VOL. 98 • NO. 5 • MAY 2017

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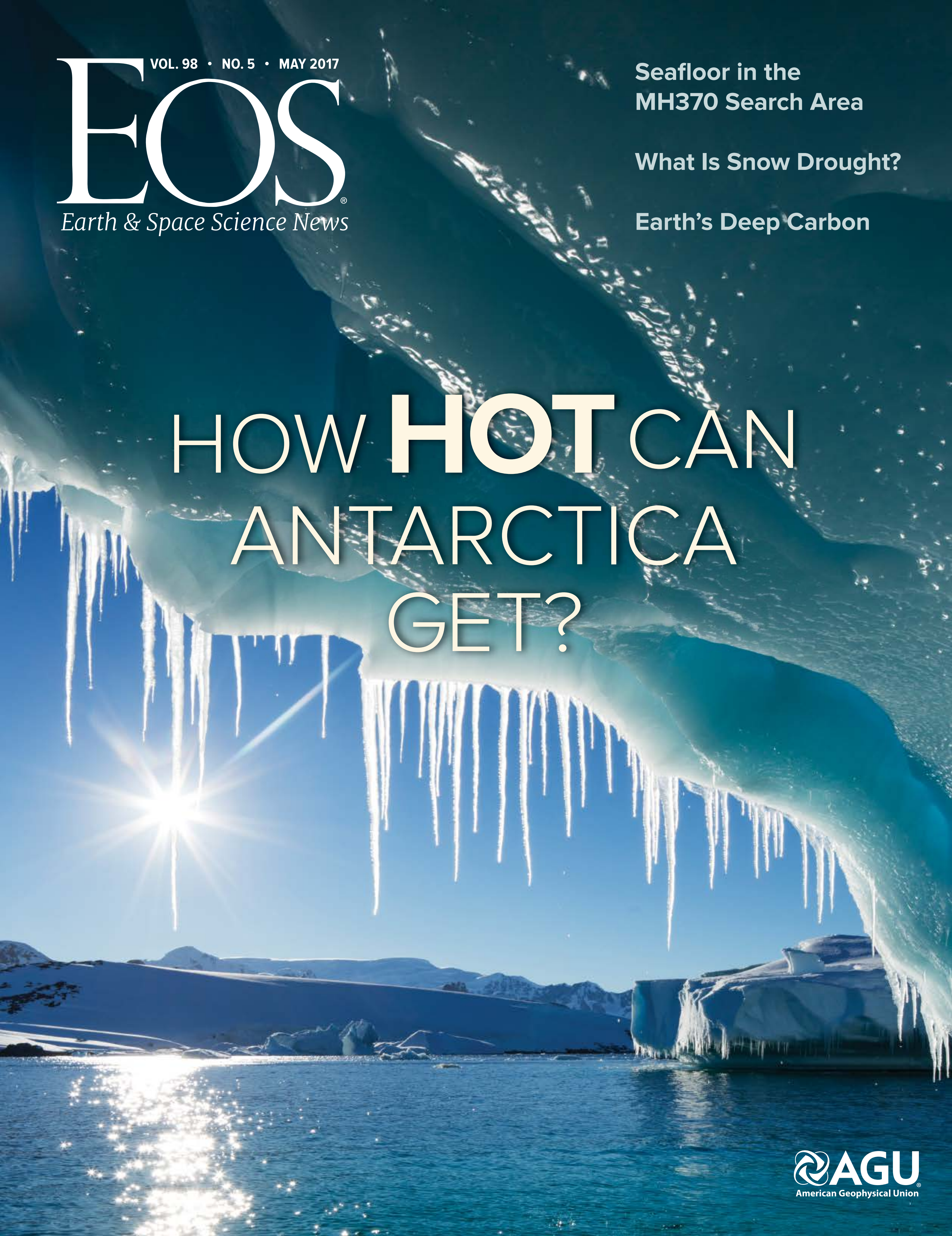
Earth's Deep Carbon



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Dr. Peter J. Webster

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Daniel P. Loucks (Cornell University)
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MAY 2017
VOLUME 98, ISSUE 5

DEPARTMENTS

On the Cover

Icicles hang from a melting iceberg near Petermann Island, off the Antarctic Peninsula. Credit: Danita Delimont/Gallo Images/Getty Images.

Eos (ISSN 0096-3941) is published monthly by the American Geophysical Union, 2000 Florida Ave., NW, Washington, DC 20009, USA. Periodical Class postage paid at Washington, D. C., and at additional mailing offices. POSTMASTER: Send address changes to Member Service Center, 2000 Florida Ave., NW, Washington, DC 20009, USA.

Member Service Center: 8:00 a.m.–6:00 p.m. Eastern time; Tel: +1-202-462-6900; Fax: +1-202-328-0566; Tel. orders in U.S.: 1-800-966-2481; Email: service@agu.org.

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Lunar Lava Tubes Could Offer Future Moon Explorers a Safe Haven

Lunar colonization isn't mere science fiction anymore. Billionaires plan to send tourists on once-in-a-lifetime trips, and politicians say that they hope to colonize the Moon in the next few decades. There may even be ways for human colonists to harvest water from ice that may be permanently shadowed in certain caves.

But where could a human colony actually live? The Moon has no atmosphere or magnetic field to shield it from solar radiation, and micrometeorites constantly rain onto its surface. That's no environment for our squishy, earthling bodies.

Scientists studying the Moon's surface may have found the answer: Humans could shelter in lunar lava tubes. The Moon is covered in huge swaths of ancient basaltic lava flows. Earth's volcanoes can also erupt in similar flows, with basalt sometimes running as molten rivers. In these rivers, the outside cools faster than the inside, creating a hard shell. The remaining lava pours out, leaving a hollow space behind.

Do similar lava tubes exist on the Moon?

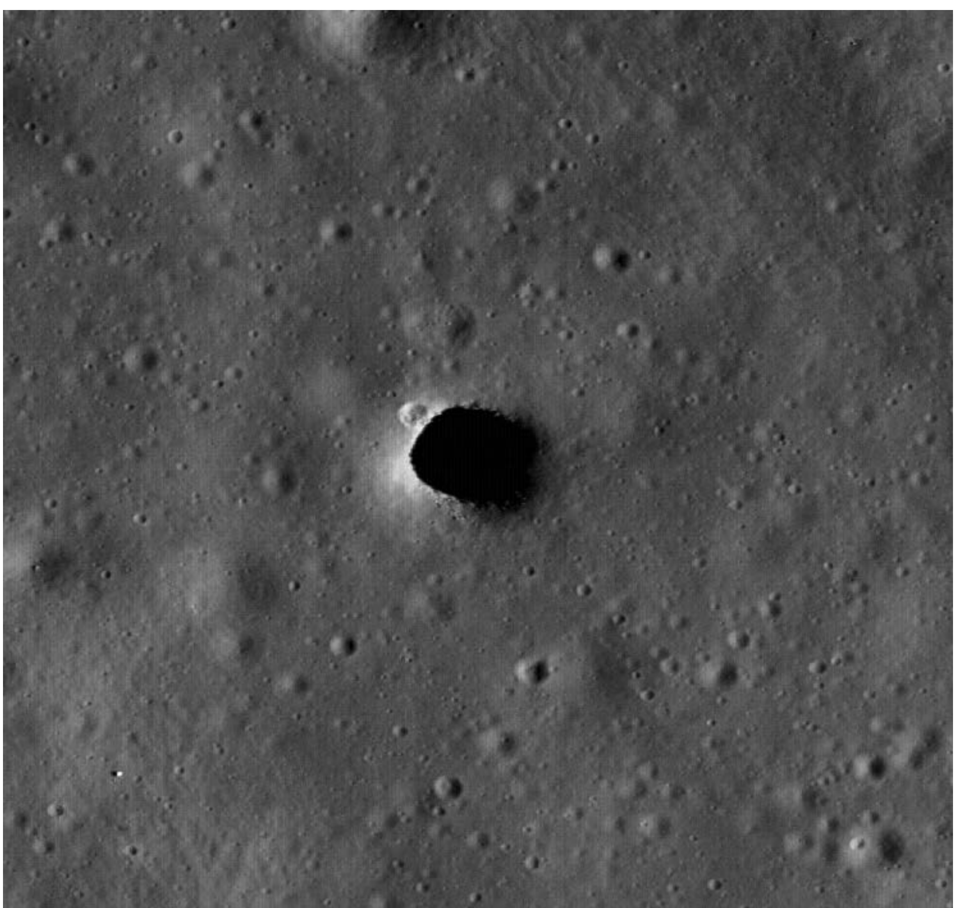
In a presentation on 22 March at the 48th Lunar and Planetary Science Conference (LPSC) in The Woodlands, Texas, Junichi Haruyama, a senior researcher at the Japan Aerospace Exploration Agency (JAXA), discussed one such lava tube that he suspects may be snaking underneath the Moon's surface.

Searching for Lava Tubes

In 2009, Haruyama and his team spotted evidence of a dark hole in the Moon's Marius Hills region in data from the Japanese lunar orbiter SELENE (Selenological and Engineering Explorer), also known as Kaguya. What the researchers didn't know was whether the pit led to something larger below. Two narrow surface depressions called sinuous rilles, which scientists think represent collapsed portions of lava tubes, stretch away from the pit. Could the pit be a skylight opening to an intact lava tube's long, narrow passage?

Ancient basaltic lava flows called maria cover much of the Moon, similar to the much younger Columbia River basalts in the western United States. Because the Moon's gravity is one sixth that of Earth's, gravity doesn't impede lava flow as much, allowing lava to spread widely across the surface. Nonetheless, lunar lava tubes may have formed in an Earth-like way, Haruyama said.

If humans ever got access to the tubes, "the science would be amazing."



NASA/GSFC/Arizona State University

The Marius Hills pit on the Moon, spotted in 2009 by scientists at the Japan Aerospace Exploration Agency. The pit stretches 65 meters across and could be a skylight leading down to a lava tube, the scientists say.

Last year, another team spotted gravity anomalies that suggested hollow, narrow spaces around the Marius Hills pit. These data came from NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission, which consists of two spacecraft orbiting the Moon. The orbiters can detect these anomalies by measuring how much the Moon's gravity tugs on them. Areas of more mass tug on the spacecraft more, whereas hollow areas have less mass and so tug on GRAIL less.

To confirm GRAIL's findings, Haruyama and his colleagues turned again to SELENE's data, looking closer at the sinuous rilles. They specifically looked at data from SELENE's Lunar Radar Sounder (LRS), which imaged the subsurface using low-frequency radio waves.

The LRS data revealed hollow space more than 100 meters deep in some places and tens of kilometers long underneath one of the rilles near the pit. The pit itself looked to be 50 meters deep. These data led researchers to believe that the pit could, indeed, be a collapsed portion of a lava tube roof. These data also match the gravity readings from GRAIL, Haruyama said.

Exploring the Tubes

If humans, via rover or their own two feet, ever got access to the tubes, "the science would be amazing," said Brent Garry, a geophysicist at NASA Goddard Space Flight Center. The tube's interior tempts with pristine surfaces, absent of lunar soil or bombardment by micrometeorites, he said. These surfaces could offer answers to questions about the Moon's origin and formation.

In another LPSC presentation on 22 March, Garry described a way to closely explore these tubes, using lidar. On Earth, scientists use lidar scanners to map both land and the ocean floor. More recently, they have started using lidar to map Earth's many cave systems.

Over the past 2 years, Garry and his team used a lidar scanner to map the inside of a lava tube at Craters of the Moon National Monument and Preserve in Idaho. The park is named for the otherworldly feel of its basaltic lava flows. Apollo astronauts even studied the geology of the park before ever stepping on its namesake.

Lidar scanners work by pinging their surroundings with beams of laser light and measuring the time it takes for the light to bounce back. The scanners can take millions of data points every second, allowing for the creation of highly detailed 3-D maps. They also don't depend on sunlight, which could make them useful in a shadowy lunar pit. Garry suggests that lidar would be extremely useful in mapping centimeter- to millimeter-scale features, helping future explorers determine the structure of a lava tube.

How to get the scanner into a tube is another story, one that would involve transportation using a rover, Garry said.

Future of Lunar Exploration

Haruyama and Garry agree that lava tubes could, in theory, shield humans from the Sun's unfiltered radiation and the wide surface temperature fluctuations experienced on the Moon: Temperatures over 1 Moon day (27 Earth days) can range between 123°C and −153°C. In contrast, Earth's average temperature is only about 16°C.

What's more, lunar lava tubes likely have flat floors like those on Earth, easing the way for vehicles or instruments, Haruyama said.

However, long-term human colonies on the Moon likely won't happen in the near—or even far—future. Ben Bussey, chief exploration scientist for the Human Exploration and Operations Mission Directorate at NASA, explained during a NASA town hall meeting at LPSC that NASA's deep-space habitability plans are currently focused on reaching Mars and that "plans don't call for going onto the lunar surface before going to Mars."

But if those plans ever change, at least we know we might have a place to crash—figuratively, at least.

By **JoAnna Wendel** (@JoAnnaScience), Staff Writer

Study Finds That Coastal Wetlands Excel at Storing Carbon

Bethany Augliere

Mangroves currently cover 14–15 million hectares around the world but are steadily disappearing. These coastal forests trap an estimated 31–34 billion kilograms of carbon every year, making them carbon storage powerhouses.

As humans continually add carbon dioxide to the atmosphere, getting rid of the excess greenhouse gas has become a priority. Scientists are searching for new ways to remove carbon from the atmosphere and put it into long-term lockdown.

The ocean's ability to soak up carbon like a sponge is well known, but researchers are now taking a fresh look at ocean shores. Our planet has about 620,000 kilometers of coastline, long enough to wrap around Earth about 15 times.

In a recent paper in *Frontiers in Ecology and the Environment* (http://bit.ly/Environ2017), researchers analyzed multiple ways in which nature captures carbon in marine ecosystems, a reservoir known as blue carbon. They found that coastal mangroves, seagrasses, and tidal marshes, or coastal blue carbon, provided particularly effective and long-lasting carbon storage.

