results with the maximum available solar power across seasons, time of day, and dust activity, noting where power levels exceeded theoretical power requirements for a crewed mission to Mars.

"We were excited to find that there are many locations across the planet where winds are strong enough to provide a really stable power resource."



Future Mars missions could be powered by wind. Credit: NASA/JPL-Caltech/USGS

The Answer, My Friend, Is Blowin' in the Wind

The model revealed that wind power on the Martian surface peaks in the midlatitudes and poles during each hemisphere's winter; at night, dawn, and dusk; and during dust storms that occluded sunlight. Slope winds, similar to thermally driven mountain and valley breezes on Earth, are particularly strong on Mars along crater rims and down volcanic highlands. Akin to Earth's land and sea breezes, the temperature contrast at the winter poles creates powerful polar vortices. These sites had the highest wind power potential.

The researchers identified 13 new regions with good wind potential and confirmed that 10 prospective landing sites identified by NASA have sufficient wind for energy generation. "Some regions—for example, in the midlatitudes and poles, with fascinating geologic histories, and close to subsurface water ice deposits that could be valuable resources for a human mission—that had been previously dismissed on the basis of estimated solar power availability are back on the table," Hartwick said.

"This is a really interesting and useful first step along the way [to human exploration on Mars]," said Bruce Banerdt, a planetary geophysicist at NASA's Jet Propulsion Laboratory and principal investigator of the InSight mission, who wasn't involved in the research.

Don Banfield, a planetary scientist at NASA Ames who also was not part of the study, agreed. "This work has not been done before. They did a nice job of looking at how wind power resources might be distributed on Mars."

The next step, Hartwick said, will be to use an extremely high resolution weather model and zoom in on those regions to get a better sense of small-scale wind variations in response to the local topography and other unique atmospheric changes.

"They've used a very well established model for analyzing Martian winds," Banerdt said. But "we still have only limited ground truth on Mars" against which to directly compare the data, he added.

NOAA Geophysical Fluid Dynamics Laboratory's Lucas Harris agreed that given the limited direct observations available on Martian winds, "the validation of the model is similarly limited," adding, "I don't think that's going to be a showstopper, though. This is neat stuff."

"This is neat stuff."

A Tale of Turbines

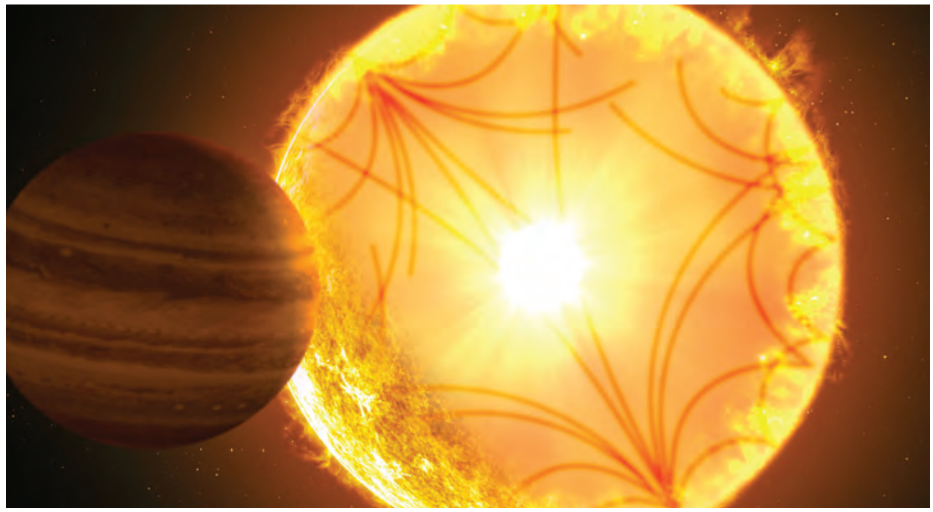
"It is unlikely that we'll see big wind turbines on Mars in the near future, unless SpaceX's Starship proves successful," said Banfield, who was part of an effort to develop a turbine to sustain a polar mission on Mars. "But I do hope that we'll develop small ones."

Isaac Smith of York University in Toronto, who was part of that same effort, also pointed out the logistical constraints and costs of transporting equipment to the Red Planet but added, "Wind energy gives us another tool to use on Mars, that we might not have otherwise."

"This paper is a fantastic resource for those planning human or robotic Mars missions and demonstrates that wind energy should not be discounted," said Claire Newman, a dust storm expert at Aeolis Research who has worked on the InSight, Curiosity, and Perseverance missions. "I would love to see Mars's wind energy explored further."

By **Alakananda Dasgupta** (@AlakanandaDasg1), Science Writer

"Hot Jupiter" Is in a Possible Death Spiral



Kepler-1658b is spiraling closer to its star in this artist's rendering. Credit: Gabriel Perez Diaz/Instituto de Astrofísica de Canarias

A distant planet is in a death spiral and is poised to be engulfed by its parent star.

Kepler-1658b is the first inspiraling planet discovered around an "evolved" star—one that has moved out of the prime of its life. The star—Kepler-1658—is about 1.5 times the mass of our Sun and has expanded to almost 3 times the Sun's diameter in its late stages of life, earning it the designation of subgiant.

Should Kepler-1658b maintain its current path, it will meet its fate in about 2.5 million years.

As the complicated discovery of the planet and its star has shown, however, nothing is certain. "It's a very confounding system," said Ashley Chontos, a postdoctoral fellow at Princeton University and a member of the team that discovered the planet's shrinking orbit.

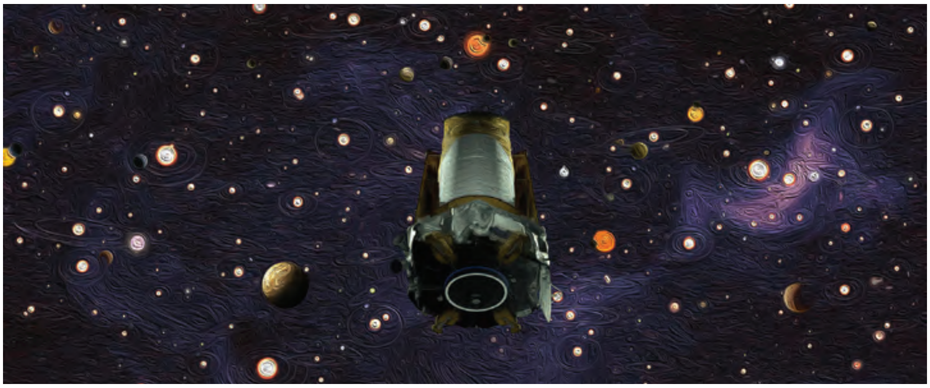
Kepler-1658b was the first exoplanet discovered by the Kepler space telescope, which found thousands of bodies over its lifetime using the transit technique. The telescope measured tiny dips in a star's brightness when a planet crossed in front of it.

Early in its mission, which ended in 2018, Kepler recorded such dips from Kepler-1658. However, astronomers had initially cataloged the star as belonging to the main sequence—stars like the Sun that are still burning the hydrogen in their cores. Researchers expected the star to be much smaller than it is, so the initial transit signals "didn't make sense," said Shreyas Vissapragada, a postdoctoral researcher at the Harvard-Smithsonian Center for Astrophysics and the lead author of the new study (bit.ly/Kepler-death-spiral). The transit indicated a planet roughly the size of Neptune, our solar system's third-largest planet. However, the system also produced a secondary eclipse as the planet passed behind the star. At Kepler-1658's distance, a Neptune-sized planet wouldn't be bright enough to see, so there would be no evidence of the secondary eclipse.

Kepler-1658b was discarded as a false positive and forgotten about.

"Suddenly, a close-in hot Jupiter made sense."

That is, until Chontos began looking at vibrations on the surfaces of stars in the Kepler catalog. Because the telescope kept a constant eye on the stars in its field of view, recording brightness levels every half hour or less, it detected "jiggles" caused by sound waves reverberating through the stars. Piecing



Kepler stares into a galaxy filled with its exoplanet discoveries in this illustration commissioned for the space telescope's retirement. Credit: NASA

together the vibrations—a technique known as asteroseismology—revealed details about the stars' interiors.

In the case of Kepler-1658, the vibrations showed that the star was much farther along in life—and hence about 3 times bigger—than expected. That meant the transiting planet was 3 times larger as well, making it big enough and bright enough to contribute to the system's overall brightness when it wasn't eclipsed by the star. "Suddenly, a close-in hot Jupiter made sense," Chontos said. "That discovery was completely accidental."

A hot Jupiter is a massive planet comparable in size to Jupiter—the giant of our own solar system—that orbits so close to its star that it is extremely hot. In this case, Kepler-1658b is about the size of Jupiter, but with almost 6 times its mass. "Even the combined masses of all the planets in [our] solar system don't add up to that," Chontos said. The planet orbits its star once every 3.85 Earth days, compared with an 88-day period for Mercury, the Sun's closest planet.

Changing a Planetary Clock

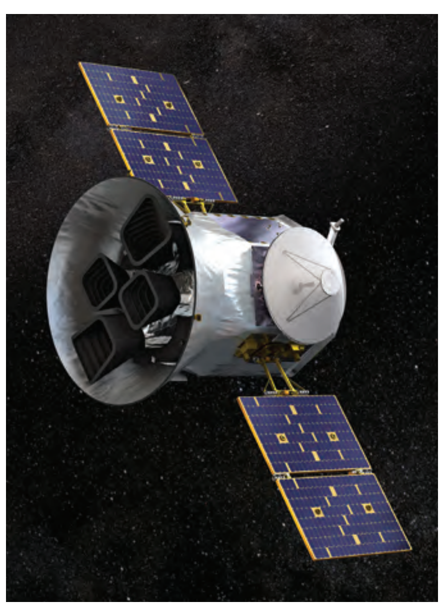
Kepler observed the system for about 4 years, so it obtained a good, but not perfect, measurement of the orbital period. It appeared to show that Kepler-1658b followed a steady path around the star.

At the same time Chontos was studying the system's vibrations, though, Vissapragada was conducting his own observations. (One night, in fact, he and Chontos bumped into each other during runs at the 200-inch Hale Telescope at Palomar Observatory, where both were looking at the system.)

Vissapragada obtained data from two Hale sessions plus three monthlong sets of observations by the Transiting Exoplanet Survey Satellite (TESS), a space telescope designed to discover and study exoplanets. When combined with the earlier Kepler data, the data provided a 13-year baseline of observations.

"They showed that the clock had changed—the transits were happening measurably earlier than they were predicted to occur," Vissapragada said. Kepler-1658b's orbital period was decreasing by 131 milliseconds per year (plus or minus about 20 milliseconds), suggesting that the planet will spiral into the star in about 2.5 million years.

The shrinking orbit is probably the result of tidal effects. "We think we know the total energy in the system," Chontos said. "The planet is depositing energy in the star, causing it to rotate faster and the planet's orbit to shrink." A small amount of the system's total energy could be dissipated in the planet as well, explaining some minor oddities in its orbit, Vissapragada added.



The Transiting Exoplanet Survey Satellite (TESS) is depicted in space in this illustration. Credit: NASA Goddard Space Flight Center

Ruling Out the Alternatives

An inspiral isn't the only possible explanation for the apparent change in orbital period, however. The timing could appear to change if the system were moving toward us, for example. By measuring the system's radial velocity—its motion toward or away from us—the team ruled out that possibility. It also ruled out the possibility that we see only part of the orbit's precession period—a "wobble" in the orbit. "We think we've ruled out all other probable causes," said Vissapragada.

"The evidence for inspiraling planets is plausible, and this paper presents good arguments for this being the case for this planet," said Girish Duvvuri, a graduate research assistant at the University of Colorado Boulder, who has studied the demise of exoplanets but was not involved in this project. "While I can't say they've exhausted all alternative hypotheses, they covered everything I can think of."

Even so, no one can say the fate of Kepler-1658b is sealed. The process of orbital evolution for planets around evolving stars is poorly understood, so several outcomes are possible.

"The whole dissipation process is very complicated," Chontos said. "It involves the obliquity, eccentricity, distance—all these different aspects of the orbit that can change over time. While it's going inward now, there's nothing to say that the orbit won't circularize and its migration will stop—just halt. At some point, the planet might even migrate outward. But right now, that's all just speculation."

The astronomers said they hope to narrow down the possibilities with additional observations of the system by TESS and other ground- and space-based telescopes. And they said that finding similar systems will help as well.

"We need to look at more of these systems to pin down exactly how that evolution works," Vissapragada said. "TESS should give us a lot more examples over the next decade, so we'll have a fairly large sample to see if this mechanism is common."

By **Damond Benningfield,** Science Writer

The Rise of Gaming-Based Virtual Field Trips

Visiting the Whaleback anticline near Shamokin, Pa., takes only a click of the mouse. Credit: Whaleback anticline field adventure/Max Needle

You're flying over a hill of rock that's as big as a whale's back and just as gray and speckled. You touch your feet down onto the beast and peer at the scratch marks along its fault lines.

You're not in a dream, but on a game-based virtual field trip to the Whaleback anticline—an iconic exposure of folded rock in central Pennsylvania. Designed using a popular gaming engine, the virtual "field adventure" allows users to clamber on, fly over, and extract real-world data from the landscape around them.

"It's very open-ended," said University of Washington (UW) geologist Juliet G. Crider, one of the scientists behind the Whaleback experience. "Because you're using tools and extracting actual data, you can do real analysis on the data that you've collected in the game."

The Whaleback virtual experience and games like it are changing the way researchers, students, and the public experience unique geologic sites.