The 2015 Paris Agreement has intensified pressure on nations that signed the pact to meet carbon goals and find better ways to sequester carbon. There are many solutions, but deciding which is most effective—oceans, forests, mangroves, or kelp farming, for example—can be daunting. In addition, many studies use different timescales or measurements, further muddying carbon storage comparisons.

"The goal of the paper was to try and compare apples to apples," said Jennifer Howard, lead author of the paper and marine climate change director at Conservation International in Arlington, Va. On 1 February, she and her colleagues published their detailed report online, which compares carbon storage by coastal blue carbon ecosystems with storage by algae and marine animals.

Carbon Storage Powerhouses

Plants take carbon out of the atmosphere, storing it in leaves, roots, and branches. On land, when vegetation falls to the ground, the bits break down quickly, releasing carbon back into the atmosphere. Not so in coastal wetlands. There, Howard explained, tidally driven

Jack Flanagan, CC BY 2.0 (http://bit.ly/ccby2-0)

A tidal marsh on the East Coast of the United States. Recent research found that mangrove forests, seagrasses, and salt marshes like this one, which are the three main types of coastal blue carbon ecosystems, trap and store carbon more effectively than other marine ecosystems.

salt water saturates soil twice a day in mangrove forests and tidal marshes and continuously in seagrass ecosystems, which are perpetually submerged. Saltwater inundation inhibits the microbial breakdown of plant debris, trapping it in the soil. The authors note that 50% to 90% of coastal blue carbon storage occurs in the soil, not the plants. "You can still see intact leaves 3 meters down," Howard said. "The carbon is stable."

Vegetation trapped in coastal blue carbon soils can be meters thick and hundreds of years old. By contrast, kelp, which also grows in coastal forests, lacks the extensive root systems that collect debris and sediment that become carbon-rich soils typical of coastal wetlands. Living kelp plants trap carbon for only a short time because of their relatively short life spans.

Howard said that kelp and other organisms that trap carbon—phytoplankton, corals, and fish—are always discussed at international meetings. She and her colleagues scoured recent research on the abilities of those organisms and coastal wetlands to hold carbon. They consolidated the findings and used the same units of measurement and timescales to compare coastal blue carbon to other ecosystems like phytoplankton and kelp. Howard notes that although all ocean ecosystems are important, coastal blue carbon is the standout, not only in how long it can retain carbon but also in how much it can trap.

Manageable Natural Storage

The study confirms that "these [coastal blue carbon systems] are hot spots for carbon storage," said Patrick Megonigal, associate director of research at the Smithsonian Environmental Research Center in Edgewater, Md.; he was not an author of the study. In addition, those coastal ecosystems have the ability to be managed to preserve and extend their boundaries and therefore their impact on carbon emissions, Megonigal noted. How readily ecosystems respond to human management strongly affects their value in climate mitigation, he said.

The study found that annually, coastal mangroves, tidal marshes, and seagrasses each trap and store 2 to 35 times more carbon than ocean phytoplankton. The large range results from the challenges in mapping these ecosystems. Coastal blue carbon areas are often identified using remote sensing, which takes satellite scans of Earth and divides the surface into pixelated blocks. In those images, "it's very hard to distinguish a marsh from a field and sometimes even bare ground," said Megonigal. "It's partly a matter of [needing] higher-resolution data," he said.

Fifty percent of the world's mangrove forests have vanished over the past 50 years.

Mapping by remote sensing is next to impossible for seagrasses because they live underwater. "Most people would be surprised that we don't know where they are," said Howard. "We rely on awesome remote sensing, but it only gets you so far with water" in the way.

Blue Carbon Benefits

The researchers noted that nations counterbalancing their emissions by fostering coastal blue carbon ecosystems could also get other benefits. These ecosystems help strengthen biodiversity, tourism, fisheries, and storm protection.

According to the Blue Carbon Initiative, a global program focused currently on coastal ecosystems as a bulwark against climate change, 50% of the world's mangrove forests have vanished over the past 50 years. The mangrove disappearance allows the trapped, thick, blue carbon soils to be washed away, releasing carbon back into the system. It also eliminates storm buffering, leaving communities much more vulnerable to harsh weather. Managing and restoring mangroves helps offset carbon emissions while providing valuable habitat, ecosystem health, and land conservation.

Coastal blue carbon systems are also adaptable to sea level fluctuations, as long as the changes aren't too fast. "They can build themselves up over time, increasing soil height," said Howard.

Howard noted that 150 countries that signed on to the Paris Agreement have coastal wetlands, but only 29 are currently talking about coastal mitigation. Now that the new study is out, she hopes it will awaken greater interest in that option. "If countries knew how big a sink [coastal blue carbon] is," Howard said, "they might be excited."

By **Sarah Derouin** (email: sarah.derouin@gmail.com), Science Communication Program Graduate Student, University of California, Santa Cruz

Scientists Witness Glacial Outburst Flood Near Mount Everest

Bidhya Sharma

A glacial outburst flood from Lhotse Glacier on 12 June 2016 threatens a stone wall adjacent to the village of Chukhung, Nepal.

The black water, heavy with debris, came tumbling apparently out of nowhere, gushing over the rocky terrain and pushing boulders around like toys.

This torrent, known as a glacial outburst flood, forms when water stored deep within a glacier is released without warning. A team of scientists witnessed this rare event firsthand as one spilled down the Lhotse Glacier near Mount Everest on 12 June 2016.

Their view, captured on video, affords researchers and the public an up close look at the mechanics of a glacial outburst flood. “All of our studying was suddenly brought into focus, and revised, as we witnessed this event,” said Elizabeth Byers, a hydrologist at the consulting firm Appalachian Ecology in West Virginia and a member of the team. The team published its scientific findings and video in a communication brief in February in *The Cryosphere* (http://bit.ly/CryoGOF2017).

“Glacial outburst floods are widespread, but observations of them are rare, especially by scientists,” said Mark Carey, a glacier researcher at the University of Oregon not involved in the study. “This firsthand assessment illuminates more details about how floods work.”

Racing Downhill

In 2016, a team of American researchers was working in Nepal near Imja Lake, one of the region’s largest glacial lakes. They were collaborating with local communities to improve awareness of glacial lake outburst floods, a perennial danger for those downstream of Imja Lake and its notoriously unstable moraine dam. On the morning of 12 June, some of the scientists were doing fieldwork near Lhotse Glacier, an avalanche-fed glacier that originates at the peak of Lhotse, the fourth-highest mountain in the world.

Byers remembers hearing what sounded like a rockfall. She then saw a “black tongue of water, boulders, and silt” racing downhill toward the village of Chukhung. She grabbed her camera and shot the video.

“I have never experienced such adrenaline,” Byers said. “I felt powerless to help people…and at the same time experienced utter fascination at the geologic process unfolding before my eyes.”

The glacial outburst flood that Byers and her colleagues witnessed slowly subsided over the next hour. But the trail below the researchers had been washed away, and the only route to Chukhung was over the glacier itself, crossing an ice bridge with water still moving rapidly below it, Byers recalled.

The scientists hurried over the ice bridge and down into Chukhung. They found that all of the villagers were accounted for and that the community had lost only one outhouse. The large rock wall that the community had built 1 year earlier—using donations from the scientists after Nepal’s devastating 2015 earthquake—had held. “It was twisted in some places but was enough to keep the floodwaters from destroying the village,” said Byers.

The scientists later estimated that more than 2 million cubic meters of water—enough to fill the Empire State Building twice—had been released in the flood.

Hidden Deep Within

Although the scientists were in Nepal to better understand floods from glacial lakes, the glacial outburst flood—in which the water spilled not from a lake but from within the glacier itself—provided them with an important opportunity to examine flow patterns from sudden events. Beginning on 14 June, the researchers returned to Lhotse Glacier to do fieldwork and reconstruct the path of the floodwater.

The scientists measured and photographed the terrain and found sinkholes, ponds, uprooted alpine shrubs, and wet sediments, all signs of recent flooding. They also examined satellite imagery of Lhotse Glacier taken in May and noted 274 ponds atop the ice. By measuring the ponds’ areas in the images and using a known relation between pond area and volume, the scientists were able to estimate the total volume of all of the visible bodies of water.

Assuming that all of the ponds had drained completely, their total volume would be only about 20% of the estimated flood volume, the researchers calculated. Thus, “a significant amount of the floodwater was stored in the glacier’s subsurface,” the authors wrote.

Ice like Swiss Cheese

Within a glacier, water travels in conduits, which can be as large as several meters across. Swiss cheese is “a very good analogy” to explain a glacier’s interior structure, said David Rounce, a glaciologist at the University of Texas at Austin and a member of the research team.

Sometimes those conduits can become blocked by ice or debris such as sand and boulders. When sufficient water pressure builds up behind the natural dam to cause it to burst, the torrent that’s released can be substantial, like the flooding that the team observed in June.

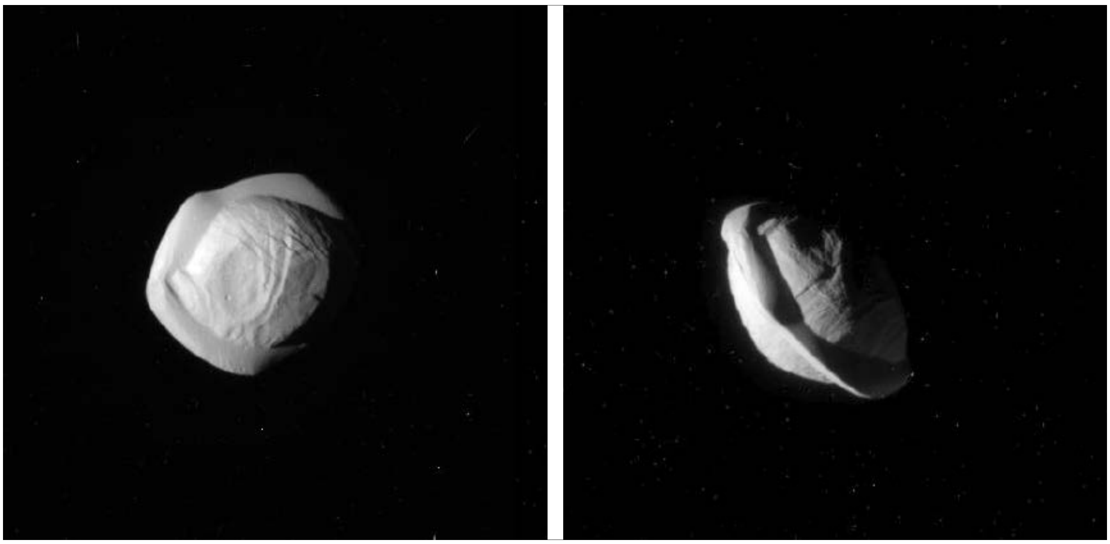
“These floods are particularly difficult to prepare for because there is often no visual evidence of their threat,” said Duncan Quincey, a glaciologist at the University of Leeds who reviewed the paper.

No one can predict when another glacial outburst flood might strike, but team members will have their cameras ready on future field campaigns. “It’s possible that we’ll witness another one,” said Rounce.

By **Katherine Kornei** (email: hobbies4kk@gmail.com; @katherinekornei), Freelance Science Journalist

To see a video of the glacial outburst flood at Lhotse Glacier, visit http://bit.ly/Eos_Flood.

Images of Pan, Saturn’s Ravioli Moon, in Unprecedented Detail



NASA/JPL-Caltech/Space Science Institute

(Left) A newly released raw image of Pan, one of Saturn’s innermost moons, showing a polar view. (right) Another raw image of Saturn’s moon Pan, with its bulging equator at an angle. The ridge is material along Pan’s equator. The new, detailed images have a resolution of 150 meters; Pan itself is 35 kilometers wide.

It’s a flying saucer! No, a celestial empanada! Or space ravioli? Nope—the weird raw images released by NASA’s Jet Propulsion Laboratory on 9 March feature Saturn’s tiny moon Pan and its equatorial fringe in unprecedented detail.

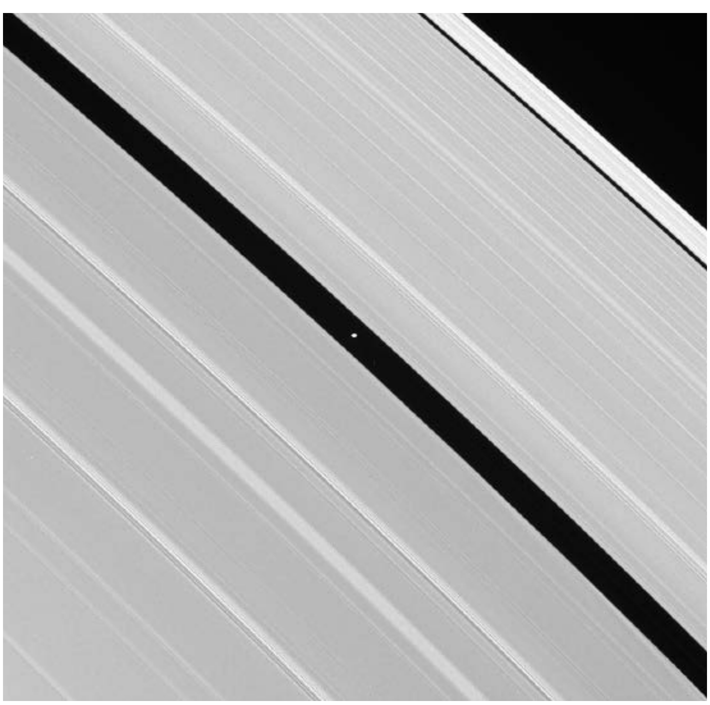
The Cassini spacecraft, which has been orbiting Saturn since 2004, will crash into Saturn later this year. But its final descent brings the spacecraft closer than ever to Saturn’s rings and offers scientists a wealth of new research opportunities.