Welcome to Whaleback

Whaleback is a popular destination for mid-Atlantic geologists. A former strip mine, the site features a spectacular sandstone anticline that rises out of the valley, nicknamed Whaleback. The sandstone layers, exposed after coal miners stripped away overlying rock, crest upward into a ridge more than 10 meters (33 feet) tall. Unlike most anticlines seen in roadcuts, the entire fold is exposed at the surface in three dimensions.

In the virtual experience, as in reality, the Whaleback anticline sits nestled in a canyon surrounded by cliffs (bit.ly/virtual-Whaleback). A cloudless blue sky hangs overhead, and the treeless landscape (they've been digitally removed) makes for straightforward viewing.

Users can toggle keyboard commands to walk or fly across the terrain from a first-person view. With a virtual geodetic compass, they can measure the orientation of the fold's layers, which correlate to real values at the site.

The game allows students to learn about the size, shape, and orientation of the anticline while exploring, as well as draw a profile and produce a plot of the orientations of the fold's key features.

Taking Field Trips Virtual

The Whaleback anticline virtual experience, created by researchers at the University of Washington, is just one of several initiatives that interweave gaming and the geosciences. Leeds University's bucolic landscapes immerse students in hours-long mapping exercises, and Imperial College London's Virtual Sardinia sends students flying above a volcano via jet pack.

Virtual field experiences offer many benefits: Scientists can visit sites repeatedly, saving money and time; researchers and students with disabilities gain access to remote sites; and apprehensive students can learn the basics of fieldwork before entering the field.

Still, virtual field trips are relatively novel, and translating geologic data into a virtual game space has its technical challenges. To help, the designer of the Whaleback virtual experience, Mattathias Needle, has published a tool kit for others to design custom immersive virtual field trips just like Whaleback.

Inspiration Strikes

Needle, a doctoral student, was on his way to a party one Friday night in 2017 when he stopped by the University of Washington's 3D printing lab.

"I went into Google Earth VR for 5 minutes, and my interest in going to the party just dissipated," said Needle. He wondered how he could create something similar for Whaleback, the area he is researching for his geology doctorate. He'd spend the next 2 years answering that question.

> **"I went into Google Earth VR for 5 minutes, and my interest in going to the party just dissipated."**

At the time, Needle and his adviser, Crider, were studying the geologic structures of Whaleback to reconstruct how the fold had formed. Several years before, Crider's previous doctoral student flew a drone around the site. The thousands of overlapping photos collected formed the basis of a 3D terrain model equipped with real coordinates and dimensions.

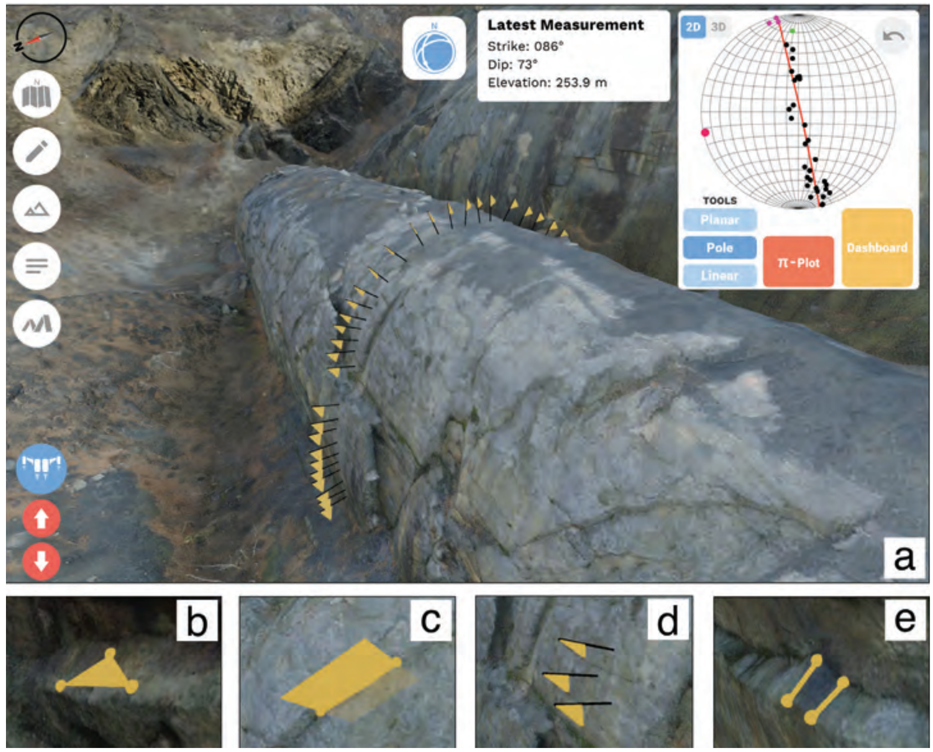
Needle and Crider do not consider themselves gamers, but the UW Reality Lab incubator connected them with computer science undergraduates. Together, they re-created Whaleback as a virtual space run on the open-source Unity game engine, which powers many popular games, including Pokémon Go. The Whaleback web browser–based game launched in 2021 and has racked up more than 1,900 plays.

"I am 100% a visual learner.... So what you are doing is right up my alley and genuinely allowed me to learn more about structural geology, on a conceptual level, than any of my other previous classes," one student wrote to the designers in a classroom review after exploring the virtual site.

"It will be really interesting to see where the team takes the project," said Earth scientist Clare Bond of the University of Aberdeen, who was not involved with the work but has written about the merits of virtual learning. "As more virtual field environments are developed and shared, the richer the resource is for teaching and learning."

Other virtual outcrops are available within 3D viewers, such as Sketchfab's eRock from the University of Aberdeen, or within proprietary software such as the Norwegian Research Centre's LIME. These virtual environments allow users to number locations, ask questions, view pop-up photos, and more, but they aren't gaming based.

"I am 100% a visual learner.... So what you are doing is right up my alley."



Users can place (a and d) orange flags, (b and c) planes, and (e) lineations on the virtual Whaleback to extract real-world data. Credit: Image adapted from Needle et al., 2022, https://doi.org/10.5194/gc-5-251-2022

Hybrid Learning

In the past, the lack of fieldwork opportunities has turned students with disabilities away from pursuing geoscience degrees. Students who cannot attend field trips may be given independent assignments that are less rigorous and stymie bonds with other students.

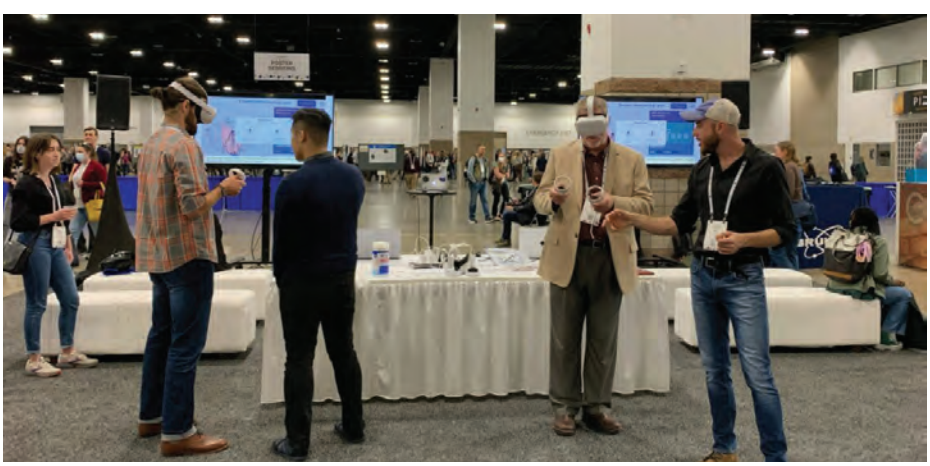
"The UW virtual field geology project is a great example of the future of field-based education," said the University of Cincinnati's geoscience education researcher Christopher Atchison, who was not involved with the effort.

"The integration of in-person, virtual, and hybrid pedagogical methods has the potential to reduce barriers of access and inclusion while increasing field safety and awareness," Atchison added.

The Whaleback anticline virtual experience is now available in virtual reality, too. Unity supports multiple platforms and is easily adaptable, Needle explained. He said he hopes others will create virtual field adventures, too. He published the workflow from Whaleback on GitHub and in the *Journal of Structural Geology* (bit.ly/workflow-GitHub; bit.ly/workflow-JSG).

The possibilities are endless for other disciplines; archaeology, architecture, and planetary sciences could all create virtual experiences, Crider said.

David Kessler, program manager of the University of Washington's Reality Lab, said he thinks the applications can go even further. "If microscopic data sets are available," Kessler said, "the team could adjust the tool kit to let users explore that terrain at different size scales—effectively shrinking themselves down like Ant-Man."



Geological Society of America conference attendees explore the Whaleback anticline in virtual reality. Credit: University of Washington

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

Centuries-Old Archive Reveals Far-Flung Impacts of Major Eruptions

In 1815, an Earth-shattering explosion sent roughly 130 cubic kilometers of gaseous fumes, ash, and rocks high into the atmosphere above the Indonesian island of Sumbawa. Mount Tambora had blown its top. Temperatures tanked worldwide as sooty debris circulated in the skies of the Northern Hemisphere, blocking the Sun's rays. The chilling effects lasted through 1816—later dubbed the "Year Without a Summer."

More than two hundred years later and 16,000 kilometers away from Mount Tambora, geoscientist Alice Bradley and her team of undergraduate researchers at Williams College are studying how Tambora and other major volcanic eruptions affected the climate in New England. Their source material is a weather data set that dates back more than 2 centuries to the Tambora eruption. It has been updated daily by Williams staff and students ever since.

The team's statistical sleuthing revealed temperature dips in New England following major volcanic events, including three iconic blasts in South Asia: Tambora, Krakatoa in Indonesia in 1883, and Mount Pinatubo in the Philippines in 1991. Bradley presented her group's work at AGU's Fall Meeting 2022 (bit.ly/weather-data-sets).

"You take climate, and then you throw a big explosion into it, things get exciting quickly," Bradley said.

Two Centuries of Notes

Early records from the Williams College physical weather archive are contained in a series of books, a collection so large that it's housed in an off-campus storage facility. The first researchers recorded temperature and precipitation three times daily, a habit established by archive cofounder Chester Dewey in 1816. He took measurements outside his campus home until staff built a dedicated thermometer shelter. Then in 1837, workers began recording the data at Hopkins Observatory—one of the oldest existing astronomical observatories in the United States.

Little is known about the dutiful staff and students who maintained the record throughout the years. Aside from the founders, no one signed their name. "The number of hands that might have been involved, we have no idea," said Williams archivist Sylvia Kennick Brown. Observers shifted to digital records in the 1970s, and Brown began officially archiving the entire data set in 1988. It's wonderful and surprising that the continuous record survived, she said. Prior to the official archive program, the observations were being squirreled away in attics and basements.

When Bradley learned of the data set, which is now publicly available through the college's geosciences department, she quickly realized that it coincided with several major volcanic events. With the right methods, her team could test how these eruptions affected the weather a world away.

Statistical Sleuthing

Differences in measurement standards and locations, as well as advances in technology made it difficult to directly compare archival data across various time frames. Instead, the team identified weather anomalies against baseline periods lasting 5–10 years prior to or after each eruption.

Then, to test whether these observations matched theoretical predictions, the team compared the anomalies against climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) Model Intercomparison Project on the Climatic Response to Volcanic Forcing (VolMIP), which predicts climatic changes that might unfold following a major volcanic eruption.

> **"The number of hands that might have been involved, we have no idea."**

According to the team's analysis, daily low temperatures after the Tambora and Pinatubo eruptions were often more than 5°C below baseline.

These differences exceeded VolMIP's predictions, the researchers found. This means that either the models do not capture the full experience of climate in New England or the

A massive ash cloud ascends over Mount Sinabung in Indonesia. The active stratovolcano last erupted in May 2021, spewing volcanic ash and smoke 3,000 meters into the air. At 2,400 meters, it pales in comparison with Mount Tambora, which towered over the landscape at nearly 4,300 meters prior to its eruption in 1816. Credit: Yosh Ginsu, Unsplash historic data set needs to be expanded, Bradley said.

A number of historical accounts corroborate the cooling seen in the data set, said Cornell climatologist and Northeast Regional Climate Center director Arthur DeGaetano. DeGaetano, who was not involved in the research, expressed surprise at the extent of the record. “It would be among the longest continuous records in the United States,” he said.

“It would be among the longest continuous records in the United States.”

The team now hopes to secure funding to rebuild the old weather stations in their original locations and equip them with instruments resembling those from their original years of operation. This kind of calibration will make the database more useful for historical analysis across decades, Bradley said. And in time, it will contribute to our understanding of the effects of climate-changing events.

Windows to the Past

Today, researchers at Williams College collect, log, and preserve weather records automatically using a weather station at Hopkins Memorial Forest. Automation saves time and energy, but still, part of the project’s appeal is unearthing the analog impressions recorded by past generations of students and staff, Bradley said.

For instance, during the Year Without a Summer, the average temperature in Williamstown, Mass., was only about 1°C below baseline. But this small shift had significant consequences for residents. Their notations included these entries in 1816:

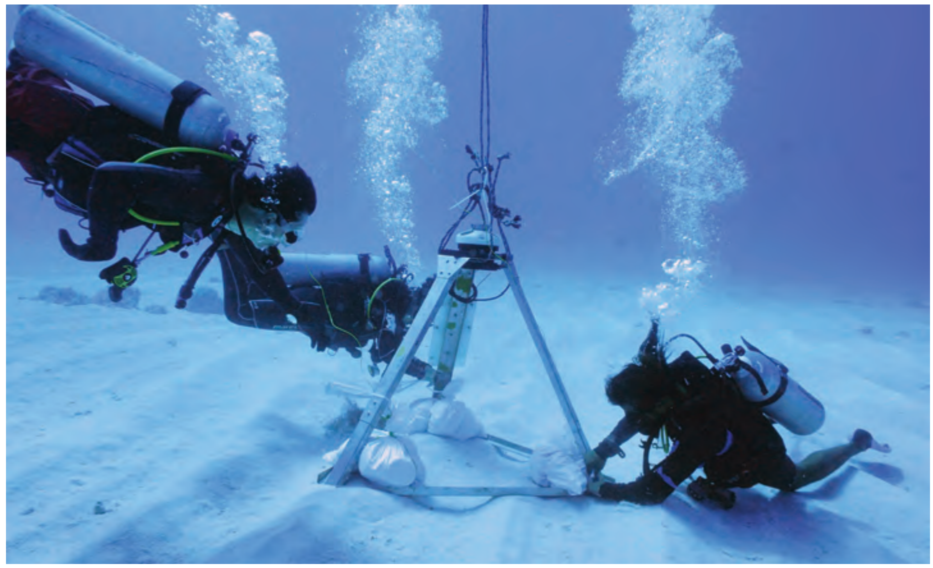
June 6: “Snowed several times, turned the ground white.”

June 10: “Heavy frost—vegetables killed.”

The archive provides data for scientists to quantify weather anomalies, sure. But for the curious eye, it’s more than that: It’s a log of the human experience.

By **Shannon Banks** (@SbanksOwl), Science Writer

Scientists Improve Hurricane Resilience in the Colombian Caribbean



Researchers install sensors on the seafloor to measure ocean currents. Credit: C. E. Marin/Nortek

In November 2020, Hurricanes Eta and Iota struck 2 weeks apart, causing dozens of deaths and widespread damage to San Andrés, a Colombian archipelago off the eastern coast of Nicaragua. On the island of Providencia, 98% of the infrastructure was destroyed or significantly damaged. The events led local officials, researchers, and residents to search for new strategies to manage hurricane risk in the region.

In the wake of the disaster, a group of researchers from the Universidad Nacional de Colombia installed acoustic sensors in the Caribbean Sea to measure wave heights and ocean currents. The data allowed them to predict how wind gusts and waves would affect the archipelago during future tropical storms, said Juan David Osorio-Cano, a researcher at the Universidad Nacional de Colombia San Andrés campus. The research could be used to improve the resilience of the archipelago to hurricanes and other extreme weather.

Changing Winds

Despite the islands being in Hurricane Alley—a region of warm water that extends from northern Africa to Central America that births many tropical storms—few major storms have struck the region historically.

“Hurricanes were mostly underestimated in the archipelago because most locals never, or hardly ever, had been exposed to a hurricane directly,” Osorio-Cano said. Between 1818 and 2005, only 11 hurricanes were recorded, according to data from the Colombian government. This is very low in comparison with other islands in the Caribbean. Cuba, for example, has an average of three hurricanes per year.

Local officials have been working with scientists for years to create weather models that can help them prepare for weather events and develop adaptation and mitigation strategies for climate change because there is growing concern that a warmer climate is making extreme weather events more powerful and more common. “There is ample scientific evidence that hurricanes in the Caribbean have been increasing in magnitude, power, and frequency during the last few decades,” said Andres Fernando Osorio Arias, a researcher at the Universidad Nacional de Colombia Medellín campus.

Iota and Eta made the risk of flooding and critical infrastructure loss more evident. Two weeks after Eta struck, the Corporación para el Desarrollo Sostenible del Archipiélago de San Andrés, Providencia y Santa Catalina (CORALINA), a government agency that works on sustainable development, partnered with the Universidad Nacional to use ocean sensors to collect data and produce materials that

This aerial photo showcases the destruction in the archipelago of San Andrés after Hurricane Iota. Credit: Daryl Lung and C. E. Marin/Nortek

would identify the locations that are more vulnerable to flooding during a tropical storm or hurricane.

"Understanding hurricanes in real time is very difficult," said Osorio Arias, explaining that before Iota, few institutions or scientists in Colombia collected oceanographic data. He added that traditionally, most officials in Colombia have relied on data from NOAA to make decisions. He explained that by collecting local data, scientists can create more reliable weather models that decisionmakers can use to mitigate risk during extreme weather events.

By collecting local data, scientists can create more reliable weather models that decisionmakers can use to mitigate risk during extreme weather events.

Filling Data and Communication Voids

In January 2021, Osorio-Cano moved to San Andrés to lead a group of 15 people including professors, students, and contractors in the effort to collect data using Nortek brand sensors. The sensors send acoustic signals into the water, which bounce off particles and return to the device, recording currents and waves in the ocean in the process, explained Cristobal Molina, senior sales engineer for Latin America and the Mediterranean at Nortek.

The team from the Universidad Nacional and contractors from CORALINA placed the sensors on the ocean floor near the coast of San Andrés for 10 days, then repeated the process for another 10 days off Providencia. The effort yielded data on the movement and flow of ocean currents in the islands. The researchers also collected meteorological and topographical information from the region.

With the data, the researchers used models to reconstruct the weather history of the islands, simulate the conditions during past hurricanes, and formulate the most likely scenarios for future storms. They created maps of risk probability identifying the most vulnerable locations for flooding and wind damage on the San Andrés islands to help CORALINA design the islands' prevention and contingency plans.

The risk maps created as part of the project were used in October 2022 when Hurricane Julia passed through the archipelago and 13,000 people were evacuated from risk zones. No deaths were reported.

Collecting more local data, like those from the sensors, is a big step to improve risk management on the islands, said Carolina Velásquez, the technical-scientific coordinator of risk management at the Universidad Nacional San Andrés campus, who was born on the island but was not involved with the acoustic sensors project. But there is room for improvement, she said.

In Colombia, risk management has traditionally worked like the telephone game: Data, weather forecasts, and risk bulletins take time to reach vulnerable populations, she explained. In addition, the reports are not easy to understand and are hardly ever released in Raizal, a creole language native to the islands. The lack of accessible information can affect the well-being of the population during extreme weather events. Even after Hurricane Julia, the Colombian president said that most individuals on the islands were still not following the risk management protocols. Without crystal clear communication lines, official messaging can be confusing or, worse, may not get through at all.

Velásquez argued that risk management needs to be holistic and consider local communities' needs and perspectives to be successful. "In the islands, before Iota, we were living blindfolded" to hurricanes and their risks, she said, explaining that a successful risk management strategy should have constant data collection and investments in education for the natives of the archipelago.

Among the best courses of action to prepare for the next hurricane is "strengthening the building capacity of the islands in educational, technical, scientific, and risk management skills," Velásquez added.

By **Santiago Flórez** (@rflorezsantiago), Science Writer

Twenty Years of NSF Funding Show Racial Disparities

NSF funds one quarter of all U.S. federally funded research in the sciences. Credit: iStock.com/JHVEPhoto

In 2020, geologist Christine Yifeng Chen was sitting on Zoom in her Asian Americans and Pacific Islanders in Geosciences group when she heard something startling: It was an open secret that Asian geoscientists had a more challenging time getting National Science Foundation (NSF) funding than other principal investigators (PIs). Chen, who recently received her Ph.D. from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, remembered thinking, "Huh?"

Chen and her friend Sara S. Kahanamoku were pointed to a corner of the NSF website that hosts reports describing the funding outcomes of NSF's grants by race and ethnicity back to the 1990s. After digging in to the data, they discovered that the rumor was true, and they noticed that it wasn't just Asian PIs who were funded less often, but other groups too.

"We also noticed that there was this pattern that white PIs were actually not only experiencing higher than average funding rates but that this advantage was, in fact, increasing over time," said Chen, who is now a postdoctoral scholar at Lawrence Livermore National Laboratory.

Chen, Kahanamoku, and their colleagues found "pervasive racialized disparities" in NSF funding awards across 20 years of data, according to their paper published recently in *eLife* (bit.ly/NSF-disparities). "The prevalence and persistence of these racial disparities in funding have cascading impacts that perpetuate a cumulative advantage to white PIs across all of science, technology, engineering, and mathematics," they wrote in the paper.

"There are people in the pipeline right now who are being affected by these [funding] decisions."

"NSF welcomes the attention this paper brings to questions about racial disparity in federal funding," said an NSF spokesperson. "Racial disparity is one of the reasons NSF has been releasing federal-funding demographic data to the public every year since the 1990s."

The Numbers

NSF receives tens of thousands of funding proposals annually and over the past 5 years has accepted about a quarter of them. The agency sends most proposals to outside experts for review, then considers the recommendations and issues funding awards. Applicants voluntarily select a race and ethnicity at submission, but external reviewers do not see the answers.

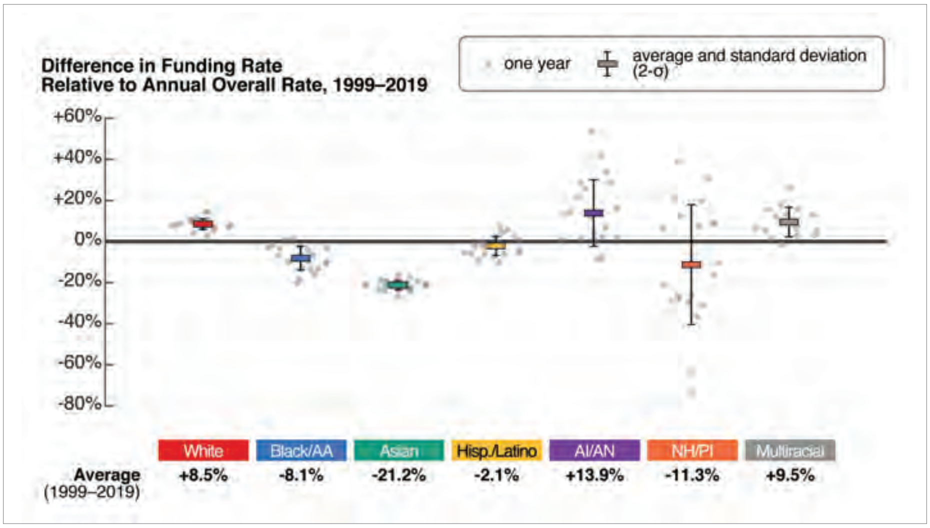
In the latest analysis, proposals from white PIs were about 9% more likely to be funded than those from the average applicant between 1999 and 2019. And this advantage has grown. In 1999, proposals from white PIs had a 3% greater chance of being funded than those of the average applicant. In 2019, the most recent year analyzed, white PIs were 14% more likely to secure funding.

In contrast, between 1999 and 2019, NSF was 21% less likely to fund proposals from Asian PIs than those from the average applicant. Native Hawaiian and Pacific Islander PIs and Black and African American PIs were similarly disadvantaged, landing funding 11% and 8% less often, respectively, than average.

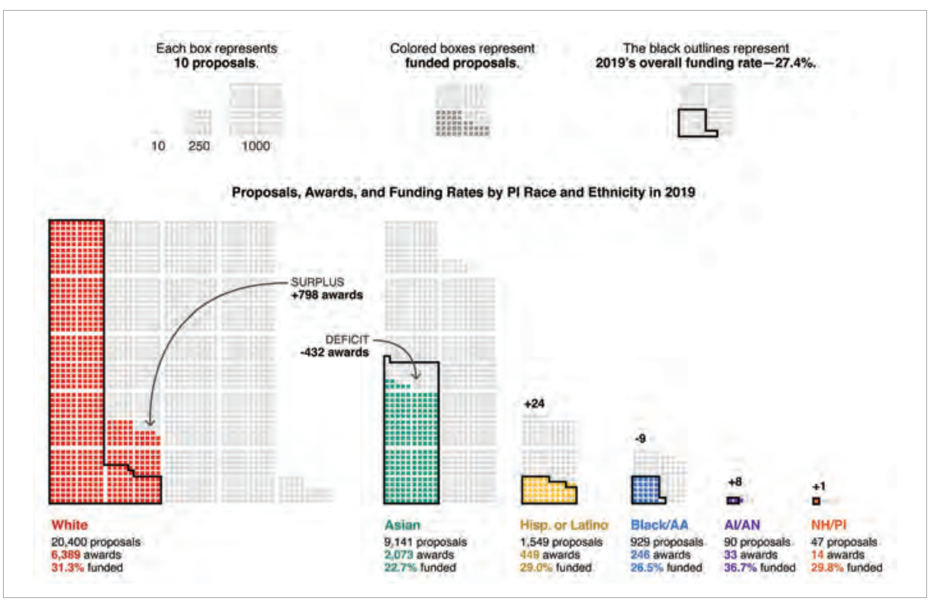
These statistics translate into differences in the funding rate among each group. Considering the number of proposals submitted by white PIs in 2019, this group would have received nearly 800 fewer awards if it were funded at the average NSF rate for that year (27%). This "award surplus" is countered in part by a "deficit" of 432 awards to Asian PIs.

"There are people in the pipeline right now who are being affected by these [funding] decisions," said Chen. NSF supports one quarter of all federally funded research in the sciences.

The racial stratification in funding rates is more apparent when comparing the types of grants awarded, the study finds. Black and African American PIs and Asian PIs had a lower success rate for research proposals than nonresearch proposals, although data distinguishing the two types of awards were available only from 2013 to 2019. Nonresearch awards support lab upkeep, teaching, or professional development and typically include less money than research awards.