This is because the spacecraft has entered its “ring grazing orbits,” Carolyn Porco, leader of the imaging science team for Cassini and current visiting scholar at the University of California, Berkeley, told *Eos.* Throughout its orbit around Saturn’s poles, Cassini passes Saturn’s equator and is now “just skimming the outer portion of the rings,” she continued.

This close orbit allows the spacecraft to take close-up pictures of moons like Pan, which orbits Saturn at a distance of 134,000 kilometers. The new images of the 35-kilometer-wide moon feature a resolution as fine as 150 meters.

“It’s just startling. The detail is startling,” Porco said of the new images.

Scientists have known about Pan’s tutu-shaped waistline for a long time. Ten years ago, Porco and her team published two papers describing how the bulge could have formed. From computer models, the researchers suspect that as the moon coalesced, material from Saturn’s rings fell onto the tiny moon’s equator and built up its disklike silhouette.



NASA/JPL-Caltech/Space Science Institute

Can you spot Pan? It’s the tiny, bright dot in the middle of the Encke Gap, in Saturn’s A ring. For millions of years, Pan has been gathering material onto its surface and kicking material out of its way to form the 325-kilometer-wide gap.

Over millions of years, Pan blazed a trail through Saturn’s A ring, clearing what’s now known as the Encke Gap. The influx of material onto Pan’s equator has decreased but likely continues to some degree to this day, which is why the bulging belt itself looks smoother than the rest of the moon, Porco noted.

“Aside from just the sheer joy of seeing something so alien at such a level of detail,” the images will be helpful to scientists studying small moons, asteroids, or comets, Porco continued. Studying Pan will be particularly helpful when scientists think about how material builds up on a small body that has very weak gravity.

So images like these have “an extension beyond the Saturn system,” she said.

You can see more raw images of Pan at http://bit.ly/SaturnRaw2017.

By **JoAnna Wendel** (@JoAnnaScience), Staff Writer

Kilimanjaro's Iconic Snows Mapped in Three Dimensions

In 1936, Ernest Hemingway described the top of Kilimanjaro as being "as wide as all the world, great, high, and unbelievably white in the sun." However, the mountain's ice cap has been shrinking in recent decades because of warming temperatures, and only fragments of it remain today.

In new observations of those fragments, researchers have revealed the thickness and volume of Kilimanjaro's largest remaining ice field with ground-penetrating radar. Several previous studies documenting the retreat of Kilimanjaro's ice used aerial imaging that showed changes in only two dimensions.

Using ground-penetrating radar, "you basically see straight down into the glacier," said physicist Pascal Bohleber of the Institute for Interdisciplinary Mountain Research of the Austrian Academy of Sciences in Innsbruck, who led the team that brought ground-penetrating radar to Kilimanjaro's nearly 6000 meter high summit for the first time. "It's like an X-ray of the glacier."

In addition to providing a new perspective on the vanishing ice, periodic radar measurements of the mountain's ice in three dimensions could enhance scientists' understanding of how the remaining ice fields are changing, Bohleber said.

Carried Up, Up, Up

Although researchers regularly use ground-penetrating radar to peer inside glaciers, "it's never really been done on Kilimanjaro," Bohleber told *Eos*. That's largely because of Kilimanjaro's relative isolation, he explained. "In the Alps, we can fly the equipment in [using a helicopter]." But finding a helicopter and pilot able to fly above 5000 meters in eastern Tanzania isn't easy, he said, so "everything has to be carried on the back of a porter up the mountain."

In September 2015, after receiving funding from the National Geographic Global Exploration Fund, Bohleber and four other scientists met at Kilimanjaro International Airport. They drove to Kilimanjaro National Park and then hiked the Umbwe trail up the mountain's flanks. Roughly 45 porters accompanied the scientists, carrying the group's equipment, which included ground-penetrating radar antennas and receivers, batteries, solar panels and chargers, and laptops.

After 6 days of climbing through progressively thinner air and sleeping in tents each night, the group reached the broad slope of Kilimanjaro's summit and set up camp near one edge of the Northern Ice Field, the largest remaining ice field atop Kilimanjaro. Bohleber brushes off the difficulties he and his colleagues encountered, which included unexpected delays and altitude sickness. "You're so focused on work up there that you hardly think about anything else," he said.

A Peek Inside

Ground-penetrating radar emits radio waves that travel down through the ice, bounce off internal structures or the bed of loose, silty sand below, and return to the receiver. Using the known speed of radio waves through glacial ice, researchers can then calculate the depths at which those reflections occurred and map out the size and shape of the glacier.

Over the course of 3 days, Bohleber and his colleagues obtained thousands of measurements while dragging their radar equipment over the surface of the Northern Ice Field. The team then calculated the depth of the bed below the ice at many different locations and extrapolated the data to create a map of ice depth. They found that the ice ranged in thickness from roughly 6 to 54 meters, with the thickest section running along a ridge oriented roughly east–west, the researchers reported on 9 February in *The Cryosphere* (http://bit.ly/Cryo2017).

The team confirmed the accuracy of their ground-penetrating radar measurements using a simple, low-tech test: They showed that the depth calculated along ice cliffs at one edge of the ice field was consistent with the depth measured by hanging a rope off the same edge.

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Mount Kilimanjaro.

Tracking the Loss

"This study provides a strong complement to previous airborne, satellite, modeling, and ice core studies of the Kilimanjaro ice fields," said Kimberly Casey, a glaciologist affiliated with NASA Goddard Space Flight Center and the U.S. Geological Survey who was not involved in the study.

In fact, by comparing their new map of ice depth with data from ice cores sampled by other researchers in 2000, Bohleber and his colleagues found that the ice

Doug Hardy, UMass Geosciences

This cliff face along an edge of Mount Kilimanjaro's Northern Ice Field reveals orderly horizontal layering of the glacier's ice

field had fallen in height by an average of 6 meters over 15 years. Other glaciers at lower elevations on Kilimanjaro have decreased in height even more substantially, said Bohleber.

Using their depth measurements and the known extent of the ice, the team calculated the total ice volume of the Northern Ice Field to be roughly 12 million cubic meters. That's enough ice to fill all of Manhattan's Central Park to a depth of 4 meters. This volume estimate is useful for monitoring ice loss, said Bohleber.

An Edge Below the Ice

Besides shedding light on the depth of Kilimanjaro's ice, the new measurements also revealed the topography of the underlying sandy bed. Kilimanjaro is a dormant volcano, and the team detected an edge of one of its crater rims below the ice.

"We're measuring what the bed topography looks like," said Bohleber. That's an improvement over previous studies, which simply assumed that the bed was flat, he explained.

The team also demonstrated that the layering of ice within the Northern Ice Field was very regular and horizontal. "At least for the upper 30 meters in the central plateau area, it's like a layered cake," said Bohleber. That discovery means that ice samples from the Northern Ice Field's exposed walls are representative of its interior, good news for scientists who are studying the ice structure from the outside.

Bohleber and his colleagues are looking forward to using their methods to trace the evolution of the Northern Ice Field in three dimensions. He said his team hopes to take measurements on the summit again in a couple of years to create a new three-dimensional map. Comparing it with the current one would help the researchers track the rate of ice loss in detail, he explained.

By **Katherine Kornei** (email: hobbies4kk@gmail.com; @katherinekornei), Freelance Science Journalist

Cities Smarten Up and Go Green

CIENS Urban Conference 2016: Smart and Green Cities—For Whom?
Oslo, Norway, 13 October 2016

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Rooftop gardens, like the one shown here atop Chicago's City Hall, can improve urban water management while providing additional green spaces for residents. Participants at a meeting in Oslo, Norway, discussed the societal implications of such "smart and green" urban development that aims to reduce sprawl, shorten commutes, and use space efficiently.

According to the United Nations, two thirds of the world's population will live in cities by 2030. As cities around the world expand, they are pursuing smart and green development to reduce sprawl, shorten long commutes and their associated pollution, and use space efficiently. Smart cities use information and communication technologies to enhance the use of urban infrastructures.

In October 2016, the Oslo Centre for Interdisciplinary Environmental and Social Research (CIENS) invited participants to a 1-day conference in Norway (http://bit.ly/SmartGreenCities2016). Approximately 80 attendees, including urban planners and entrepreneurs, participated in discussions of the societal potential for and implications of smart and green urban development trends. Strategies like green-blue infrastructure—that is, vegetation aligned with urban water bodies—have proven to have a positive impact on human health, contribute to good urban water management, and ameliorate the negative consequences of climate change by absorbing excess rainwater runoff or providing a cooling effect during warm periods.

The conference was structured around four topics:

- the potential of smart and green cities, including concepts and strategies for development;
- sociotechnical and infrastructural changes necessary for smart and green city development;
- societal impacts and challenges of smart and green city development; and
- city case studies and shared experiences.

Several presentations showed the potential of innovation and technological change for urban sustainability. Conference participants learned about modeling approaches to assess social, economic, and ecological implications of future urban developments. Participants also discussed indicators of feasibility, such as political support or perceived benefits of smart and green developments, along with how to recognize them. Such indicators can be used to help guide development decisions.

The presentations featured case studies of cities currently working to become greener and smarter but also drew attention to some of the challenges associated with smart city development. Here are four examples, both good and bad, that stand out.

Amsterdam, Netherlands: The city cooperates with research institutes under the umbrella of the Amsterdam Institute for Advanced Metropolitan Solutions to develop tailored solutions to become a circular, connected, and vital city.

Stockholm, Sweden: A former industrial site, Hammarby Sjöstad, is about to be converted into an ecocity district. A development of 140,000 new homes will take into account future climate change, biodiversity, and ecological values in addition to property developers' interests. Technical, building, mobility, communication, and green-blue infrastructure issues were considered in an integrated way.

Stakeholder collaboration is evident in the innovative vacuum waste suction system at the site, which collects and sorts waste more effectively than traditional waste systems. The system incinerates nonreusable waste, providing locally generated heat and electricity. At the same time, the system helps to prevent local air pollution, as garbage trucks are rendered obsolete.

Trondheim, Norway: Not all development progresses smoothly. Attendees discussed how in Trondheim, officials granted developers permission to erect a several-story-high building adjacent to one equipped with solar panel walls, considerably reducing electricity production. Smart and green development requires cross-sectoral communication and collaboration, and when communication breaks down, smart development falters.

India: In 2016, the central government launched a smart cities mission aimed at developing 100 sustainable and citizen-friendly satellite towns to foster the urban transition to sustainability. The mission agenda addresses adequate water and electricity supply, sanitation and waste management, efficient urban mobility and affordable housing, urban safety and security, health, education, and sustainable management of the environment, as well as robust Internet access and public participation via e-governance.

The conference was funded by CIENS and the Research Council of Norway (grant 261528).

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Using Archives of Past Floods to Estimate Future Flood Hazards

Cross Community Workshop on Past Flood Variability
Grenoble, France, 27–30 June 2016

Uta Löser

Floodwaters in the Elbe River reached an all-time high in August 2002, inundating this street in Dresden, Germany, and requiring the evacuation of as many as 33,000 residents. Last June, the Floods Working Group of the Past Global Changes project hosted a workshop to address the urgent need for better assessments of flood hazards by systematically using evidence from past floods.

Worldwide, floods cause greater economic damage and loss of human life than any other type of natural disaster. We urgently need better assessments of flood hazards to reduce the societal impact of extreme floods caused by Earth's rapidly changing climate, among other factors.

One way of assessing flood hazards is to examine past floods using the records provided by hydrological instruments. We can extend this knowledge back through the Holocene or beyond using historical documents and natural archives (including alluvial, marine, and lake sediments; tree rings; and cave formations). These extended records can provide valuable information about long-term flood trends.

To promote the systematic use of paleoflood evidence, the Floods Working Group of the Past Global Changes (PAGES) project organized the first interdisciplinary workshop on past flood variability. The meeting brought together geologists, geographers, historians, meteorologists, climatologists, statisticians, and hydrologists who investigate past flood events globally. The workshop aimed to coordinate further efforts to share disciplinary experiences, promote interdisciplinary collaborations, and integrate results and analysis. In all, 46 researchers from 16 countries attended.

Despite the wealth of flood archive data, it is still challenging to compare different data sets or integrate these data into risk assessments.

The workshop held three sessions that focused on a review of available flood archives for the reconstruction of flood occurrence and magnitude, an assessment of multiarchive flood approaches for more precise and complete regional flood assessments, and a consideration of statistical and modeling tools that can be applied to flood reconstruction and identifying potential forcing mechanisms that include climate and land use change.

The workshop highlighted the wealth of existing flood archive data, which span daily to millennial timescales. Despite the wealth of data, it is still challenging to compare different flood archive data sets or integrate these data into risk assessments. Some geographic areas, particularly Africa, Central and South America, and southern Asia, are underrepresented.

At the meeting, the PAGES Floods Working Group agreed to create a joint database collecting all flood archive information to encourage systematic use of paleoflood indicators. A joint database will help handle different flood archives with different resolutions. It will also facilitate the development of hydrological and statistical tools to analyze floods from a multiarchive data set.

In addition, the Floods Working Group identified the need to further involve climate modelers, hydrologists, and risk managers to improve understanding of the physical processes controlling the occurrence and magnitude of floods. Attendees agreed that these scientific collaborations and synergies could help contribute to the present debate about climate drivers and the human impact on flood generation. The use of climate and hydrological modeling is critical to testing climate-flood relationships suggested by interpretations derived from paleoflood archives.

Within the next 3 years, the PAGES Floods Working Group will foster further collaborations among scientists from different archive communities and identify key questions for the broader flood community. The focus will emphasize the exchange of experiences with the use of data about past floods; archive-specific methodological aspects; and the advantages, challenges, and limitations of each archive.