This chart shows the average difference in the funding rate for racial and ethnic groups compared with the median applicant. The plot highlights that white PIs have a funding rate 8.5% above average, whereas Black and African American PIs have a funding rate 8.1% below average. Gray dots show each year, and horizontal bars show the 20-year average. AI/AN = Alaskan Indian and Alaskan Native, and NH/PI = Native Hawaiian and Pacific Islander. Funding rates for multiracial PIs were available only for 2005–2019. Credit: Chen et al., 2022, https://doi.org/10.7554/eLife.83071, CC0 1.0 (bit.ly/cc01-0)



This infographic depicts award surpluses and deficits calculated by Chen and colleagues. Credit: Chen et al., 2022, https://doi.org/10.7554/eLife.83071, CC0 1.0 (bit.ly/cc01-0)

The Geosciences Are Not Immune

White PIs in the geosciences had tailwinds, too.

Data from 2012 to 2016 reveal that white PIs in the NSF Directorate for Geosciences received an average surplus of about 4 dozen research awards annually.

Furthermore, white PIs had the highest submission rates to all NSF directorates, whereas Black and African American PIs had the lowest submission rates to all directorates, said Chen.

Geologists Rachel Bernard and Emily Cooperdock wrote in a 2018 *Nature Geosciences* comment that the racial and ethnic diversity of geoscience Ph.D. graduates had changed very little over the preceding 40 years, despite improvements in the gender balance over the preceding 40 years (bit.ly/geosciences-diversity).

Data from 2012 to 2016 reveal that white PIs in the geosciences received an average excess of 46 research awards annually.

Closing the Gap

"This is the first time, to my knowledge, researchers have conducted such a comprehensive investigation into NSF-wide demographic data," said Bernard, a geologist at Amherst College who reviewed the paper for *eLife*. The researchers of the latest work, which was also presented at AGU's Fall Meeting 2022, did an "excellent" job, she said (bit.ly/NSF-disparities-FM22).

"While some people may disagree with the authors' conclusions—namely, that these disparities are a result of systemic racism within science and society as a whole—you can't argue with the data itself," said Bernard.

An NSF spokesperson told *Eos* that this year the agency is launching a new initiative that specifically addresses barriers and challenges that can affect competitiveness for external funding, called Growing Research Access for Nationally Transformative Equity and Diversity (GRANTED). The program will target PIs at less-research-intensive institutions with training, support research institutions to strengthen research services offered, and hold listening sessions and other meetings to improve NSF offerings.

The number of awards needed to bridge some racial disparities is small, Chen said. "If [NSF] just funded a small number of proposals, it would have a huge impact on reducing or even eliminating some of the disparities in funding rates."

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

Overcoming the Challenges of Ocean Data Uncertainty

Data characterizing the ocean are inherently estimates and are therefore uncertain. This is true of all in situ and remotely sensed observations—of, say, sea surface temperature or sea level—as well as of outputs and forecasts from numerical models and of analysis products resulting from the synthesis of observations and models.

The typical meaning of uncertainty with respect to data is a familiar concept for scientists: A numerical value quantifying the state of a variable can be associated with one or more ancillary numerical values characterizing the possible error. However, it is essential to distinguish between quantifying *error* and quantifying *uncertainty*. The error of an estimate, defined as the difference between the estimate and the true value of a variable, cannot be known—if the true value were known, the estimate could be corrected. In contrast, the uncertainty of an estimate can be assessed using various statistical, theoretical, and numerical methodologies.

In oceanography and climate science, the nature of uncertainty associated with different types of data—for instance, direct and indirect observations versus analysis products—has been semantically and philosophically debated [*Parker*, 2016]. This sort of debate is helpful because inadequate understanding and treatment of data uncertainty persist in the research community, decreasing the potential usefulness of—and confidence in—many data sets.

As a requirement for proposing, planning, and implementing ocean observing, modeling, and analysis systems, we advocate that resulting data should be accompanied by clearly described and easily accessible uncertainty information. To put it bluntly, an ocean data set may otherwise be of the highest scientific quality, but if quantified uncertainties do not accompany it, it will not be useful to scientists or other stakeholders [*Moroni et al.*, 2019].

Uncertainty Completes the Data

The effort to reconstruct changes in global mean sea level since the first known sea level measurement was taken in the mid-19th century (i.e., the observational era) and to attribute these changes to driving factors is a field in which uncertainty quantification is at the core of the scientific investigation process. Understanding these changes requires measurements of ocean temperature, cryospheric and terrestrial water mass distributions, and sea surface height at numerous locations and times. From these observations, the contributions of global ocean thermal expansion and global ocean mass change to global mean sea level change can be determined.

The sea level budget is considered "closed" when the sum of these independent components agrees with direct measurements of total sea level, meaning that the body of existing observations is sufficient to interpret the causes of sea level change. Only recently, thanks to the assembled efforts of many individual studies across the interdisciplinary fields that contribute to sea level science, has the sea level budget been closed within quantified uncertainties—an achievement that testifies to our adequate understanding of processes influencing sea level, and their uncertainties, at the global scale [*Frederikse et al.*, 2020].

This example illustrates that determining the magnitude of uncertainties associated with ocean data is necessary not only so that these data can be used meaningfully in scientific investigations but also because uncertainty quantification makes the data complete. In other words, uncertainty quantification is necessary to evaluate the confidence—or the doubt—one can have in ocean data.

An ocean data set may otherwise be of the highest scientific quality, but if quantified uncertainties do not accompany it, it will not be useful to scientists or other stakeholders.

Challenges with Ocean Data

Uncertainty is a major focus of metrology, the science of measurement, and standards for uncertainty quantification are well cataloged in documents in that field. These documents should serve as starting points for oceanographers to lay out a strategy for quantifying the uncertainties in their data [e.g., *Joint Committee for Guides in Metrology*, 2008].

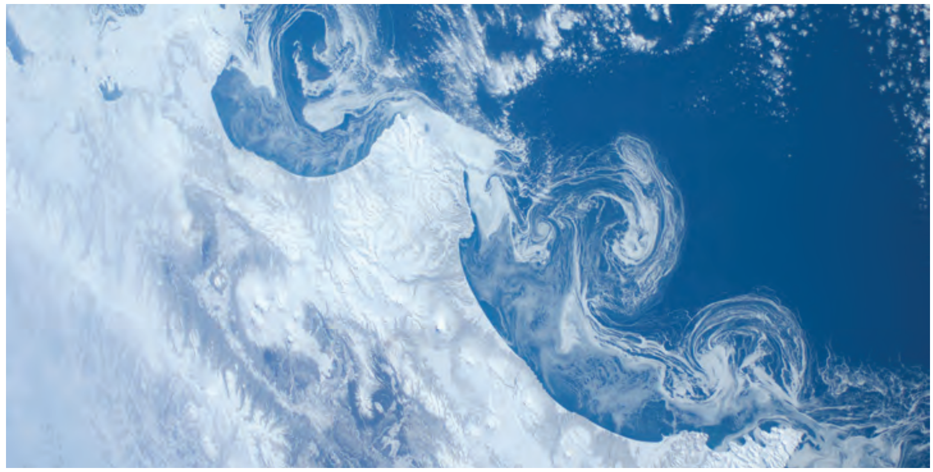
Yet some concepts that are applicable to bench measurements in metrology, such as being able to repeat observations under the exact same conditions, are difficult to translate to the oceanographer's laboratory—the ocean—because the ocean and the climate system in which it is embedded are constantly changing. For example, repeat sampling of hydrographic properties (e.g., temperature, salinity, oxygen) in some remote parts of the ocean has occurred only after decades, if at all. And some high-resolution, global, numerical ocean models can be run only once because of prohibitive computational costs, so the statistical distributions of their output under different initial conditions are not known.

There are also challenges distinct to oceanography and related fields. Satellite measurements offer indirect estimates of ocean surface properties that are calibrated and validated with in situ observations, yet these "cal/val" exercises are burdened by multiple sources of uncertainty. One such source is representation error, which can arise because pointwise in situ measurements (e.g., of sea surface temperature) do not always agree with satellite measurements, which represent averages of physical quantities over the satellite's ground footprint. In this case, the measured values disagree because they represent different quantities, and natural variability at short spatial scales masquerades as a possible error in either measurement. Uncertainty related to representation error can be understood only by combining geophysical theories, extensive observations, and methodological knowledge.

In oceanography, as in other fields, the example of representation errors illustrates the necessity to identify sources of errors correctly and to strive to characterize them with appropriate and traceable uncertainties. This is a challenge because the classification of uncertainties (or errors) based on established statistical principles does not necessarily and readily map onto the idiosyncratic classifications used in ocean science. As an example, biases (systematic errors) and random errors are often conflated in ocean observations for lack of appropriate knowledge.

Another example is in climate and ocean modeling, for which there is a need to consider structural or model uncertainties separately from uncertainties due to the chaotic behavior of the Earth system [*National Research Council*, 2012]. Further, when models and observations are combined to generate state estimates or forecasts, confidence in their outputs can be accurately assessed only if observational uncertainties are available and are carefully propagated through the machinery of data assimilation, in which models and their output are repeatedly updated to incorporate new observations [*Leutbecher and Palmer*, 2008].

Effective communication of uncertainties among observationalists, modelers, and theoreticians is thus essential. This communication requires coordinated efforts and standardized protocols among these groups—a tall order considering that different oceanographic disciplines have traditionally been insular and have used distinct vocabularies to describe uncertainty. Such disconnects might be remedied if ocean scientists put greater emphasis on training in statistical sciences and collaboration with experts in that field.



This view from the International Space Station shows sea ice floes and eddy currents near the coast of Russia's Kamchatka Peninsula. Credit: NASA JSC Earth Science and Remote Sensing Unit

A Gap in Guidance

Researchers in observational oceanography have made great strides in understanding oceanic circulation through nationally and internationally coordinated efforts. It's perhaps surprising, then, that seminal community documents about ocean observing systems do not contain recommendations for quantifying, propagating, and communicating uncertainty estimates. Many do not even mention uncertainty or error. Examples of such documents include the Global Ocean Observing System: 2030 Strategy (produced by the United Nations Educational, Scientific and Cultural Organization's Global Ocean Observing System (GOOS) expert panel in 2019) and the Framework for Ocean Observing (which resulted from the OceanObs'09 conference).

Such omissions are problematic because these documents guide high-level, programmatic funding allocations. Observational and modeling research efforts should target ocean variables with the largest (or entirely unknown) uncertainties for study, so that these uncertainties can be reduced. If uncertainty quantification is not included explicitly in guiding documents, however, efforts to incorporate uncertainty measures into observing and analysis systems are unlikely to be prioritized.

Community-Driven Solutions Are Emerging

In recent years, solutions to some of the challenges highlighted above have begun to emerge from groups within the research community [e.g., *Matthews et al.*, 2013], and discussions of the importance of quantifying and communicating uncertainty in ocean data are becoming more widespread [*Merchant et al.*, 2017]. Collectively, these efforts aim at improving the understanding, derivation, communication, and use of the uncertainties in ocean in situ, remote sensing, and model products.

In 2013, the U.S. Climate Variability and Predictability Program (US CLIVAR)—which contributes to both the U.S. Global Change Research Program and the World Climate Research Programme's international CLIVAR program—released a 15-year science plan that includes a goal to better quantify uncertainty in observations, simulations, predictions, and projections of climate variability and change. Since then, US CLIVAR has funded activities promoting ocean uncertainty quantification, including the working groups Large Initial-Condition Earth System Model Ensembles, Emerging Data Science Tools for Climate Variability and Predictability, and Ocean Uncertainty Quantification. This latter group (which we are leading), named OceanUQ, is a research community platform that aims to develop strategies and best practices for ocean uncertainty quantification through informational blog posts, web-based educational resources, a forum, and, ultimately, community meetings and trainings.

The international CLIVAR program has organized the CLIVAR Global Synthesis and Observations Panel's Ocean Reanalysis Intercomparison Project to evaluate historical ocean state estimates with reliable uncertainties. Other ongoing international efforts include the Ocean Best Practices System, which exists to develop and promote well-established and standardized methods across ocean research, operations, and applications.

Meanwhile, databases like the International Quality-Controlled Ocean Database are being expanded to facilitate assessment of uncertainties using in situ observations. And Earth Science Information Partners has established the Information Quality Cluster to collect information on key aspects of uncertainty in Earth science data [*Moroni et al.*, 2019].

Progress toward summarizing the state of knowledge on uncertainty for ocean variables has also been made. For example, GOOS publishes estimates of random uncertainty and uncertainty in the bias of measurements of Essential Ocean Variables (e.g., sea surface temperature, sea state) in its specification sheets. Workshops and special sessions at community meetings, including the OceanObs'19 conference, have also led to specific recommendations for improving ocean uncertainty quantification, such as providing more training and publishing best practices documents.

Opportunities on the Horizon

Ocean sciences have now entered the realm of "big data." Some of the many benefits of this development include increasing our knowledge of natural variability and thus of the statistically random nature of ocean data. But the vast increase and diversification of ocean data also exacerbate challenges related to uncertainty. It does not have to be this way, however. Instead, this explosion of data availability is an opportunity to apply not only established statistical methods but also novel data science methods.

In the past, analyzing uncertainties in data has typically occurred as a separate step from the data analysis itself, a step that is too often skipped in the research process. But we can now apply data-driven methods, such as Gaussian process regression, that can estimate uncertainties alongside the estimation of the quantities of interest themselves [*Kuusela and Stein*, 2018]. At the same time, the accelerating movement in the Earth sciences toward providing open data and open software through online platforms can help demystify uncertainty quantification for many researchers by providing explicit methods and instructions.