Researchers interested in joining the Floods Working Group are encouraged to visit its website (http://bit.ly/PAGES-floods). Video recordings of the workshop presentations are available online at the meeting website (http://bit.ly/floods-workshop).

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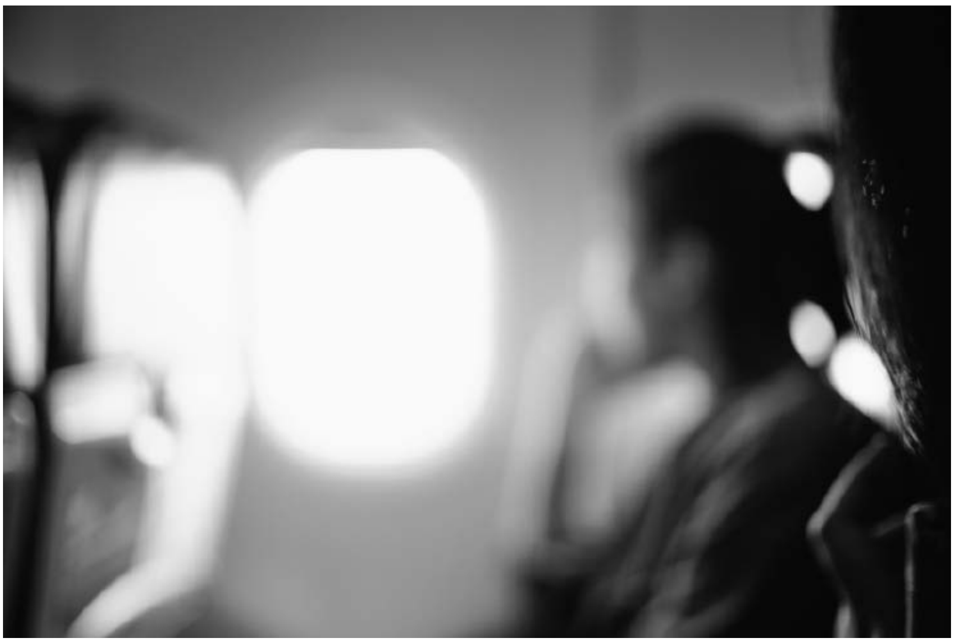
Airline Flight Paths over the Unmapped Ocean



nateemee/iStock.com

Most airline passengers have no idea how little of the ocean floor beneath them has been mapped.

March marked 3 years since Malaysia Airlines flight MH370 disappeared, and no trace of it on the seafloor has yet been found. MH370 is believed to have deviated from its intended flight path. Yet even the typical routes taken by overseas flights are often over unknown seafloor.

In fact, of the total over-ocean distance covered by all unique overseas flight routes, 60% is above unmapped areas. The quality of mapping that does exist varies widely, and the lack of data and variance in quality hinder searches for missing aircraft, hazard assessments, and the pursuit of baseline scientific knowledge. A modest effort could fix this lack of data.

Uneven Coverage

Only a small percentage of Earth's seafloor has been mapped [*Copley*, 2014; *U.S. National Ocean Service*, 2014]. For example, *Smith and Marks* [2014] reported that only 5% of the southeastern Indian Ocean seafloor had been covered by echo soundings on 8 March 2014, when Malaysia Airlines flight MH370 went missing.

In mid-2014, the MH370 search area was moved to an area where data coverage was only 1% at the time the aircraft was lost. In January 2017, the search was suspended after 120,000 square kilometers had been mapped in efforts to find the aircraft. This is roughly one third of the area shown in Figure 1 and 0.0336% of the area of Earth's ocean floor.

In contrast, 86% of the eastern Mediterranean seafloor is mapped in the region where EgyptAir flight MS804 crashed on 19 May 2016, and 30% of the equatorial Atlantic is mapped where Air France flight AF447 fell on 1 June 2009. Comparing these three search regions at the same scale shows that ocean mapping varies enormously from region to region (Figure 2). The AF447 search region also illustrates the strong bias toward mapping of mid-ocean ridges at the expense of other areas [*Smith*, 1998].

Following the Airplanes

To illustrate the extent of ocean mapping under aviation routes, we compiled a list of these routes using data from the Open Flights project on GitHub (http://openflights.org/). These data list the originating and terminating airports of regularly scheduled commercial flights and whether the service is nonstop.

The actual path taken by any particular flight is determined as air traffic controllers direct each flight to a sequence of waypoints and may change as weather and traffic loads change. We did not have this level of detail, so we approximated flight routes as great circles connecting the originating and terminating airports. Because the Open Flights data do not indicate the locations of intermediate stops, we analyzed only nonstop routes.

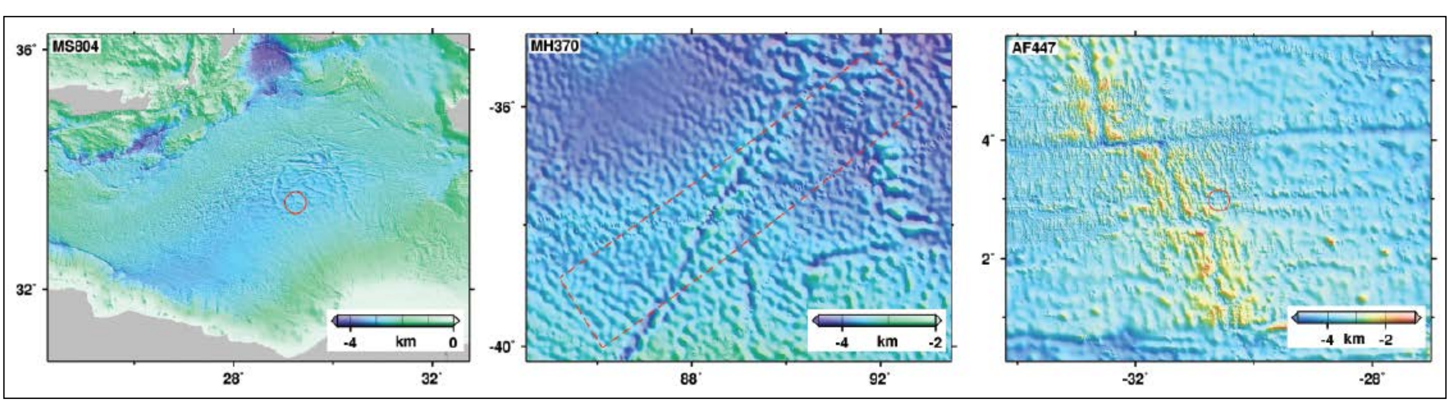


Fig. 1. Shaded relief images of the seafloor terrain in 800- × 600-kilometer regions containing the search areas for (left to right) EgyptAir flight MS804, Malaysia Airlines flight MH370, and Air France flight AF447. Approximate search areas are outlined in red. Seafloor terrain models are from EMODnet Bathymetry Consortium *[2016] and* Weatherall et al. *[2015]. Note the variances in search area, seafloor resolution, and ship tracks over the search area.*

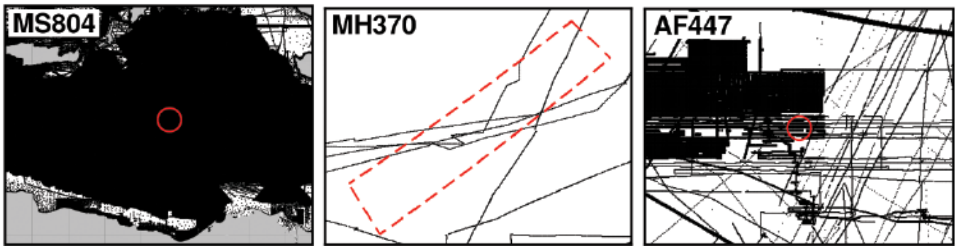


Fig. 2. Depth measurements available at the time of the EgyptAir flight MS804, Malaysia Airlines flight MH370, and Air France flight AF447 crashes (black dots).

Some pairs of airports (e.g., New York's John F. Kennedy and London's Heathrow) are served by many airlines flying many flights in each direction, but our analysis used each unique pair of airports only once, regardless of the frequency of flights between its airports.

We generated a great circle route connecting each airport pair, sampled that route every 1 kilometer of distance along its path, and then classified each sample point as being over mapped ocean, over unmapped ocean, or not over ocean. We found that the total distance along any individual route includes as many as 9201 kilometers flown over unmapped ocean (Figure 3, top). Half of all over-ocean routes fly more than 200 kilometers over unmapped ocean, and 10% of the over-ocean routes fly more than 2000 kilometers over unmapped ocean. The longest contiguous unmapped ocean segment along any one route (Figure 3, middle) is 2293 kilometers, traveled when flying between New York's Kennedy and Beijing's Chongqing Jiangbei airports. More than 20% of routes have a longest unmapped segment exceeding 200 kilometers. On most routes, more than half of the over-ocean portion is over unmapped ocean (Figure 3, bottom).

We found a total of 19,024 unique nonstop routes. Of these, 11,665 fly at least 1 kilometer over ocean, and 10,686 fly at least 1 kilometer over unmapped ocean. The total route distance is slightly more than 33.4 million kilometers, 33% of which is over ocean, with 60% of the total over-ocean distance being over unmapped ocean. These numbers do not indicate the probability that an aircraft or a passenger is over unmapped ocean because our analysis is unable to account for the number of aircraft and passengers flying each route over a given period of time.

Our Criteria

An analysis like our airline route survey has to define how many depth readings it takes to list an area as mapped. Depth measurements that can be readily obtained and used without specialized access, licensing, or payment, which we call "available" data, are quite variable in their sampling density and in the age, technology, and accuracy of the sounding and navigation systems used. All these variations are irregularly distributed over the globe [*Smith*, 1993; *Wessel and Chandler*, 2011].

We divided the global seafloor area into equal-area square tiles 1 nautical mile on a side and considered any tile mapped if it contained one or more available echo soundings. For context, modern hull-mounted multibeam echo sounders (MBES) map a swath of the ocean along the ship's path, but the vast majority of available data (95% of coverage by area) are point values—one depth measurement at one place, typically an analog measurement made by a wireline or a single-beam acoustic sounder [*Smith*, 1993].

Our method produces a generous overestimate, with some tiles having only one sounding. In addition, the majority of available data are poorly navigated and error prone [*Smith*, 1993; *Wessel and Chandler*, 2011]. Even by this generous definition, however, only 8% of the global ocean is mapped [*Wessel and Chandler*, 2011, Figure 8].

In the 92% of ocean area where depth has not been measured, satellite altimetry interpolates the gaps between available soundings [*Smith and Sandwell*, 1997; *Becker et al.*, 2009; *Weatherall et al.*, 2015]. This approximation strongly underestimates seafloor topography and roughness [*Becker and Sandwell*, 2008], with a variety of consequences that affect sciences, from earthquake and tsunami hazard assessment [*Mofjeld et al.*, 2004] to ocean circulation [*Gille et al.*, 2004] and mixing [*Kunze and Llewellyn Smith*, 2004] and climate forecasts [*Jayne et al.*, 2004].

Addressing the Data Shortage

All of Earth's ocean floors deeper than 500 meters (i.e., exclusive of territorial waters and continental shelves) could be mapped by GPS-navigated MBES for 200 ship-years of effort (e.g., 40 ships working for 5 years), at a total cost of $2–3 billion [*Carron et al.*, 2001]. According to the NASA scientists we consulted, this is less than the cost of NASA's next mission to Europa.

We hope that our survey of the state of ocean mapping from the perspective of over-ocean flight routes makes the relevance of ocean mapping and the current lack of mapping information clear to the public.

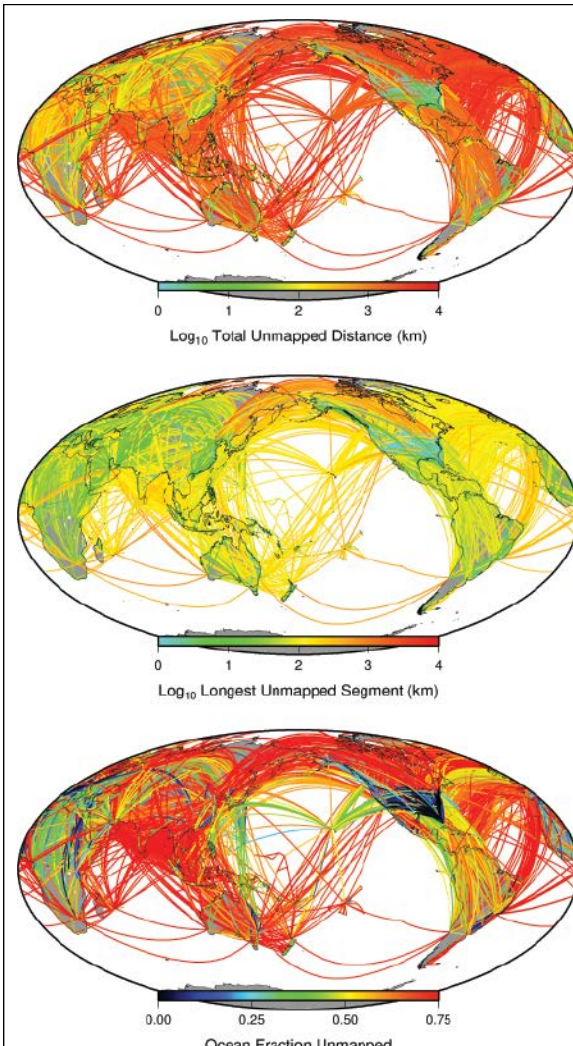


Fig. 3. Great circle routes of commercial airline flights, showing (top) total distance along each route that is over unmapped ocean, (middle) the longest segment of any route that is over unmapped ocean, and (bottom) the relative fraction of each route that is over unmapped ocean (ratio of total unmapped ocean distance to total ocean distance).

All of Earth's ocean floors deeper than 500 meters could be mapped at a total cost of $2–3 billion.