With the profusion of new data and methods, new concerns are also emerging. Ocean data can be highly monetized—for the purpose of ensuring the safety of human operations at sea, for example—and thus, commercial enterprises have entered the arena of collecting ocean measurements. For proprietary and profitability reasons, these companies may be reluctant to communicate the uncertainty or doubt that should be associated with their data products. As commercially sourced ocean data products are acquired and provided for research use, they, too, should include quantification of uncertainties to improve their utility in scientific investigations.

We argue that cultural change is needed in the oceanographic community. Ocean data–generating endeavors of all flavors should include a plan for uncertainty quantification alongside their standard data management plan. In addition, published studies should explicitly address how data uncertainties affect results and conclusions. Yet communication of uncertainty in data sets or products need not necessarily be formulated in terms of highly technical probability density functions or statistical concepts; it should be tailored to intended users. For example, reports from the *Intergovernmental Panel on Climate Change* [2021] demonstrate how uncertainty representation can take a variety of forms, both quantitative and qualitative, depending on the context and intended use of (and audience for) the data.

By continuing current efforts and capitalizing on new opportunities to develop standardized guidance for ocean scientists and to promote the importance of quantifying and communicating uncertainty, we can make valuable and hard-earned ocean data more accessible and usable. We can also increase the confidence that scientists and others have in analyses—of sea level change and many other important ocean processes—performed with these data.

Acknowledgments

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Welcome to a New Era in GEOSCIENCES DATA MANAGEMENT

By Saima May Sidik

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As databases proliferate and harmonize, it's becoming easier for scientists to repurpose information and work across disciplines.

In the waning days of August 2017, Hurricane Harvey dumped more than 30 trillion gallons of water on Texas's Gulf Coast. At least 68 people died. Hundreds of thousands of structures were flooded, and tens of thousands of people had to leave their homes. All told, the storm inflicted $125 billion in damages.

In the wake of the disaster, state and federal officials were forced to reckon with a familiar problem: access to information. "They always struggle with the data aspects of the problems that they're confronted with," said hydrogeologist Suzanne Pierce of the Texas Advanced Computing Center. During the storm, modelers would have been able to produce accurate predictions more easily if they'd had more information at their fingertips, Pierce said. Afterward, some rural communities struggled to apply for recovery funding because they couldn't easily provide a full picture of how Harvey had affected their areas.

Harvey brought Texas's data infrastructure problems into sharp focus and spurred the creation of the Texas Disaster Information System (TDIS), with Pierce as the director. The group is collecting data and models from a wide range of sources—including the National Weather Service, insurance providers, and the U.S. Army Corps of Engineers—so that these resources are readily available to disaster managers. Their first product, a centralized location for flood risk data and models, launched in September 2022 in collaboration with the Texas Water Development Board.

Texas's data management struggles are emblematic of a problem throughout the geosciences: Researchers are buried by data served up by myriad tools from seismometers to satellites to social media. Put together, this information could reveal untold truths about our planet and improve the lives of the people living on it. But too often those data languish in personal computers or filing cabinets. Without appropriate databases and smooth submission and search processes, scientists struggle to share and access information.

Fortunately, a common set of best practices, clever computing tricks, and dedicated data experts are helping scientists overcome these barriers and make sure newly produced data enter the public realm. Meanwhile, data librarians and volunteers are making the most of scant resources to preserve data collected before the digital age.

These efforts are making it easier for scientists to synthesize their work with information from other disciplines. "In some ways, there's a loosening of the boundaries between projects so that we can all learn together," Pierce said. And that's the way science should work, "in its most idyllic form."

FAIR Standards Extend the Shelf Life of Data

In 2014, several dozen scientists—from disciplines spanning from biology to computer science—gathered in Leiden, Netherlands, to figure out how to give data a life span beyond the project for which they were generated. Information must be Findable, Accessible, Interoperable, and Reusable, or FAIR, they wrote in a summary of the proceedings.

For Audrey Mickle, a data librarian at Woods Hole Oceanographic Institution (WHOI), the mindset underlying FAIR is nothing new. She and other librarians have always striven to make sure scientists can retrieve information quickly and easily. But FAIR codifies this mindset and presents a strategy for maximizing the usefulness of data. "FAIR, to me, is sort of like taking everything that we've been traditionally doing to the next level," Mickle said.

> "FAIR, to me, is sort of like taking everything that we've been traditionally doing to the next level."

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FAIR was on Pierce's mind when she and her colleagues designed TDIS's infrastructure. Data and corresponding metadata are logged into the system, she said, and query tools ensure that they're easy to track down. Intuitive organization makes data easily downloadable and therefore accessible. TDIS's designers encourage depositors to name their data's attributes using the same terminology found in models so that future users can easily connect the two, making the data interoperable. And if users add the results of simulations to TDIS, they must include a description of their methods, allowing users to reproduce the work; the methods are therefore reusable.

TDIS is far from the only organization thinking in FAIR terms; the Deep-time Digital Earth (DDE) program is a massive effort to promote the FAIR framework in the geosciences. "My ambition is very much to see all the kinds of data about our planet integrated into one source, with open access," said mineralogist and astrobiologist Robert Hazen of the Carnegie Institution, one of the scientists behind DDE.

To achieve this goal, DDE scientists will link and expand existing databases and harmonize their structures. Sometimes they'll need to create whole new databases.

Sedimentologist Chengshan Wang of the China University of Geosciences, the president of DDE's executive committee, sees the project as a way of helping scientists from disparate fields and geographic areas communicate with one another. Right now, many discoveries are describes in terms of "local knowledge," he said. For example, he was involved in a publication about the Tibetan Plateau that describes the region only in terms of local place names—an impediment for outsiders trying to understand the work.

At age 71, Wang continues to steer the direction of the collaboration he started in 2018. "The biggest project for me is right now," he said. "I want to enjoy my retirement, but [I have] no time to be retired!"

Being FAIR is not always easy. Bringing ongoing long-term projects in line with new standards can be a headache, because scientists must tweak their data collection practices partway through their efforts, said Jennifer Bayer, the coordinator of the Pacific Northwest Aquatic Monitoring Partnership for the U.S. Geological Survey (USGS). Inequity is also an issue. For example, USGS employs people who help scientists apply and pay for digital object identifiers, or DOIs,

If nobody requests the data, they remain in their original format. Cataloging and preserving materials are more than enough work for the library's three staff members, and money seldom becomes available just to support digitization.

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that uniquely identify information, making it easy to find. Bayer said that many organizations, such as Indigenous tribes, may not have the same level of support. There's a need to "level the playing field with access to those kinds of resources," she said.

A complementary framework known as CARE (Collective benefit, Authority to control, Responsibility, and Ethics) aims to ensure that the shift toward data accessibility does not compromise the rights of Indigenous Peoples to control data about their people, lands, and resources. The intersection between FAIR and CARE is "the sweet spot that we're looking for," Bayer said.

Rescuing Data

FAIR assumes that data are digital, said USGS data specialist Frances Lightsom. But tucked in the back corner of a USGS equipment warehouse in Falmouth, Mass., is a treasure trove of data, most of which have never seen the inside of a computer. Ten collapsible shelves, designed to slide so that only two shelves have an aisle between them at any time, line the Woods Hole Coastal and Marine Science Center Data Library. Reams of paper, film, CDs, VHS tapes, and punch cards fill the shelves, which reach 10 feet above the floor. Asked how much data the library holds, Lightsom, who is the library supervisor, said pensively, "I don't think we have ever added it all up."

These days, Lightsom and her colleagues usually add to the library by rescuing nondigital data from the nooks and crannies of retiring USGS scientists' offices. Researchers can search the library's catalog, then request that data librarian Linda McCarthy digitize resources that are relevant to their work.

Seismological records are among the most requested, Lightsom said. Seafloor data are difficult to collect, and the techniques used to seismically image the subsurface can be harmful to marine mammals, so the data that exist are precious.

If nobody requests the data, they remain in their original format. Cataloging and preserving materials are more than enough work for the library's three staff members, and money seldom becomes available just to support digitization. As a result, Lightsom estimated that she and her colleagues have digitized only about 1% of the library.

Down the road at the WHOI Data Library and Archives, library codirector Lisa Raymond has noticed over her 30-year career at WHOI that researchers have become less eager to use nondigital data. "When I first worked here, people would come here all the time," she said. "They just have different expectations now."

Retired information technology professional Thomas Pilitz volunteers his time to digitize the library's resources, helping prevent them from slipping into the past. He's digitized close to 5,000 cards carrying information that WHOI scientists collected from the 1930s to 1960s, during research cruises on the vessel *Atlantis*.

Each card is about 6 by 8 inches and carries such information as water temperature, oxygen content, and salinity. Pilitz scans the cards, creates comma-separated values (CSV) files containing the data, and compiles documents that record additional details about the research cruises. After more than 250 hours of work, he's about halfway through the collection.

Despite the efforts of volunteers such as Pilitz, only "a teeny percentage" of the library's physical resources have been digitized, said Raymond. She and Lightsom both worry that as time goes by, the nondigital data will be lost. Some media degrade, and accidents can happen. Some rooms at the WHOI Data Library and Archives are climate controlled and protected by waterless fire suppressant systems, but the USGS library has no such protection. Worse still, the metadata that describe some resources live only in researchers' memories. "It's scary, because you rely on their longevity," McCarthy said.

Making Metadata Manageable

Fortunately, almost all data that are collected today are digital, making them easier to manage. "If [they] kept coming in on paper, we'd be out of luck," Lightsom said. But capturing the metadata that researchers need to understand a digital data set can be time consuming—a big deterrent for overworked scientists.

When data systems architect Chris Jordan and his colleagues designed the stable isotope database IsoBank, they wanted to make metadata entry as easy as possible. But to serve researchers from a wide variety of fields, they needed to capture "an extraordinarily complex and interrelated set of metadata," Jordan said. He and his colleagues created a choose-your-own-adventure-style system.

Scientists enter some preliminary information about their data, which kicks off an iterative process in which the database prompts the scientist to enter more information—some required, some only recommended—then adjusts based on the results. Jordan estimated that the system saves researchers from 1 hour to several hours compared to the time it would take if they had to familiarize themselves with all of the metadata that could possibly be entered and decide for themselves which were relevant.

Computer scientist Yolanda Gil of the University of Southern California described another iterative process that yielded a robust metadata framework called the Paleoclimate Community Reporting Standard (PaCTS).

Instead of bringing researchers together in person for hours of meetings and whiteboarding, they and their colleagues crowdsourced the framework online. First, one scientist described the kind of metadata that should be included. Then another scientist took that description and added additional metadata terms that would be valuable, and so on.

An algorithm developed by Gil's group aided the scientists by suggesting terms they might want to use—similar to Google Search's autocomplete feature—and organized the terms into an ontology. An

“If you’re working with data that [come] from outside your core area, how do you ensure that you’re doing the right thing with [them]?”

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editorial board made final decisions about which metadata terms would be included. Gil is very proud of their role in developing PaCTS. Without this metadata framework, “I don’t know that today [the paleoclimate community] would have a good way to make their data more integrated,” they said.

Helping Scientists Use Data More Responsibly

Even meticulously documented data can become “the Wild West” once scientists begin analyzing them on their personal computers, said artificial intelligence practitioner Ziheng Sun of George Mason University. Sun and his colleagues designed and developed a piece of software called Geoweaver, which allows scientists to compose and share analysis workflows so they can standardize high-quality protocols.

Geoweaver is built around FAIR principles, such as encouraging users to share their entire workflows, including how they prepared the data and produced their results, to make sure other users have everything they need to reuse the methods. Sun hopes that making standardized workflows easily available will allow Earth scientists to process data quickly, which could move scientists closer to analyzing extreme weather events such as hurricanes and tornados in real time.

Community is also key to making data accessible, said geochemist and IsoBank cofounder Gabriel Bowen of the University of Utah.

“If you’re working with data that [come] from outside your core area, how do you ensure that you’re doing the right thing with [them]?” he asked. Sometimes scientists need to connect with one another and pool their knowledge to work with data responsibly. Early IsoBank design workshops forged many such connections. Bowen said he would like to see the next stage of IsoBank involve the development of computational tools—and communities around those tools—so that scientists can easily make use of the data “in standardized, robust ways.”

Reaching Beyond the Typical Sources

Some scientists are looking outside the usual realms of academic and government data to advance their research.

When hydrologist Kai Schröter of Technische Universität Braunschweig wanted to assess how vulnerable residential buildings were to flooding and estimate their potential for economic loss, he and his colleagues turned to OpenStreetMap, a crowdsourced tool that captures local knowledge about roads, trails, buildings, notable landmarks, and more. Registered users can edit OpenStreetMap directly; municipalities and companies also contribute data. Anyone with an Android phone can contribute by completing quests, during which they visit locations in search of information that’s missing from the map.

The dimensions of houses, cafés, schools, and other buildings are described in a clear, structured way, which sparked Schröter’s interest in OpenStreetMap’s research potential. Because of this clarity, “you can very easily handle large amounts of data, and you can filter the data, and you can process [them] for other applications,” he said.

OpenStreetMap easily checks three of the four FAIR boxes, Schröter said. Finding and accessing the data simply require perusing the organization’s website; the data are clearly documented, making them interoperable. Reusability is where things get a little trickier: OpenStreetMap changes constantly as contributors make updates, and there’s no readily accessible archive.

“What you need to do is record a snapshot of the data that you have used,” Schröter said. Otherwise, other scientists may get different results when they try to replicate a study using a later version.

Crowdsourced databases come in all forms; some researchers are finding meaning in the public’s off-the-cuff social media comments.

Computer scientist Barbara Poblete of the University of Chile and her colleagues turned to Twitter to reveal how residents of Chile perceived earthquakes. “It takes just a few seconds for people to start tweeting,” Poblete said, and their comments can help seismologists and first responders understand shaking throughout a region.

Twitter data have historically been quite easy to find and access, Poblete said. But many algorithms used to analyze human language require humans to indicate the meaning of a subset of the language sample (also known as annotating) before machines can interpret the rest. This is where issues of interoperability arise.

There’s no standard format for language annotation, Poblete said. Each research group develops annotations that fit its needs. Annotation is also much more common in English than in other languages, putting researchers studying countries such as Chile, where Spanish is the dominant language, at a disadvantage.

Poblete and her colleagues are working around the second problem by creating a system that can automatically collect ground motion information about earthquakes when numerous people in a particular area tweet about shaking, without relying on annotated data, and therefore can be used in any language.

Back in Texas, Pierce is also working toward using natural human language to complement structured data in descriptions of events such as Hurricane Harvey. She and her collaborators have funding to record residents’ memories of disasters, then look for trends in these stories that can help answer questions such as where storm-related flooding is likely to occur, how deep the water will get, and how long it will take to subside.

Information collected by eyes and ears can become “a new knowledge layer,” complementing information collected by mechanical sensors in a comprehensive data ecosystem, Pierce said. After all, lived experiences are the ultimate reflection of how humans interact with Earth.

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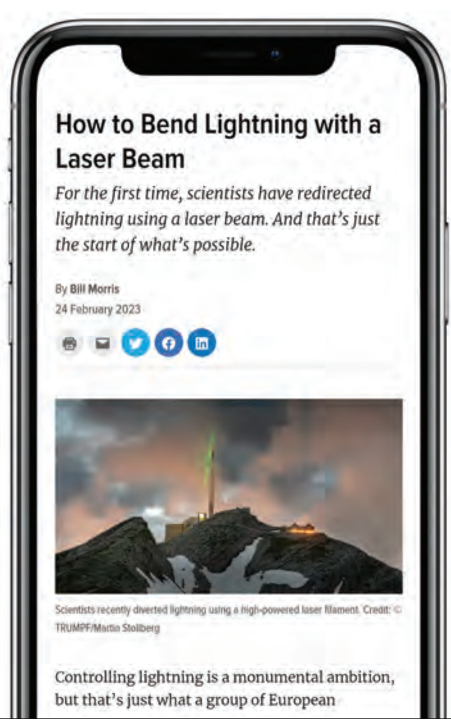

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DELUGES OF DATA Are Changing Astronomical SCIENCE

BY KATHERINE KORNEI

Astronomers today are more likely than ever to access data from an archive rather than travel to a telescope—a shift that's democratizing science.

In this composite image of the Tarantula Nebula, the blue and purple patches represent X-ray data from the Chandra X-ray Observatory, and the red and orange gas clouds, which look like roiling fire, represent infrared data from the James Webb Space Telescope. Credit: X-ray: NASA/CXC/Penn State Univ./L. Townsley et al.; IR: NASA/ESA/CSA/STScI/JWST ERO Production Team

Radio telescopes in Chile—part of the Atacama Large Millimeter/submillimeter Array (ALMA)—point toward the night sky. Credit: ESO/C. Malin, CC BY 4.0 (bit.ly/ccby4-0)

For scientists who study the cosmos, hard-to-grasp numbers are par for the course. But the sheer quantity of data flowing from modern research telescopes, to say nothing of the promised deluges of upcoming astronomical surveys, is astounding even astronomers. That embarrassment of riches has necessitated some serious data wrangling by myself and my colleagues, and it's changing astronomical science forever.

Gone are the days of the lone astronomer holding court at the telescope. Modern astronomy is most decidedly a team sport, with collaborations often spanning multiple institutions and particularly large scientific endeavors regularly producing papers with more than a hundred coauthors. And rather than looking through an eyepiece, like astronomers of yore, researchers today collect an enormous array of observations across the electromagnetic spectrum, from X-rays to radio waves, using sophisticated digital detectors. In recent years, scientists have also probed the universe using gravitational waves—an advance made possible by exquisitely sensitive instrumentation.

With research-grade telescopes peppered across all seven continents—and also in space—there's no shortage of astronomical data. And thanks to advances in detector technology, cosmic data are being collected more rapidly, and at a higher density, than ever before. The challenge now is storing and organizing all of those data and making sure they're accessible and useful to a wide variety of scientists around the world.

Bringing the Data Home

Only a few decades ago, just about everyone engaged in professional observational astronomy would have traveled to a telescope to collect their own data. That's what Chuck Steidel, an astronomer at the California Institute of Technology, remembers doing as a graduate student in the 1980s. Between 1984 and 1989, he made four trips by himself to Chile.

Steidel's destination was Las Campanas Observatory, where he used a telescope to observe "quasi-stellar objects," intensely bright and distant astronomical bodies believed to be powered by supermassive black holes. To transfer the astronomical data that he collected back to his home institution for analysis, Steidel recorded them onto dinner plate–sized magnetic storage tapes known as 9-track tapes.

Each observing run generated a lot of tapes to haul back to the United States, said Steidel. "A weeklong observing run would take about 24 of these, or two boxes, weighing about 40 pounds each." The load was too bulky to bring with him on an airplane, however, so Steidel had to ship the tapes back to the United States via boat, a process that took several weeks.

Around the time Steidel began advising graduate students of his own in the mid-1990s, technology had marched on, and

magnetic cassette tapes were in use for data storage. The palm-sized disks held far more data than 9-track tapes, and they weren't nearly as cumbersome to transport. It was suddenly possible to carry telescope data home immediately after an observing run, said Alice Shapley, an astronomer at the University of California, Los Angeles who joined Steidel's group as a graduate student in the late 1990s.

By the late 2000s, when I was a graduate student in astronomy working with Shapley, digital video discs (DVDs) were the preferred medium for transporting astronomical data. I remember leaving Hawaii's W. M. Keck Observatory one morning bleary from a lack of sleep but content to have my observations literally in hand on thin disks that I could slip into my carry-on luggage.

My experiences in graduate school differed from those of my adviser and her adviser in more than just the ways in which we transported our data, however. Steidel obtained all of the data for his thesis by traveling alone to a telescope. Shapley also collected much of her thesis data herself, but she supplemented her observations with data provided by other members of her adviser's research group. I, on the other hand, gathered a significant portion of my data from astronomical archives.

Data for Everyone

The concept of a data repository for astronomical observations is relatively new. It was just over 2 decades ago that the Sloan Digital Sky Survey (SDSS) started amassing data from a modest-sized telescope in southern New Mexico and making those observations available in the form of a catalog, said Ani Thakar, a computational astronomer at Johns Hopkins University in Baltimore, and a catalog archive scientist with SDSS. "Before SDSS made [its] data public to the world, there was nothing like it," he said.

During its first phase of operations, from 2000 to 2005, SDSS increased the number of known galaxies from 200,000 to 200 million. "It ushered in the era of big data in astronomy," said Thakar. SDSS is still going strong today; it recently celebrated its eighteenth data release, and the archive now includes observations of nearly half a billion unique objects. From developing high-quality processing pipelines to building server-side analysis tools, the goal has always been to streamline data storage and access and provide high-quality observations that are useful to the scientific community, said Thakar.

Many more astronomical archives exist today. The Mikulski Archive for Space Telescopes (MAST), managed by the Space Telescope Science Institute in Baltimore, is one of the largest. MAST contains images, spectra, and other forms of observations from more than 20 telescopes and space missions. Some of those data—amounting to several petabytes in all—were gathered by individual scientists observing specific celestial objects; others were obtained as part of systematic sky surveys.

The point of amassing all of those data in a searchable archive is to help ensure that they're useful to the larger scientific community in perpetuity, according to David Rodriguez, an astronomical data scientist at the Space Telescope Science Institute and a classmate of mine from graduate school. "We collect and archive all of that information and make it available to everyone," he said.

No longer are observations gathered by a researcher the sole purview of that researcher and their collaborators forever—instead, they're often archived and released to the public after some predetermined proprietary period (typically 12 months). That democratic access to data is changing astronomical science.

"IT'S A WAY TO **DISCOVER DATA SETS**."

Astronomers once stored telescope data on 9-track tapes. Credit: Hannes Grobe, Wikimedia, CC BY-SA 2.5 (bit.ly/ccbysa2-5)

The ability to pluck existing data from an archive can be a godsend for researchers working on a timeline. I know that firsthand—I was able to access Hubble Space Telescope data, which were critical to both my master's and doctoral theses, from archives rather than having to write applications to use the telescope, which is heavily oversubscribed. (In the most recent round of proposals for so-called General Observer programs with the Hubble Space Telescope, astronomers asked for more than 5 times the amount of telescope time available.)

Particularly for early-career scientists seeking to finish a dissertation or establish themselves in a research track, applying for telescope time is a stressful experience fraught with uncertainty. Having access to archival data means that it's no longer necessary to travel to a telescope, a potentially expensive and time-consuming endeavor. (However, some telescopes, like those at the W. M. Keck Observatory in Hawaii, can be remotely accessed.)

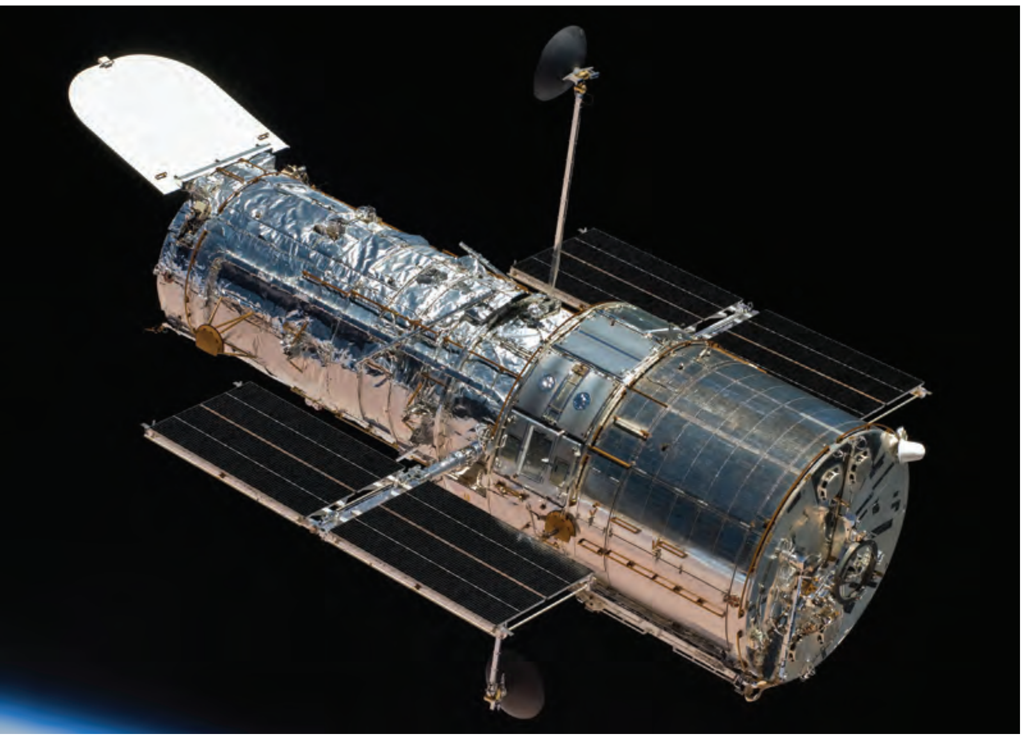
The resources needed to apply for, and collect, telescopic observations in the traditional way can be substantial. It's therefore not surprising that researchers based in countries with a lower gross domestic product per capita tend to produce a larger fraction of publications based on archival data than researchers living in more affluent countries.

Astronomical archives clearly provide more equitable access to data, but they're valuable for another fundamental reason, too: They open up new research avenues. The very act of digging through a data repository often turns up unexpected observations that might have been taken years ago and that a researcher didn't know existed, said Rodriguez. "It's a way to discover data sets." Those data could prove useful for current or future research projects or even spur entirely new investigations, he said.

Organized and Accessible

A key tenet of any archive is that its data are well organized and accessible. That's where Rodriguez plays a key role: He helps standardize all of the metadata—for instance, the date of the observation, the name of the object being observed, and its sky coordinates—associated with astronomical observations in MAST. "I work toward consolidating the various types of metadata we have across all missions," said Rodriguez. The goal is to ensure that data from different telescopes and space missions can be easily and uniformly queried in the MAST database, he explained.

"THE LEGACY OF AN OBSERVATORY DEPENDS ON HOW MUCH PEOPLE USE THE **ARCHIVED DATA**."



The Hubble Space Telescope has been observing the universe since 1990. Credit: NASA, Public Domain

Ample data show that archival observations are being put to use. Hundreds of scientific papers are published each year using data from MAST, and that number has increased by more than a factor of 2 since the early 2000s.

A separate archive devoted to just one astronomical observatory—the Atacama Large Millimeter/submillimeter Array (ALMA), an ensemble of radio telescopes in the Atacama Desert of Chile—has seen similar successes. Data from ALMA are funneled into the ALMA Science Archive for public access after a 12-month proprietary period.

Adele Plunkett, an astronomer working with the ALMA Science Archive, said that it's easy to access the observations, which number in the tens of millions of files and total more than a petabyte. "You don't even need to create an account. You can just go to our website, and you can start browsing and downloading the data," she said.