Acknowledgments

Comments by two anonymous reviewers improved the manuscript. The views expressed here are solely those of the authors and do not constitute a statement of policy, decision, or position on behalf of the National Oceanic and Atmospheric Administration or Service Hydrographique et Oceanographique de la Marine or the U.S. or French governments.

References

Becker, J. J., and D. T. Sandwell (2008), Global estimates of seafloor slope from single-beam ship soundings, *J. Geophys. Res., 113,* C05028, https://doi.org/10.1029/2006JC003879.

Becker, J. J., et al. (2009), Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30PLUS, *Mar. Geod., 32*(4), 355–371, https://doi.org/10.1080/01490410903297766.

Carron, M. J., P. R. Vogt, and W.-Y. Jung (2001), A proposed international long-term project to systematically map the world's ocean floors from beach to trench: GOMaP (Global Ocean Mapping Program), *Int. Hydrogr. Rev., 2*(3), 49–55.

Copley, J. (2014), Just how little do we know about the ocean floor?, *Sci. Am.,* 9 October 2014, http://www.scientificamerican.com/article/just-how-little-do-we-know-about-the-ocean-floor/.

EMODnet Bathymetry Consortium (2016), EMODnet digital bathymetry (DTM), http://doi.org/10.12770/c7b53704-999d-4721-b1a3-04ec60c87238.

Gille, S. T., E. J. Metzger, and R. Tokmakian (2004), Seafloor topography and ocean circulation, *Oceanography, 17*(1), 47–54, https://doi.org/10.5670/oceanog.2004.66.

Jayne, S. R., L. C. St. Laurent, and S. T. Gille (2004), Connections between ocean bottom topography and Earth's climate, *Oceanography, 17*(1), 65–74, https://doi.org/10.5670/oceanog.2004.68.

Kunze, E., and S. G. Llewellyn Smith (2004), The role of small-scale topography in turbulent mixing of the global ocean, *Oceanography, 17*(1), 55–64, https://doi.org/10.5670/oceanog.2004.67.

Mofjeld, H. O., et al. (2004), Tsunami scattering and earthquake faults in the deep Pacific Ocean, *Oceanography, 17*(1), 38–46, https://doi.org/10.5670/oceanog.2004.65.

Smith, W. H. F. (1993), On the accuracy of digital bathymetric data, *J. Geophys. Res., 98*(B6), 9591–9603, https://doi.org/10.1029/93JB00716.

Smith, W. H. F. (1998), Seafloor tectonic fabric from satellite altimetry, *Annu. Rev. Earth Planet. Sci., 26,* 697–747, https://doi.org/10.1146/annurev.earth.26.1.697.

Smith, W. H. F., and K. M. Marks (2014), Seafloor in the Malaysia Airlines flight MH370 search area, *Eos Trans. AGU, 95*(21), 173–174, https://doi.org/10.1002/2014EO210001.

Smith, W. H. F., and D. T. Sandwell (1997), Global seafloor topography from satellite altimetry and ship depth soundings, *Science, 277*(5334), 1956–1962, https://doi.org/10.1126/science.277.5334.1956.

U.S. National Ocean Service (2014), How much of the ocean have we explored?, http://oceanservice.noaa.gov/facts/exploration.html.

Weatherall, P., et al. (2015), A new digital bathymetric model of the world's oceans, *Earth Space Sci., 2*(8), 331–345, https://doi.org/10.1002/2015EA000107.

Wessel, P., and M. T. Chandler (2011), The spatial and temporal distribution of marine geophysical surveys, *Acta Geophys., 59*(1), 55–71, https://doi.org/10.2478/s11600-010-0038-1.

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For more on efforts to map the seafloor in the search area for Malaysia Airlines flight MH370, see page 24.

Defining Snow Drought and Why It Matters

On 12 February, water resource managers at the Oroville Dam in California issued an evacuation warning that forced some 180,000 residents to relocate to higher ground. The story of how conditions got to this point involves several factors, but two clearly stand out: the need to prevent water shortages during a record drought, followed by one of the wettest October–February periods in California history.

The situation in winter 2016 at Oroville Dam highlighted difficulties that many reservoir managers face in managing flood risks while simultaneously storing water to mitigate severe droughts and smaller snowpacks. Central to this difficulty is the idea of "snow drought," a term gaining traction in both scientific and lay literature.

Snow drought refers to the combination of general drought and reduced snow storage. However, among references to snow drought, we observe conditions that reflect a lack of winter precipitation or a lack of snow accumulation during near-normal winter precipitation.

These two uses of the term snow drought have different scientific underpinnings and different implications for water supply forecasting and management. To clarify future uses of this terminology, we propose a new classification to differentiate "dry snow drought," due to lack of precipitation, from "warm snow drought," where temperatures prevent precipitation from accumulating on the landscape as a snowpack.

> We propose a new classification to differentiate "dry snow drought" from "warm snow drought."

Here we use snow conditions during winter 2015 on the West Coast of the United States to illustrate the difference. We also show how snow drought, if not properly incorporated into management decisions, can heighten the potential for emergency situations like the one that unfolded at Oroville Dam.

Subtle Definitions with Important Implications

Drought means different things in different contexts. "Meteorological drought" is defined as a period of below-average precipitation. "Hydrological drought" refers to water storages and fluxes falling below long-term averages.

Then there's "anthropogenic drought," the phenomenon of how most projections of future drought include increases in severity and duration that reflect increasing water demand due to warming [*Diffenbaugh et al.*, 2015]. Add to this the emerging term "snow drought," and you now have a fairly complex picture.

Although meteorological droughts remain difficult to predict in the western United States, widespread declines in snowpack have been observed across the region. These declines, which have been attributed to warming air temperatures and related trends, reflect earlier snowmelt and shifts from snow to rain [e.g., *Hamlet et al.*, 2007; *Harpold et al.*, 2012].

Despite decades of research on changing snowpacks, recent extreme lows in snowpacks have revealed the extent of the unique challenges that snow droughts pose for water managers. For scientists and resource managers to plan for challenges to come, they need to be equipped with solid definitions of all forms of drought, snow drought included.

Winter 2015 on the West Coast: A Tale of Two Snow Droughts

The 2015 winter (from November 2014 through March 2015) highlighted two types of snow drought and their challenges for water management in the westernmost United States. The winter was abnormally warm, with temperatures in the Pacific Northwest (Washington, Oregon, and Idaho) averaging 3.0°C above normal and temperatures in the Sierra Nevada (California and Nevada) averaging 3.4°C above normal.

Winter precipitation, on the other hand, varied considerably from north to south, with the Pacific Northwest receiving 70%–120% of its normal precipitation while the Sierra Nevada received only 40%–80% of normal (Figure 1).

Despite large differences in the amounts and timing of winter precipitation, the snow water equivalent (SWE) in both regions was less than average. On 1 April 2015, snowpack contained between about 50% of the water it usually holds in the Pacific Northwest and a startlingly low 5% in the Sierra Nevada (Figure 1).

These low SWE amounts resulted from two distinct drivers of snow drought. Snow drought in the Pacific Northwest reflected a lack of snow accumulation due to warm tem-

Max Whittaker/Getty Images

A snowboarder threads his way through patches of dirt at Squaw Valley Ski Resort on 21 March 2015 in Olympic Valley, Calif.

peratures that increased rainfall and melted snowpacks, despite near-normal precipitation. Snow drought in the Sierra Nevada also reflected similarly warm temperatures but was enhanced beyond the Pacific Northwest's deficits by the lack of winter precipitation.

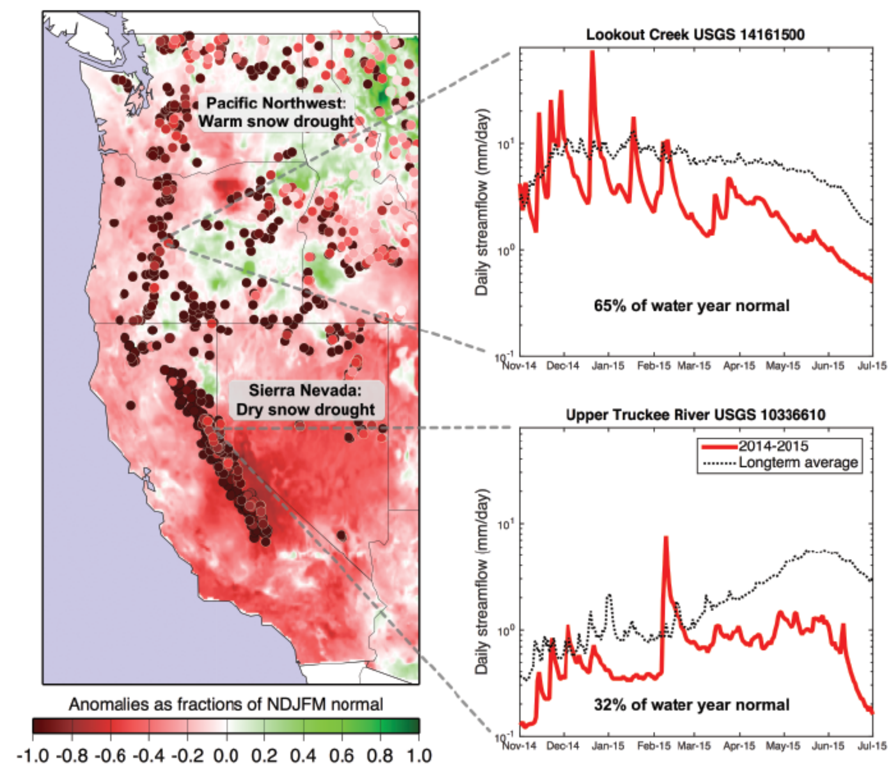
Effects of Winter 2015 on Downstream Water Resources

Streamflow responses to the different snow droughts differed considerably between the regions.

The rainfall that replaced snowfall in the Pacific Northwest yielded large winter peak streamflow events (Figure 1). With most of the water leaving basins in winter rather than during the usual snowmelt season, summer streamflow was far below normal. With less precipitation and warmer temperatures, streamflow in the Sierra Nevada lacked both large winter flows and its usual spring snowmelt pulse and fell to extremely low levels early in the summer.

Streamflow responses generally depend on topography and geology of a given basin but in this case reflect these different snow conditions across both regions. The distinct responses illustrated here have large implications for water management and ecological water availability.

However, the same term, snow drought, was used to describe snow conditions in both regions. A more nuanced definition of snow drought could facilitate discussions of, planning for, and responses to droughts and changing snowpacks.



PRISM, NRCS/CA DWR; USGS

Fig. 1. (left) Precipitation from 1 November 2014 to 31 March 2015 was near normal in the Pacific Northwest and well below normal in the Sierra Nevada (colored map), whereas 1 April 2015 snow water equivalent was below average across the domain (colored dots). (right) These differences in precipitation and snowpack led to starkly different streamflow responses at two characteristic U.S. Geological Survey stream gauges.

Defining and Quantifying Snow Drought

We propose more precise terms to distinguish between the two different snow droughts observed in the Pacific coast states in winter 2015: dry snow drought for precipitation-driven snow drought and warm snow drought for temperature-driven snow lack. Both types of snow drought have SWE that is notably less than normal.

In a warm snow drought, scenarios where SWE is low but precipitation (P) is not (thus a low SWE:P ratio) reflect that a larger than normal amount of precipitation has fallen as rain rather than snow, that an unusual amount of melt has occurred, or both [e.g., *Cooper et al.*, 2016]. If the SWE and precipitation are nearly equal (SWE:P is close to 1) and SWE is below normal, winter precipitation must also be below normal, and the lack of SWE is likely a reflection of low precipitation—a dry snow drought.

The challenge of differentiating dry and warm snow droughts using drought monitoring networks highlights a common weak point: Few drought metrics include storage and release of snow water. For example, the Palmer drought severity index (PDSI) used by the U.S. Drought Monitor treats all precipitation as rain. This simplification means that the PDSI cannot distinguish between warm and dry snow droughts.

Physically based models, such as the North American Land Data Assimilation System (NLDAS) drought monitor, represent accumulating and melting snowpacks, but their results remain spatially coarse and challenging to verify over large areas. Given different effects of warm versus dry snow drought on water-related decision making, drought monitoring needs to better distinguish between the two.

Snow Drought and Water Management

A reservoir manager is faced with balancing the following:

- capturing inflows to reservoirs so that they will still be available for use in the summer
- maintaining enough empty space in reservoirs to capture or ameliorate large flood flows, requiring that large winter flows pass immediately through the reservoirs to maintain extra storage

Snow reservoirs, the water stored in mountain snowpacks, aid both management purposes. Snowpacks are particularly important to western water supplies because they historically persisted into summer when water demand is the highest and prediction of flows is more accurate (being based on snow on the ground rather than on rains to come). The natural reservoirs of water formed by the snowpacks expand the usefulness and reliability of man-made reservoirs by releasing water predictably and closer to times of high demand.

Winter precipitation that falls as rain generates much greater flood risk than when storms deliver snowfall. So most western water management decisions, such as the amount of water to release from a spillway, rely on accurate forecasts of near-term rains and eventual seasonal streamflow amounts, the latter of which depends on the amount of water in the region's "snow reservoirs," which is reduced by snow droughts of either flavor.

In the context of reservoir management, snow drought presents different challenges. During a dry snow drought, streamflows are low, and inflows to reservoirs are reduced all year long. If one knew that such a drought would occur, precipitation and streamflow moving downstream might be captured and stored in dam-impounded reservoirs.

In a warm snow drought, streamflow arrives earlier than normal, but the prospects of a rich spring snowmelt season are limited. Reservoir management is then faced with immediate flood risks followed by subsequent drought conditions.

California and the Case of Oroville Dam

Western water woes are dynamic. To illustrate how quickly fortunes can change, consider the remarkable transition that this past fall and winter brought to California's snowpacks and streamflows after multiple years of drought.