Plunkett and her colleagues have shown that roughly 3 times more data are downloaded by users each month than are taken in anew from ALMA. That's evidence that users are accessing substantial amounts of archival data, said Plunkett. "Many people are able to access the same projects and therefore can maximize the utility of observations."

And scientists are publishing results using those archival data. In 2021, roughly 30% of ALMA-based publications incorporated archival observations, the team found. That's a significant increase from 10% just a decade ago, and it's something to be proud of, said Plunkett. "The legacy of an observatory depends on how much people use the archived data."

Wrangling large quantities of archival data takes not only technical expertise but also an eye toward how people interact with a user interface. Several of Plunkett's colleagues have backgrounds in user experience. "We think a lot about the design of the archive and the usability of it," she said. The team often takes a cue from other online platforms that involve searchable databases. "We look at Amazon and Netflix and online retailers," said Plunkett.

Archives of the Future

The next generation of telescopes is currently being developed in tandem with the next generation of data archives. Those facilities have the advantage of coming of age in a world primed for big data, said Rodriguez. One example is the Vera C. Rubin Observatory in Chile, which is slated to collect several tens of petabytes' worth of

This image of a portion of Messier 92, one of the brightest globular clusters in the Milky Way, was created with data captured by the James Web Space Telescope's Near Infrared Camera, or NIRCam. Credit: NASA, ESA, CSA, Alyssa Pagan (STScI)

images of the night sky. "They're starting from modern data technology," said Rodriguez. "They're starting cloud ready."

Beginning in 2024, the Simonyi Survey Telescope at the Vera C. Rubin Observatory will image the entire visible sky about every 3 days and will continue doing so for a decade. That massive undertaking, known as the Legacy Survey of Space and Time (LSST), will not only provide a comprehensive look at billions of stars and galaxies but also reveal how transient objects such as asteroids and supernovas vary in brightness over time, said Leanne Guy, the LSST data management project scientist at the Vera C. Rubin Observatory. "Because we can observe the sky so rapidly, we can see things changing," she said.

The observations of the LSST will essentially produce an evolving picture of the cosmos. "It will be the greatest movie of the night sky," Guy said. Not surprisingly, there will be a whole lot of data involved; the LSST will yield roughly 20 terabytes of raw data every night. Those data—in the form of images obtained at wavelengths ranging from ultraviolet to near infrared—will be transferred from Chile to the SLAC National Accelerator Laboratory in California. From there, they'll be distributed to other data-processing facilities around the world, and the final data products will be made available via Google Cloud Platform.

A set of web applications known as the Rubin Science Platform will allow users to access, view, and analyze LSST data. That's a shift away from the traditional model, in which scientists download data to their computer, said Guy. But that change is necessary, she said, because it allows researchers to efficiently mine petabyte-scale data sets. "It is no longer feasible for scientists to just download a data set to their computer and load it into memory," said Guy.

"IT WILL BE THE GREATEST MOVIE OF THE NIGHT SKY."

The deluge of astronomical observations now available to anyone with an Internet connection is changing how research is being done and even what's being researched. As scientists embrace the tools of "big data," they're able to dig into far-flung research questions that couldn't have been answered just a few decades ago, like how galaxies are arranged in space.

And graduate students around the world are already writing theses based largely, and sometimes wholly, on archival data; more than 300 astronomy Ph.D. theses have been written to date using SDSS data. Time will tell whether the experience of observing at a telescope will go the way of the dodo. Probably not, but astronomical archives are obviously here to stay.

Welcome to the era of archives.

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▶ **Read the article at bit.ly/Eos-astronomical-data**

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VITH NATURE
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BY KRYSTYNA POWELL, SAFRA ALTMAN, AND JAMES MARSHALL SHEPHERD

Natural and engineered nature-based structures offer promise for storm-related disaster risk reduction and flood mitigation, as long as researchers can adequately monitor and study them.

Beachfront homes and dunes line South Bethany Beach, Del.
Credit: Robert Kirk/Photodisc via Getty Images

The 2020 and 2021 Atlantic tropical storm seasons were extremely busy, ranking as the first and third most active, respectively, on record. Thirty named storms occurred in 2020 alone, with 23 making landfall: 11 in the United States (a record) and 13 elsewhere (also a record) around the Caribbean, the Gulf of Mexico, and even Portugal (a first). The 2021 Atlantic season produced another 21 named storms. The 2022 season was closer to average, producing 14 named storms, although several—Hurricane Ian especially—caused extensive damage.

MUCH OF THE INNOVATION NEEDED TO MEET THE CHALLENGES OF NATURAL DISASTERS WILL COME FROM MODERN ENGINEERING EXPERTISE. YET NATURE ITSELF PROVIDES TIME-TESTED EXAMPLES OF RESILIENCE AND RECOVERY FROM WHICH WE CAN LEARN.

In addition to direct impacts of episodic tropical storms, much of the coastal Atlantic region increasingly has experienced extreme rainfall, storm surges, and even fair-weather inundation exacerbated by sea level rise. Such compound weather-related disasters reveal new and heightened vulnerabilities affecting broad swaths of people, particularly in marginalized and underserved communities.

In 2003, storm surge flooding from Hurricane Isabel inundated the small coastal community of Bowleys Quarters, Md., near Baltimore. Credit: Jccohen/Wikimedia Commons, Public Domain

Protecting coastal communities from the effects (and aftereffects) of repeated pummeling by tropical storms and other disasters requires an all-hands-on-deck approach, with contributions from physical, biological, chemical, and social scientists as well as engineers, policymakers, and community members. Building this resilience also requires new solutions.

Much of the innovation needed to meet the challenges of natural disasters will come from modern engineering expertise. Yet nature itself provides time-tested examples of resilience and recovery from which we can learn. Natural and nature-based features (NNBFs) can support coastal resilience and mitigate flood risk while providing ecosystem services. Berms and dunes, for instance, are nature-based features that can be engineered or enhanced along coastlines to minimize flooding and storm damage in communities and to achieve ecosystem restoration goals.

Understanding how NNBFs perform under extreme hydrometeorological hazards and in other natural disasters in comparison with traditional infrastructure is critical. This understanding requires thorough monitoring across the life cycles of disaster events, including data on conditions before, during, and after, which allow researchers to evaluate how physically effective and cost-effective NNBF projects are in achieving their intended purposes, whether they involve coastal engineering, sustainable management, wetland restoration, or natural hazard reconnaissance. But collecting these data presents major challenges.

In a 2021 workshop hosted by the Network for Engineering with Nature (N-EWN), a multidisciplinary group of experts discussed the current state of coastal disaster monitoring, necessary communication and collaboration among researchers, improving experimental design and data collection, funding for monitoring and studies of NNBFs and natural features that serve as proxies for EWN approaches, and enhancing community involvement in monitoring projects. N-EWN, launched in 2020 through a partnership between the U.S. Army Corps of Engineers (USACE) Engineering With Nature program and the University of Georgia's Institute for Resilient Infrastructure Systems, is a community of researchers, educators, and practitioners advancing EWN solutions. As founding partners of N-EWN, our interest here is in identifying and applying lessons learned from this workshop to improve the case for EWN approaches as a means to raise community resilience to climate change and extreme weather events.

Communication, Collaboration, and Mobilization

The increasing frequency and intensity of disasters make organizational communication and collaboration among disaster monitoring groups, such as emergency management agencies, other state and federal agencies, and academic research groups, more important than ever. Growing coastal populations and competition for limited disaster-planning and response resources from federal, state, and local organizations trying to cope with other types of disasters, including the COVID-19 pandemic, further increase this need. Effective communication allows groups and agencies to share essential knowledge, information, and warnings among them and with affected communities.

The need to establish avenues of communication between lab groups (including between field and office collaborators) and determining the severity levels of events that require responses before the tropical storm season starts are important lessons. Preseason conversations allow researchers and planners to share approaches, coordinate monitoring efforts, and develop collaborations in advance.

Outlining exact plans for storm monitoring is challenging because real-world events present unexpected twists and turns, so researchers must have flexibility in their methodologies. Knowing the approaches of other groups studying similar natural features or disaster types helps researchers develop this flexibility, refine methods, and standardize data collection and reporting. Furthermore, collaborating in multiregional teams with diverse disciplinary expertise can allow for more combinations of opportunistic data gathering and formal experimental designs to be used to gather information and respond to events as they happen with a wider array of approaches.

Another lesson workshop participants reported is that when monitoring storm impacts in the field, having site-specific information and local assets accessible, along with knowledge of available methods, helps facilitate successful deployments and retrievals of sensors for data collection. The accessibility of study sites, for example, can

In September 2008, Hurricane Ike caused extensive damage to U.S. Gulf Coast communities, reducing local businesses and homes to piles of debris. Credit: Robert Haynes, USACE St. Paul District/Flickr, Public Domain

be determined by leveraging experience and local knowledge of the best access points and most vulnerable locales at sites.

A team's ability to mobilize organized responses before and after disaster events is as crucial as communication. This ability requires time and preparation. Researchers must design responses that account for the type of coastline affected and for compounding events like associated flooding or saltwater intrusions. The planned response will differ, for example, in an urban area versus a natural area like an oyster reef or an engineered area such as near seawalls or submerged breakwaters.

Before an impending storm, response teams typically check storm surge forecasts and venture to areas that might be affected

A TEAM'S ABILITY TO MOBILIZE ORGANIZED RESPONSES BEFORE AND AFTER DISASTER EVENTS IS AS CRUCIAL AS COMMUNICATION.

to assess infrastructure and the accessibility and safety of potential sites. This sort of preparatory procedure maximizes organized and standardized data collection and can help researchers avoid using a more haphazard approach, which may be costly and unfruitful. For example, stronger-than-expected winds or storm surges may dismantle sensors and equipment that aren't well sited, contributing to data loss and damage. Proper preparation also improves poststorm analysis, and standardized data collection allows for comparative analyses across multiple storm events.

Workshop discussions revealed several important elements that research teams must consider in planning effective post-disaster monitoring. These include identifying where to collect data, obtaining permits and access to sites, and planning safe travel to and from sites. Having enough time to address these issues can be the most important factor in determining which storm events to respond to. This decision can also be driven by what equipment needs to be deployed or removed to avoid damage during an event. Depending on the capabilities of a given group and conditions on the ground, the events chosen may be relatively small, like compounding sequential tropical storms, rather than big events like major hurricanes.

COMMUNITY SCIENCE IS AN EMERGING WAY FOR COMMUNITY MEMBERS TO ENGAGE IN OBSERVATIONAL MONITORING RATHER THAN BEING ONLY SUBJECTS OF STUDY BY OUTSIDERS.

Supporting Baseline Data Collection

Collecting time-sensitive disaster event data is costly. Most research groups have focused on monitoring after storms because of difficulty obtaining funding to gather prestorm data. Workshop participants actively involved in such monitoring pointed to the National Science Foundation, the U.S. Coastal Research Program, NOAA's Effects of Sea Level Rise Program and Office of Oceanic and Atmospheric Research, and state-level agencies as sources that fund poststorm evaluations.

Prestorm monitoring is just as important, however. Baseline data are necessary for understanding environmental and natural infrastructure changes related to storm protection and resilience and for informing stakeholders and policymakers of these changes. Future storm seasons will provide excellent opportunities to assess NNBFs if baseline data are collected and available beforehand and resources and plans are in place to pair them with data collected after storm events.

Teams must convince funding sources of the importance of baseline studies so that these sources understand the opportunities for and value of gathering prestorm data and conducting long-term monitoring. This funding will allow researchers to better prepare research questions, such as how different structures and environments will handle—and bounce back from—extreme weather damage. It can also offer additional advantages, including facilitating more statistically sound planning, inclusion of complex experimental designs, and clarification of and coordination across data sets to be collected (e.g., flooding, bathymetry, soil inundation, vegetation impacts, erosion).

In addition to collecting baseline data in future storm seasons, there are opportunities to identify and use existing data from past storm seasons to demonstrate the performance of natural features during storms and relate that performance to NNBFs. For example, researchers used data from Hurricane Sandy in 2012 to evaluate how effectively natural ecosystems, such as coastal wetlands, reduced wave impacts, absorbed floodwaters, and mitigated damage across 12 states. They found that wetlands in the region studied prevented $625 million in damages from flooding, pointing to the importance of incorporating natural and restored habitats into NNBF designs.

Involving Affected Communities

Another major point of discussion at the workshop was the need to enhance engagement and share knowledge from disaster monitoring work with—and gain partners among—affected communities. Participants suggested attending community outreach events for these purposes, because there is much to be learned from people living in affected areas. Engaging stakeholders such as homeowners and local natural resources users also helps research groups identify specific areas of interest when conducting regional surveys. Locals can direct research groups to important recreational areas, fisheries, and reefs, for example, and to residential areas and vulnerable infrastructure, such as hospitals and care facilities, that may be heavily affected by storms.

An important recommendation is for scientists to encourage federal agencies like the U.S. Geological Survey, NOAA, and the Federal Emergency Management Agency to facilitate community participation. These agencies can provide additional vital resources such as historical data, computing infrastructure to process and share data, access to sites, equipment, and personnel outside the monitoring teams. Such efforts can enable marginalized, underrepresented, and frontline communities often excluded from the scientific process to produce knowledge valuable for local safety and well-being.

Hurricanes Katrina in 2005, Harvey in 2017, and Michael in 2018, among other events, have revealed racial, socioeconomic, and geographic disparities in how communities recover from extreme events. For example, more affluent communities rebuilt or repaired infrastructure, whereas many communities of color and impoverished areas still show signs of damage from these storms, years later.

Considerations of equity, vulnerability, and resilience should be woven into project planning in disaster monitoring and studies. Partnering with social scientists, physical and biological scientists, and community members can help reduce gaps in the understanding and quantification of climate vulnerability of disenfranchised and marginalized communities through multidisciplinary approaches.

Community science is an emerging way for community members to engage in observational monitoring rather than being only subjects of study by outsiders. Pointing residents toward community science projects benefits both communities and researchers exploring storm events.

Many such projects exist, including those related to NNBFs. SandSnap, for example, is a collaborative crowdsourcing application created by USACE, James Madison University, and MARDA Science LLC that allows community scientists to assist in building a globally accessible public database of coastal sediment grain sizes simply by uploading mobile phone photos of beach sand. Researchers use the database to quantify storm resilience and gather information on beach nourishment projects that use sediments dredged from navigation channels. These efforts, in turn, can lead to more effective and cost-efficient approaches to coastal protection.

Other efforts in which government and nongovernmental agencies have partnered include citizenscience.gov and iCoast. These partnerships provide resources to help design and initiate community science projects and show how communities can be trained to carry out local measurements and testing. Programs such as these allow community members to gain crucial firsthand knowledge that broadens their understanding of their environment and may inform local and regional policy.

U.S. Army Corps of Engineers New York District project analyst Catharine Russamano and project manager David Gentile oversee a dune and beach reconstruction effort in Port Monmouth, N.J., on 1 July 2014 as part of a project designed to reduce coastal storm risks to the community. Credit: James D'Ambrosio, USACE New York District Public Affairs/Flickr, Public Domain

Building the Case for Nature-Based Solutions

EWN-type solutions that align natural and engineered processes—through NNBFs, for example—offer huge potential to support coastal resilience to hurricanes and tropical storms, reduce associated flood risks, and boost beneficial ecosystem services. Making a case for these nature-based solutions requires dedicated and detailed monitoring of how they respond to the compounding effects of storms and flooding.

Amid ongoing climate change, which is amplifying risks from these events, researchers must be equipped with the necessary tools and resources to conduct this monitoring. The knowledge gained will ultimately inform the design and implementation of NNBFs and EWN solutions to equitably protect communities in the face of potential disasters.

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Scientists Decipher the Seismic Dance of the Southern Alps

Scientists studied seismic activity in the Southern Alps of Italy, home to vineyards, population hubs, and economic bustle. Credit: Civvì/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Scientists have studied northeastern Italy's Montello hill, located at the southern edge of the Alps, since the late 1800s. Despite consistent research, its relationship with neighboring tectonic structures remains hotly debated.

The region hosts dense population centers and significant economic activity. For example, it's home to prosecco, a sparkling wine whose grapes are grown on the region's mountain slopes. Understanding the tectonic activity in the region is therefore critical for the population's safety, livelihood, and well-being.

In a new study, *Picotti et al.* discovered that Montello's seismically active thrust region is larger and older than previously estimated, stretching almost to the city of Treviso. They found that Montello's thrust region is shortening at a rate of 0.3–0.4 millimeter per year, whereas the nearby Bassano-Valdobbiadene thrust has an annual shortening rate of 1.4–1.7 millimeters per year. Although many regions of the Alps are considered tectonically dead, the authors conclude that the Southern Alps are, indeed, active.

The team reached this conclusion by integrating data from wells and reservoirs, seismic data from industry scientists, field observations, and microseismic measurements.

The findings are congruent with recent geological activity: The Montello region has experienced only one significant earthquake in recorded history (in 778 CE) and has generally been considered seismically quiet. Still, the authors warn that both the Montello and the Bassano-Valdobbiadene thrusts are active regions interlocked in a complex geological dance. Their seismic potential could be high, and this risk warrants future research to better evaluate hazards in the region. (*Tectonics*, https://doi.org/10.1029/2022TC007522, 2022) **—Morgan Rehnberg,** *Science Writer*

What Happens to Drugs After They Leave Your Body?

Swallowing a pill only *seems* to make it disappear. In reality, the drug eventually leaves your body and flows into waterways, where it can undergo further chemical transformations. These downstream products aren't dead in the water.

Many pharmaceuticals, for example, are designated as contaminants of emerging concern, or CECs, because they alter hormone levels or otherwise harm wildlife. Some downstream products formed during drug breakdown are even more harmful to organisms than their parent molecules. It's critical, then, to chart the chemical courses of drugs to assess risk, but this is a daunting task because these courses depend on myriad hard-to-predict reaction patterns that are difficult to observe.

In a new study, *Ceresa et al*. devise a new method to chart these reaction possibilities. The newly proposed method is based on a multimodel global sensitivity analysis. This analysis balances model fit and mathematical complexity: It generates a well-fitting model by simplifying it.

The researchers estimated how the arthritis drug diclofenac breaks down upon entering groundwater. First, using existing chemical transformation data, they built a comprehensive model of breakdown that included the gamut of possible chemical reactions. However, the estimates from this model were highly uncertain.

To adjust the model to better fit their data, the researchers quantified the relative importance of each possible chemical process and removed the least relevant ones.

This led to three simplified yet plausible models of drug breakdown. The researchers ranked these models on the basis of their fit with the data and showed that a simplified model outperformed the most complex one.

The method yielded a flexible and accurate model. The scientists say their new method is especially useful when data are limited. Applying it to other drugs, they say, could reveal the full toll that pharmaceutical pollution takes on the planet. (*Water Resources Research*, https://doi.org/10.1029/2022WR033183, 2023) **—Saima May Sidik,** *Science Writer*

Jet-Propelled Tunicates Pump Carbon Through the Oceans

A snorkeler swims through a bloom of salps in the South Pacific Ocean off the coast of New Zealand. Salps play an outsized role in the ocean's biological carbon pump, according to new research. Credit: Paul Caiger

Salps are transparent, tube-shaped jellies well known for their propulsive jetting movements. According to new research, they also take quite a bit of carbon along for the ride.

Populations of these gelatinous zooplankton—part of the subphylum Tunicata, or sea squirts—are episodic and patchy. Sometimes, though, they "bloom" and form huge aggregations. Their feces and sinking carcasses sequester carbon into the deep sea.

In a recently published study, *Steinberg et al.* show that salp-related carbon sequestration is especially prominent in retentive or low-export food webs. The authors sampled a full suite of salp-related carbon export processes during a 2018 *Salpa aspera* bloom in the subarctic northeastern Pacific Ocean.

Aboard the research vessels *Roger Revelle* and *Sally Ride*, the researchers deployed cameras and cast nets up to 1,000 meters deep during day and night. They lugged up salps and other zooplankton, sorted and weighed their catch, and trapped sinking salp feces. They also conducted onboard experiments and incorporated all of their data into a model to approximate carbon export in the study zone. The team repeated this process across three 8-day sampling cycles.

The scientists discovered that the salp blooms significantly affected local biogeochemistry. Salps increased the proportion of net primary production exported as particulate organic carbon below the euphotic zone (the ocean region bright enough to support photosynthesis) 1.5-fold. In addition, during blooms, the proportion of this particulate organic carbon export remaining 100 meters below the euphotic zone increased by a factor of 2.6.

With increasing recognition of their role in the biological carbon pump, widespread use of new technologies for salp detection and sampling will lead to a better understanding of the tunicate's unique role in the ocean ecosystem. (*Global Biogeochemical Cycles*, https://doi.org/10.1029/2022GB007523, 2023) **—Aaron Sidder,** *Science Writer*

Groundwater Replenishes Much Faster Than Scientists Previously Thought

A large part of the world's liquid freshwater supply comes from groundwater. These underground reservoirs of water—which are stored in soil and aquifers—feed streams, sustain agricultural lands, and provide drinking water to hundreds of millions of people.

For that reason, researchers are keen to understand how quickly surface water replenishes, or "recharges," groundwater stores. But measuring a vast, fluid, underground resource is easier said than done. In a new study, *Berghuijs et al.* found that recharge rates globally might be double those from previous estimates.

The research team produced an updated model of groundwater recharge using a recent global synthesis of regional groundwater measurements. They found that a single factor, climate aridity, accurately accounted for how much precipitation trickled into groundwater across the globe: Arid locations had lower recharge rates than humid ones. The aridity-based model results closely mirrored field measurements and indicated that previous models vastly underestimated recharge rates.

This finding has implications for the water cycle, the authors say. For instance, groundwater likely contributes more to river flow and plant water use than previous models predicted. That could scale up to affect the entire ecosystem.

Although groundwater might recharge more quickly than expected, the team cautions that the resource is still overused in many places, especially in arid regions. Groundwater depletion threatens water security in these areas, they say, and the impacts of climate change remain unknown. (*Geophysical Research Letters,* https://doi.org/10.1029/2022GL099010, 2022) **—Rachel Fritts,** *Science Writer*

New Tectonic Plate Model Could Improve Earthquake Risk Assessment

New Zealand is no stranger to earthquakes. Scientists estimate that more than 20,000 occur there each year, and the deadliest ones can rattle the entire nation.

The country's seismic activity stems from its position atop the boundary of the Australian and Pacific tectonic plates, which are colliding at a rate of 3–5 centimeters per year. Understanding where and how plates interact is essential for determining earthquake risk. And according to a new model of plate boundaries, some regions of New Zealand might be more at risk than previously expected.

Hirschberg and Sutherland developed a new kinematic model of the Australian-Pacific plate boundary using fault slip rate measurements and physics-based estimates where slip rates were unavailable.

The method allowed them to estimate fault slip rates across New Zealand. It generated a velocity field that like a budget, balanced deformation occurring along the plate boundary. Critically, the predicted velocities could vary across faults, which allowed model resolution approaching 10 kilometers—an order of magnitude better than many contemporary approaches.

The authors modeled the Hope Fault on New Zealand's South Island, among others. Credit: Ulrich Lange, CC-BY 3.0 (bit.ly/ccby3-0)

The authors then compared their computed velocity field to GPS observations. The model suggested that slip rates in Wellington have been overestimated, which the authors say represents decreased hazard. Meanwhile, in the northeastern North Island, differences between the model and GPS observations may be explained by uncertainty in deformation north of New Zealand or undiscovered faults within New Zealand that could pose an earthquake risk.

This new-and-improved model can be applied along other plate boundaries, the authors say, to improve risk assessment and to better target field observations in hazard-prone areas. (*Journal of Geophysical Research: Solid Earth,* https://doi.org/10.1029/2022JB024828, 2022) **—Morgan Rehnberg,** *Science Writer*

How Can We Sample More Ethically?

Sampling in locations such as Arches National Park, shown here, requires the consideration of geoheritage, the preservation of features that matter both culturally and geologically. Credit: Ben Stiefel/Unsplash

Knowledge production and advances in the geosciences are often based on information collected or measurements made at specific places and times. The practice of preserving key outcrops as type sections for future research exemplifies the value of place for science. However, the places we sample can have multiple meanings beyond those related to relatively narrow scientific investigations, especially for people who live nearby or have cultural connections to the land.

Ryan-Davis and Scalice remind us that geoscientists who sample ethically don't consider only permitting requirements. They also build relationships with stakeholders to benefit from their expertise, expand scientific participation, and obtain informed permission for fieldwork. The researchers' commentary summarizes the consensus of a broader working group formed after a town hall on the topic held at AGU's Fall Meeting 2021 (bit.ly/AGU21-sampling-field-work).

The authors summarize ways to integrate ethical and respectful behavior in the field into curricula and review processes, and they generally encourage researchers to think before sampling. (https://doi.org/10.1029/2022AV000762, 2022) **—Susan Trumbore**

Good Trouble in Committees

Committee members can play a pivotal role in advancing diversity, equity, and inclusion in the geosciences. Credit: WOCinTech Chat/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Most geoscientists end up participating in committees, even though many view the extra work as a necessary evil. Yet committees offer opportunities to advance diversity, equity, and inclusion (DEI) in science, technology, engineering, and mathematics (STEM). In fact, when making decisions about policies, funding, and personnel, committee members serve as gatekeepers who can empower innovation and cultivate agents of change. Using three examples of committees working on hiring, seminar scheduling, and award nominations, *Lewis et al*. show how rethinking committee work as "regenerative gatekeeping" can help overcome inertia and frustratingly slow progress to date on DEI in the geosciences. (https://doi.org/10.1029/2022AV000772, 2022) **—Eric Davidson**

Greetings from the Future Coasts Aotearoa (FCA) project team, all the way from New Zealand!

This picture was taken in Rangaunu Harbour, in New Zealand's far north. We had been wading through deep mud in mangroves and salt marshes, capturing critical wetland measurements that will help us understand ecosystem responses to sea level rise and habitat evolution. This component of the project aims to identify adaptation tipping points and opportunities for wetland preservation or reestablishment.

FCA aims to transform coastal lowland systems threatened by sea level rise into prosperous ecological communities. Our coastal lowlands are valued for many reasons, including being home to unique ecological wetlands, cultural sites of significance, recreational areas, highly productive agricultural tracts, and popular places to live. Sea level rise will force changes to coastal lowlands and our use of these environments. Transformation requires developing the right tools to achieve a "whole-of-system" adaptation approach across states of social and cultural well-being, economic systems, and natural environments. FCA addresses this challenge by investigating how we can successfully transform coastal lowlands in terms of what to do, why to do it, and where and when to do it.

For more information, visit bit.ly/future-coasts-aotearoa.

—**Christo Rautenbach**, National Institute of Water and Atmospheric Research, Auckland, New Zealand

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