October through December 2016 were very wet months in northern California (with precipitation totals about 170% of normal by 1 January 2017), but because several of the storms were warm rainfall, snowpack in California by 1 January was only 64% of normal (http://bit.ly/snowpacklow). The extra precipitation quickly ran off into impoundments and wetted the landscape. A long string of storms that followed in January and February filled reservoirs, in some cases to the brim.

The early winter snowpack deficits, however, signaled a real possibility that this coming summer might bring a return to drought conditions, as many of the region's reservoirs were still below average following the 2012–2015 drought. So there was a need to impound as much water as possible to provide water during what might be a summer drought.

In the case of Oroville Dam, water managers battled with a reservoir that was beyond capacity but that contained only 46% as much water on the same date in 2015 in the midst of the snow drought described above (and only 30% as much water by September 2015; see http://bit.ly/OroStorage). Not knowing how the winter would play out, California's water managers began storing water during fall rains to buffer against a potential developing snow drought, but instead, they got a record wet winter.

The (Unknown) Hydrological Effects of Snow Drought

The definitions of warm and dry snow drought help to frame science that is fundamental to water management challenges facing snow-dominated regions:

- Which form of snow drought (dry or warm) is likely to dominate in different areas under future climate scenarios?
- How and where can monitoring and management infrastructure be updated to meet the challenges associated with increasing warm or dry snow drought?

Climate models suggest that shifts from mostly dry to increasingly warm snow drought could be a consequence of regional warming [*Pierce and Cayan*, 2013]. However, shifts to warm snow drought are expected to depend unevenly on elevation, moisture sources and transport, and the timing of precipitation.

Thus, retrospective analyses of warm versus dry snow drought are needed to identify areas that have begun to shift from dry to warm (or to warm and dry) snow drought predominance, and networks and sensors for monitoring the full range of snow conditions are critical to better characterizing current and future snow droughts.

Adrian Harpold

Students from the University of Nevada, Reno, learn how to measure streamflow at Sagehen Creek Field Station in California's Sierra Nevada during a small rain-on-snow event in March 2016. Winter rain during drought, or warm snow drought, has different management implications than dry winters, or dry snow drought.

We also need better measurements of what phase (rain or snow) is falling during precipitation events. Mixes of rain and snow from place to place, storm to storm, and year to year are almost always inferred indirectly from temperature or changes in SWE [*Rajagopal and Harpold*, 2016]. But direct knowledge could help water managers manage today and plan for the future.

Another monitoring challenge is the scarcity of precipitation and SWE measurement at the highest elevations. Although emerging snow remote sensing methods are suited for filling in gaps in traditional observation systems, expanding ground-based observations of precipitation, SWE, and phase into higher elevations soon will be critical to developing the long-term records needed to define snow drought and its causes over time [*Dettinger*, 2014].

Concerted efforts by scientists, agency-run monitoring networks, water managers, and policy makers will be needed to address the pending prospects of snow drought and how it fits into decision making. For example, what should water managers do to deal with nearly record-breaking snow droughts and flood years in rapid succession? We have only to look to the reservoir behind Oroville Dam over the past 3 years to see these challenges illustrated in dramatic ways.

In response to changing snowpacks and more extreme droughts, we will need a common but nuanced definition of snow drought to facilitate efforts and better manage our water supplies. With such definitions in hand, we may be better equipped to face future water woes in the West.

References

Cooper, M. G., A. W. Nolin, and M. Safeeq (2016), Testing the recent snow drought as an analog for climate warming sensitivity of Cascades snowpacks, *Environ. Res. Lett., 11*(8), 084009, https://doi.org/10.1088/1748-9326/11/8/084009.

Dettinger, M. (2014), Climate change: Impacts in the third dimension, *Nat. Geosci., 7,* 166–167, https://doi.org/10.1038/ngeo2096.

Diffenbaugh, N. S., D. L. Swain, and D. Touma (2015), Anthropogenic warming has increased drought risk in California, *Proc. Natl. Acad. Sci. U. S. A., 112*(13), 3931–3936, https://doi.org/10.1073/pnas.1422385112.

Hamlet, A. F., P. W. Mote, and M. P. Clark (2007), Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States, *J. Clim., 20*(8), 1468–1486, https://doi.org/10.1175/JCLI4051.1.

Harpold, A., et al. (2012), Changes in snowpack accumulation and ablation in the intermountain west, *Water Resour. Res., 48,* W11501, https://doi.org/10.1029/2012WR011949.

Pierce, D. W., and D. R. Cayan (2013), The uneven response of different snow measures to human-induced climate warming, *J. Clim., 26*(12), 4148–4167, https://doi.org/10.1175/JCLI-D-12-00534.1.

Rajagopal, S., and A. A. Harpold (2016), Testing and improving temperature thresholds for snow and rain prediction in the western United States, *J. Am. Water Resour. Assoc., 52*(5), 1142–1154, https://doi.org/10.1111/1752-1688.12443.

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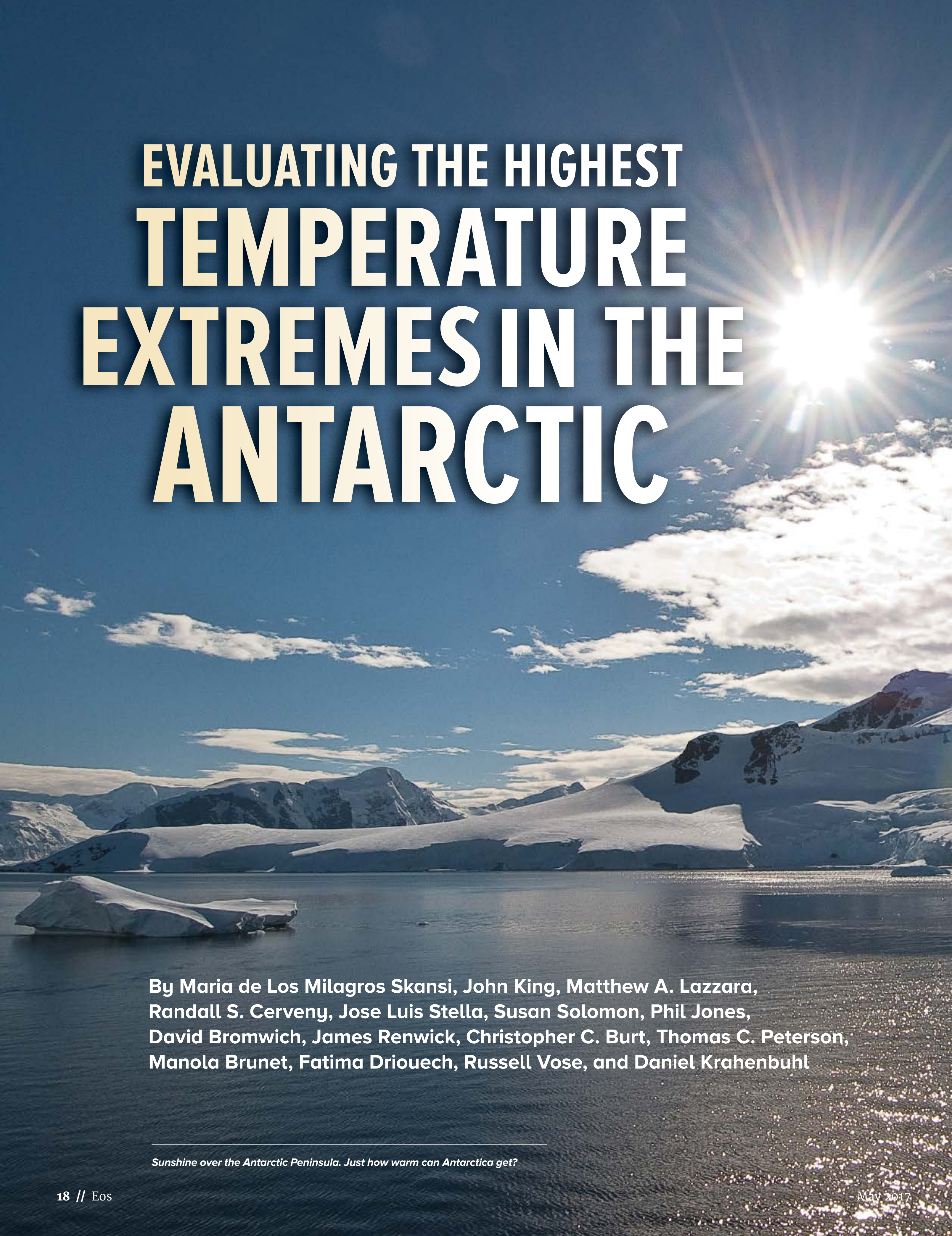
EVALUATING THE HIGHEST TEMPERATURE EXTREMES IN THE ANTARCTIC



By Maria de Los Milagros Skansi, John King, Matthew A. Lazzara, Randall S. Cerveny, Jose Luis Stella, Susan Solomon, Phil Jones, David Bromwich, James Renwick, Christopher C. Burt, Thomas C. Peterson, Manola Brunet, Fatima Driouech, Russell Vose, and Daniel Krahenbuhl

Sunshine over the Antarctic Peninsula. Just how warm can Antarctica get?

On 21 July 1983, the lowest temperature ever recorded on Earth occurred at a Russian research station in central Antarctica: The thermometer at the site read –89.2°C (–128.6°F).

But it's not just the lowest lows that have caught the attention of scientists in the Antarctic. Especially in the face of climate change, researchers have also begun to investigate how warm the planet's southernmost region can get.

Officially investigating, documenting, and verifying such high temperature extremes is the business of the World Meteorological Organization (WMO) Commission for Climatology (CCl). For this purpose, the WMO CCl has created an international evaluation committee of climatologists and meteorologists associated with Antarctic temperature measurements to establish the highest temperature extremes of the region.

Their investigation verified what is, as of now, the current record high: a balmy 19.8°C (67.6°F). This temperature was observed on 30 January 1982 at Signy Research Station at Factory Cove, Borge Bay, on Signy Island. This record, collected with instruments that follow WMO's standards, has now been made public by WMO (http://bit.ly/WMO-Antarctic-Warm).

Also recently made public are two temperature extremes in two distinct climate regimes of Antarctica: its low-lying ice sheet and continent and its high and dry plateau. On the continent, CCl verified that a

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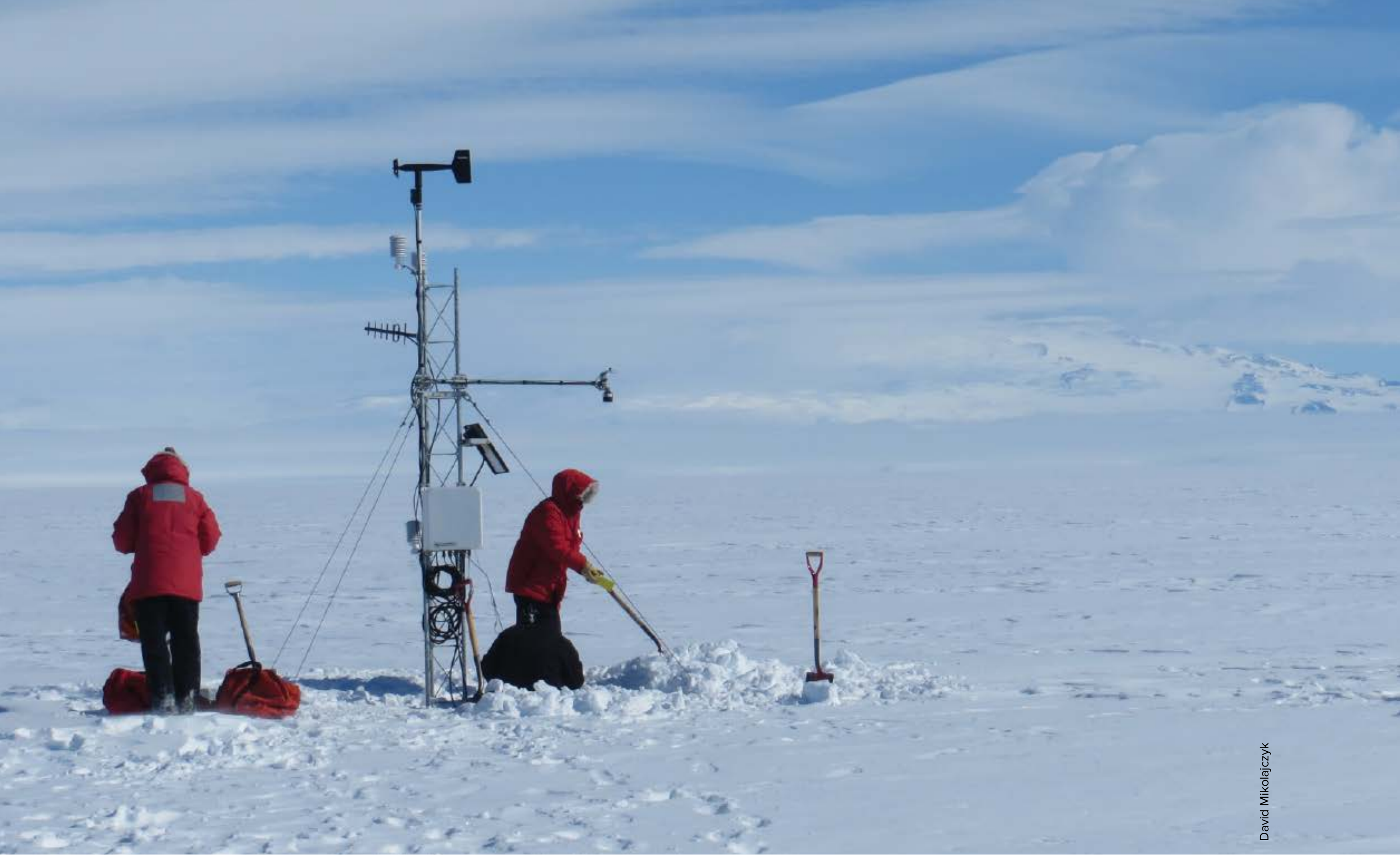

Installation and maintenance of an AWS station in the Antarctic of a type similar to the D-80 AWS, which recorded the highest temperature seen on the Antarctic Plateau (–7.0°C on 28 December 1989).

high-temperature extreme of 17.5°C (63.5°F) occurred on 24 March 2015 at the Argentine research base Esperanza, located near the northern tip of the Antarctic Peninsula. An observation of −7.0°C (19.4°F), made on 28 December 1989 at an automatic weather station (AWS) site, D-80, located inland of the Adélie Coast, has been verified by CCl to be the highest temperature recorded on the Antarctic Plateau.

The committee noted that the extremes at the Signy, Esperanza, and D-80 stations occurred during periods of warm-air advection. At Signy and Esperanza, warming from leeward winds (foehn warming) also contributed, whereas at D-80 solar heating under clear skies at high elevation was a major contributory factor. This investigation highlights the need to continually monitor all of the Antarctic region to ensure that we have the best possible data for climate change analysis at both regional and global scales.

Highest Temperature for the Antarctic Region: 19.8°C, Signy Research Station, 30 January 1982

Knowledge and verification of extreme temperatures are important in the study of global and regional climate change. They are also key in the analysis of observation practices and proper equipment selection. Similar to how WMO has documented extremes for other regions of the world during the past 10 years, an evaluation committee recently finished its examination of record-high extremes for the Antarctic region.

But what exactly is the Antarctic region? The WMO Antarctic temperature extremes committee recommended that "Antarctic region" be defined as "all of the land and ice shelves south of 60°S latitude."

The committee then examined the evidence for establishing the highest temperature of the region as 19.8°C (67.6°F), observed on 30 January 1982 at Signy Research Station (60°43′S, 45°36′W, WMO station 88925) at Factory Cove, Borge Bay. Signy Research Station is situated on the eastern shore of Signy Island (Figure 1). The research station was established in 1947 and operated as a year-round station until 1996, when it was reduced to summer-only operation. Figure 2a shows a photograph of the station in 1967.

At the time of the record observation, the Signy Research Station was operating a very basic climatological observing program. There were no dedicated meteorological observers at the station, and biological research assistants carried out the observations. These assistants carried out full synoptic observation at 09:00 local time (12:00 coordinated universal time (UTC)) every day. In addition, they collected maximum and minimum thermometer readings at 09:00 and 21:00 local time (12:00 and 00:00 UTC, respectively). The station used mercury-in-glass thermometers located in a Stevenson screen shelter. At 12:00 UTC every day, a duty assistant changed the mercury-in-steel distant-reading thermometer that provided a continuous record of temperature on a circular chart.

Between 25 and 27 January 1982, 12:00 UTC temperatures registered just above freezing but rose on and after 28 January. On 30 January the 12:00 UTC temperature read +9.6°C, and the maximum thermometer reading over the previous 12 hours was logged as +19.8°C (67.6°F), a record for Signy Research Station.

Weather Conditions During the High-Temperature Extreme

At the time of the observed record temperature, a trough of low surface pressure lay across Drake Passage, connecting low-pressure centers west of the Antarctic Peninsula and west of southern Chile. Simultaneously, a ridge of high pressure extending southward from the South Atlantic drove a strong northwesterly pattern of circulation in the vicinity of the South Orkney Islands. This can be seen in the European Centre for Medium-Range Weather Forecasts' ERA-Interim reanalysis [*Dee et al.*, 2011], one of the top computer model reconstructions of the weather of the past 150 years (Figure 3a). This flow resulted in the southward movement of warm midlatitude air from the South Atlantic sector.

Although this advection of warm air was almost certainly a necessary condition for achieving these record temperatures, it is likely that local orographic effects also played a role. Signy lies in the lee of Coronation Island when the wind flows from the northwest. The island rises to 1265 meters and may thus cause a significant foehn warming effect. The distant-reading thermometer record shows a rapid increase in temperature around 21:00 local time and a rapid decrease at around 02:30, both of which are characteristic of foehn events.

In addition, the hygrograph record shows two very rapid decreases in humidity on 29 January, the first around 09:00 local time and the second around 21:00, which would support the idea that a foehn effect played an important role. Although the anemograph does not show particularly marked wind speed changes at these times, there is a transition from almost calm conditions to very gusty, moderate winds at around 22:30 local time on 29 January, followed by a dramatic increase in wind speed at around 02:30 local time on 30 January.

Past researchers have noted the importance of the foehn warming in driving Antarctica warm events [e.g., *Elvidge and Renfrew*, 2016; *Cape et al.*, 2015; *Speirs et al.*, 2010]. Consequently, after the committee assessed the station's compliance with WMO standards, as well as foehn occurrence, it unanimously recommended acceptance of this observation as the highest temperature recorded for the Antarctic region.

Defining Subregions

Following the acceptance of the Signy observation of 19.8°C as the highest temperature recorded in the Antarctic region (all lands south of 60°S), the committee addressed the concern that such an acceptance of an island observation measured at 60°43′S does not match the common geographic interpretation of the Antarctic as a single landmass. One important goal of the committee was to improve public education about the Antarctic's quite distinct climatic regimes. Most of the general public is often surprised to learn how mild some parts of the Antarctic can be.

Consequently, the committee recommended two new subregional temperature extremes: (1) the highest temperature recorded on, or immediately adjacent to, the Antarctic continent and (2) the highest temperature recorded at or above 2500 meters (the interior plateau region of the Antarctic).

Highest Temperature on the Continent: 17.5°C, Esperanza Research Base, 24 March 2015

The committee evaluated the evidence for an observation of 17.5°C (63.5°F) made on 24 March 2015 at the Argentine research base Esperanza. If verified, this reading would be the highest temperature recorded on the Antarctic continent.

Esperanza is located near the northern tip of the Antarctic Peninsula just east of the Antarctic Peninsula mountains, which rise to around 1000 meters near this location (Figure 1). This temperature extreme occurred on the day following a reading of 17.4°C (63.3°F) measured at the Argentine research base Marambio, about 100 kilometers southeast of Esperanza, on 23 March 2015.

Temperature observations for Esperanza station (63°24'S, 56°59'W, elevation of 13 meters) began in January 1953 and have continued since. The instrumentation consists of a common (mercury-in-glass) maximum/minimum thermometer that was installed on 3 December 2005 within a pagoda-style naturally vented meteorological shelter. Figure 2b shows a photograph of the instrument shelter in 2016.

ERA reanalysis for this location at the time of the temperature extreme shows a northwest–southeast warm high-pressure ridge stretching from South America to the Antarctic Peninsula in concert with a cold trough of low pressure lying over the far South Pacific near 120°W. Together, these features drove a strong northwesterly circulation that was associated with warm air advection and strong winds perpendicular to the mountain chain in the northern part of the peninsula, conducive to the development of a foehn at Esperanza (Figure 3b).

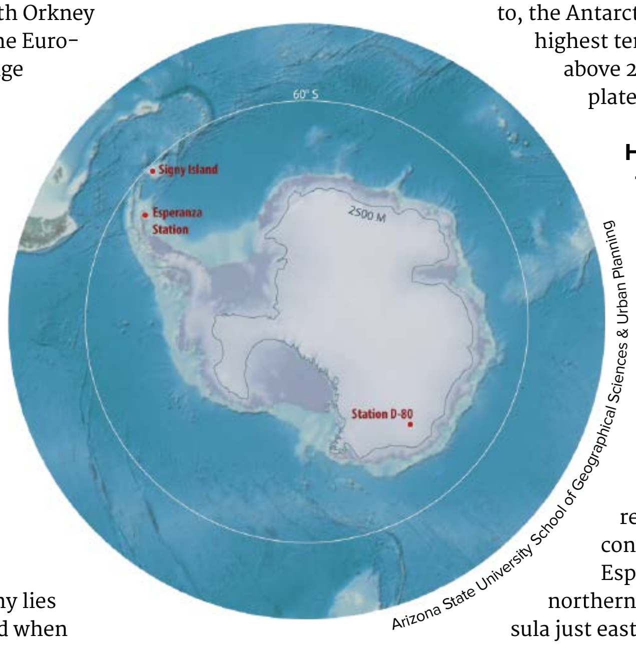

Fig. 1. The area of the United Nations/WMO Antarctic region (all lands and ice south of 60°S) with the 2500-meter elevation delineated (using the digital terrain model of Liu et al. *[2001]). Locations of the three high-temperature extreme stations (Signy, Esperanza, and D-80) are shown.*

WMO

Fig. 2. Photographs of the three stations evaluated for the Antarctic extreme high temperatures. (a) Signy Research Station in 1985 (60°43′S, 45°38′W; the Stevenson screen may be seen behind the station buildings in the extreme right of the picture), (b) Esperanza station in 2016 (63°24′S, 56°59′W), and (c) D-80 AWS in 1993 (70°6′S, 134°53′E).

Consequently, after careful evaluation of the evidence with regard to quality of observation, type and calibration of equipment, and site placement, as well as foehn occurrence, the committee recommended unanimously to accept the observation of 17.5°C (63.5°F) made on 24 March 2015 at the Argentine research base Esperanza as the highest temperature recorded for the Antarctic continent.

Highest Temperature on the Plateau

For the Antarctic Plateau, the committee evaluated the evidence for an observation of −7.0°C (19.4°F) made on 28 December 1989 at D-80 AWS, located in the interior of the Adélie Coast (70°6′S, 134°53′E; see Figure 1). The AWS operated from 14 January 1983 to 1 January 2001 at an elevation of 2500 meters [*Wendler et al.*, 1993]. The temperature was recorded with a Weed platinum resistance thermometer sensor with an accuracy of ±0.5°C. Figure 2c shows a photograph of the station upon installation in 1983.

On 28 December 1989, ERA reanalysis showed that a high-pressure ridge situated west of Tasmania around 130°E over the Southern Ocean channeled warm air southward toward D-80 (Figure 3c). This strong ridge had been persistent over the area for the previous 4 days. The committee noted that at high elevations, insolation under clear skies will warm the air, contributing to the record-high temperature. It was noted that in some cases high insolation can cause spurious warming of the temperature sensor if the sensor is not properly ventilated, but in this situation, the committee concluded that there should have been sufficient ventilation of the sensor.

Given these considerations and after ensuring that data were collected in compliance with WMO standards, the

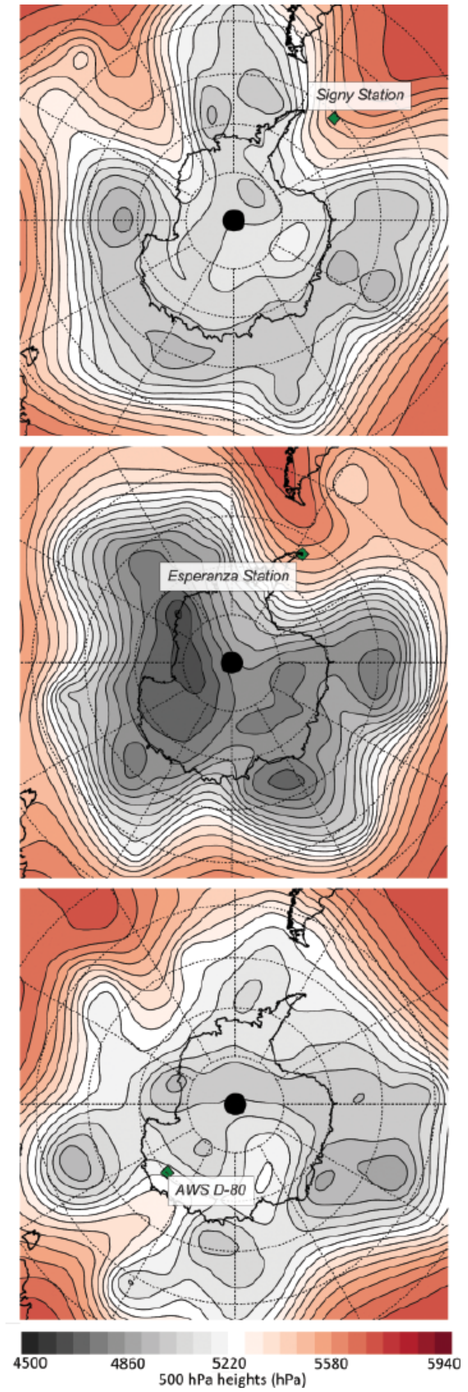

*Fig. 3. The 500-hectopascal height analyses (geopotential meters, analogous to the pressure pattern at around 5 kilometers in altitude, above the highest parts of the Antarctic Plateau) using the ERA-Interim reanalysis [*Dee et al., *2011] for (top) 00:00 UTC, 30 January 1982, when Signy Research Station recorded a maximum temperature of 19.8°C; (middle) 00:00 UTC, 24 March 2015, when Esperanza station recorded a maximum temperature of 17.5°C; and (bottom) 00:00 UTC, 28 December 1989, when D-80 AWS recorded a maximum temperature of −7°C.*

committee recommended unanimously to accept the observation as the highest temperature recorded for the Antarctic Plateau.

Importance of Establishing Antarctic Extremes

As with all WMO evaluations of extremes (e.g., temperature, pressure, wind, etc.), the extremes presented here are the highest observed temperatures placed before the WMO for adjudication that passed WMO's standards for such data. It is possible, indeed, likely, that greater extremes can and have occurred in the Antarctic but have gone unreported.

Temperature extremes in the Antarctic are important to evaluate and document in the face of changing regional and global climate. Only through continual monitoring of the entire Antarctic region can we ensure that we have the best possible data for climate change analysis at both regional and global scales.

Acknowledgments

Meteorological observations at Signy were funded by the U.K. Natural Environment Research Council. The meteorological observations at the D-80 AWS site are based upon work supported by the Division of Polar Programs, National Science Foundation, under grants ANT-1245663 and PLR-1543305. We thank Institut Polaire Français Paul-Emile Victor for its joint support of D-80 AWS. M.B. and P.J. were supported by the European Union–funded project "Uncertainties in Ensembles of Regional Reanalyses" (UERRA, FP7-SPACE-2013-1 project number 607193). M.B. was also funded by the Spanish Ministry of Economy and Competitiveness (MINECO) CGL2014-52901-P grant.

References

Cape, M. R., et al. (2015), Foehn winds link climate-driven warming to ice shelf evolution in Antarctica, *J. Geophys. Res. Atmos., 120,* 11,037–11,057, https://doi.org/10.1002/2015JD023465.

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc., 137,* 553–597, https://doi.org/10.1002/qj.828.

Elvidge, A. D., and I. A. Renfrew (2016), The causes of foehn warming in the lee of mountains, *Bull. Am. Meteorol. Soc., 97*(3), 455–466, https://doi.org/10.1175/BAMS-D-14-00194.1.

Liu, H., et al. (2001), Radarsat Antarctic Mapping Project digital elevation model, version 2, https://nsidc.org/data/docs/daac/nsidc0082_ramp_dem.gd.html, NASA Natl. Snow and Ice Data Cent. Distrib. Act. Arch. Cent., Boulder, Colo. [Accessed 29 August 2016.]

Speirs, J. C., et al. (2010), Foehn winds in the McMurdo Dry Valleys, Antarctica: The origin of extreme warming events, *J. Clim., 23,* 3577–3598, https://doi.org/10.1175/2010JCLI3382.1.

Wendler, G., et al. (1993), Katabatic winds in Adélie Coast, in *Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations, Antarct. Res. Ser.,* vol. 61, edited by D. H. Bromwich and C. R. Stearns, pp. 23–46, AGU, Washington, D. C., https://doi.org/10.1029/AR061p0023.

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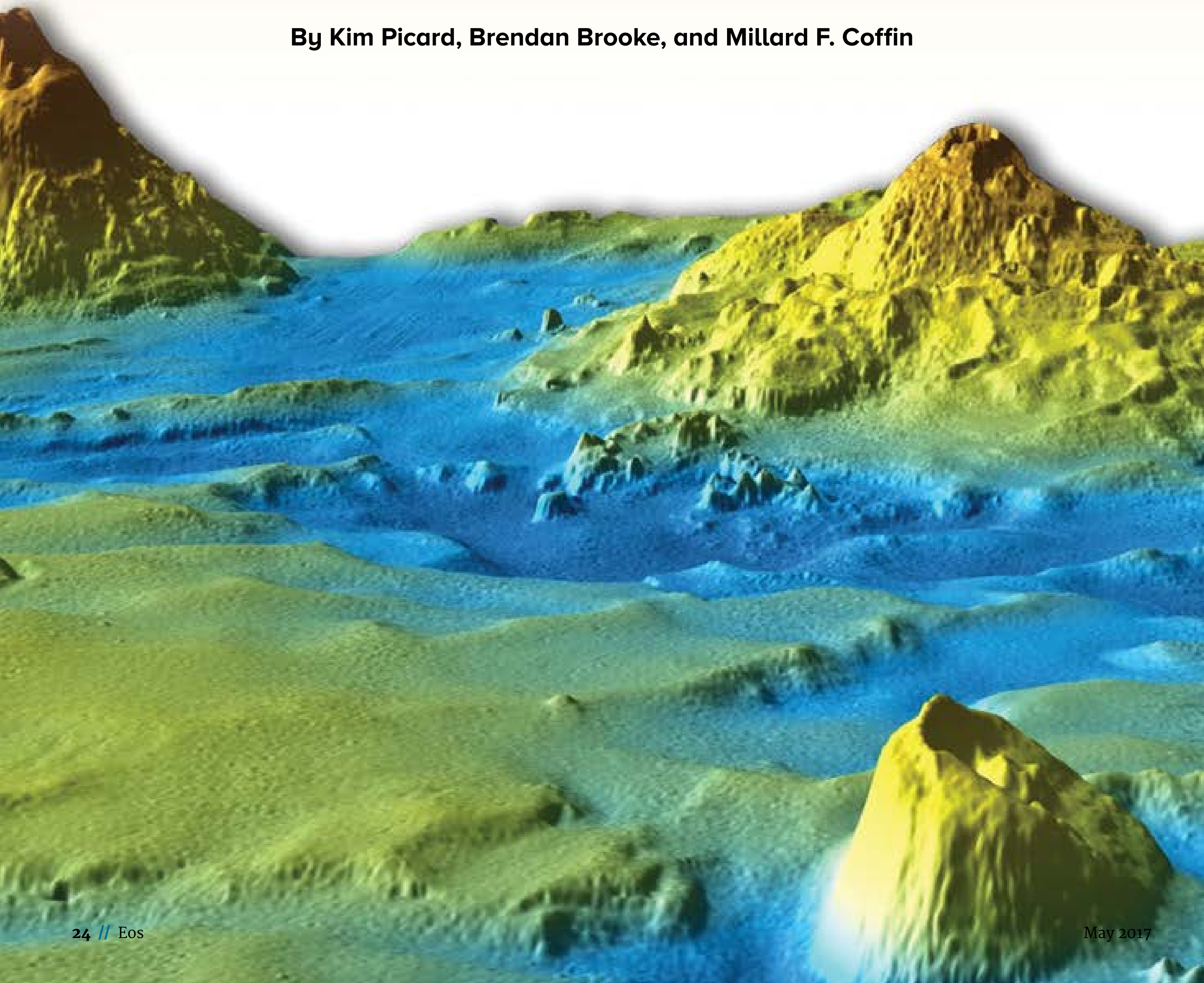
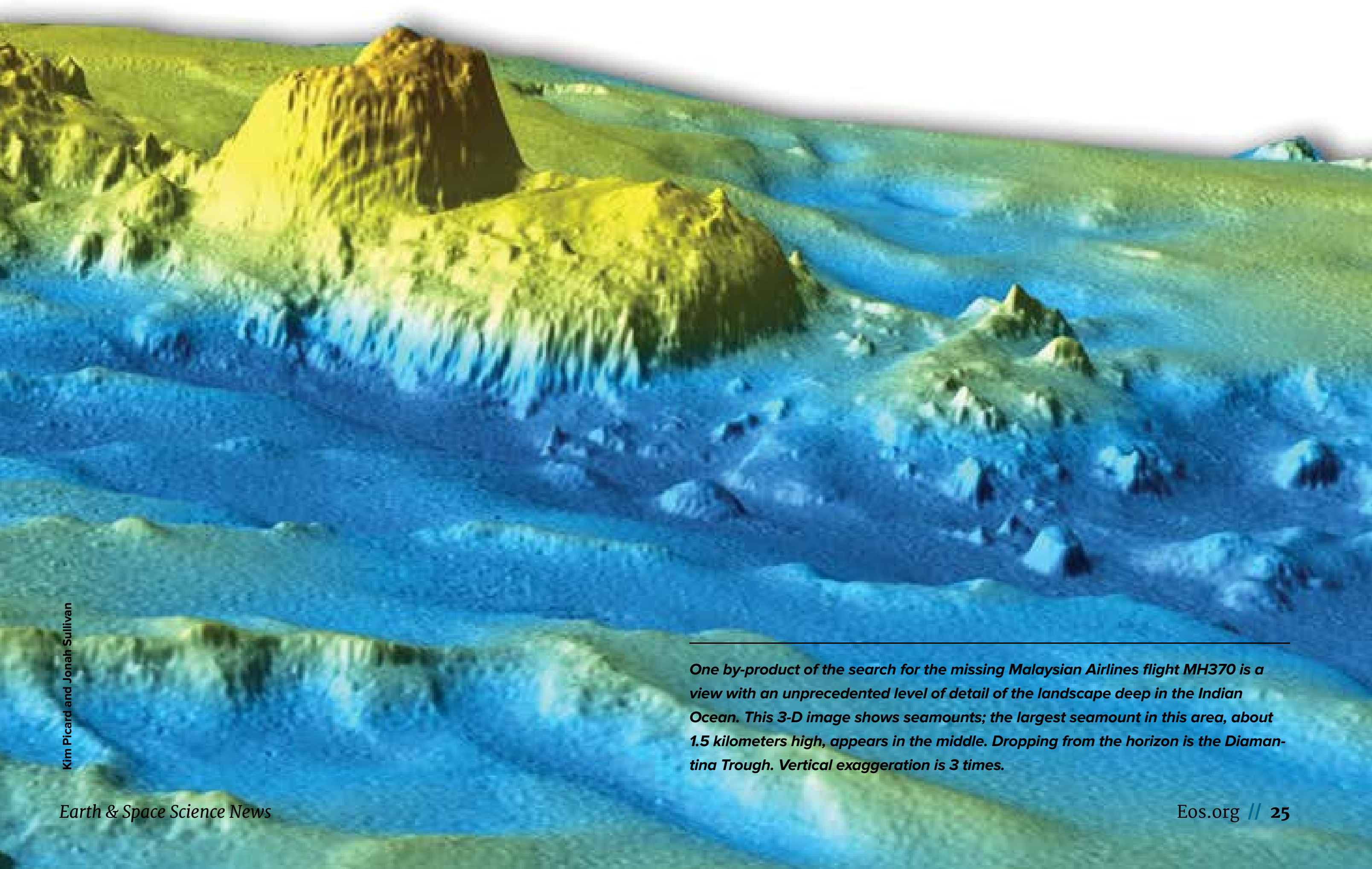
GEOLOGICAL INSIGHTS FROM THE SEARCH FOR MALAYSIA AIRLINES FLIGHT MH370

By Kim Picard, Brendan Brooke, and Millard F. Coffin



The tragic disappearance of Malaysia Airlines flight MH370 on 8 March 2014 led to a deep-ocean search effort of unprecedented scale and detail. Between June 2014 and June 2016, geophysical survey teams aboard ships used echo sounding techniques to create state-of-the-art maps of the seafloor topography and profiles of the sediments below the ocean floor in a zone spanning about 279,000 square kilometers of the southeastern Indian Ocean.

The curved search swath is 75 to 160 kilometers wide, and it sweeps from northeast to southwest. It centers on Broken Ridge and extends



Kim Picard and Jonah Sullivan

One by-product of the search for the missing Malaysian Airlines flight MH370 is a view with an unprecedented level of detail of the landscape deep in the Indian Ocean. This 3-D image shows seamounts; the largest seamount in this area, about 1.5 kilometers high, appears in the middle. Dropping from the horizon is the Diamantina Trough. Vertical exaggeration is 3 times.

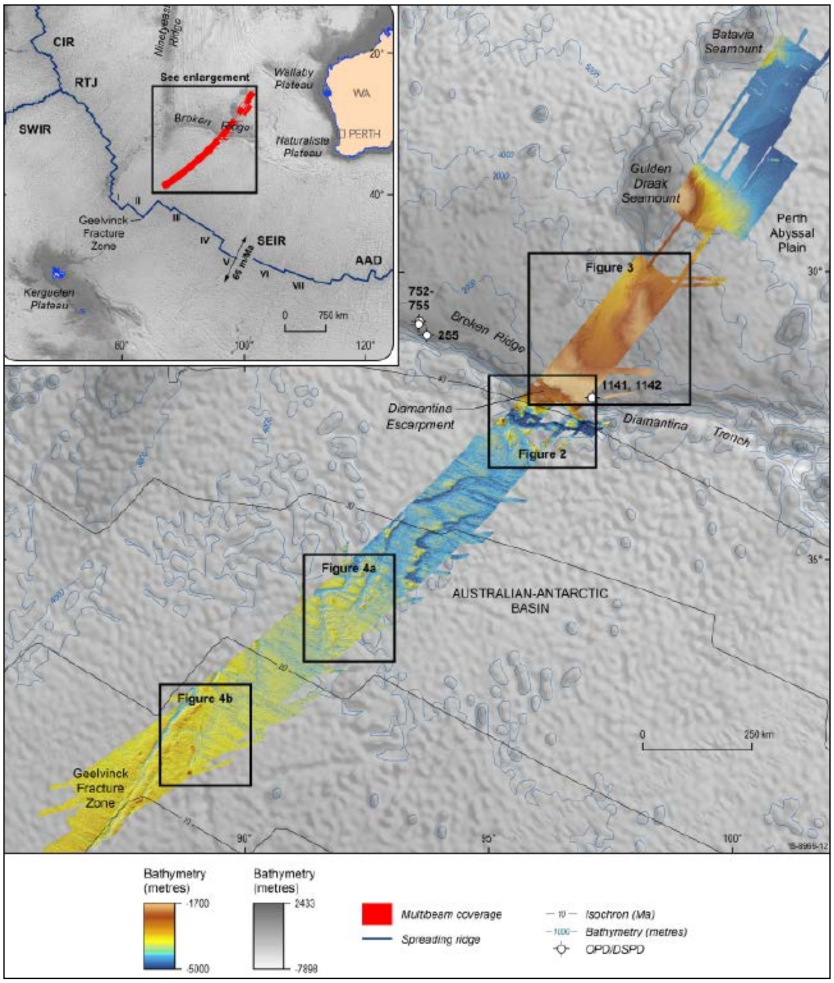


*Fig. 1. Satellite-derived gravity field (gray) [*Sandwell et al.*, 2014] and multibeam echo sounder (color) data were used to produce these maps of the MH370 search area in the southeastern Indian Ocean. The relief models are shown in Sun-illuminated (shaded relief) mode. The inset map shows the MH370 search area that was mapped with multibeam echo sounding (shown in red). This map highlights the Southeast Indian Ridge (SEIR) and the Kerguelen Plateau, and it includes estimated spreading rates of the SEIR [*Argus et al.*, 2011], lines delineating regions of approximately equal age (isochrons) [*Müller et al.*, 2008], and interpretations of SEIR segments (I–VII) [*Small et al.*, 1999]. Other abbreviations are AAD, Australian-Antarctic Discordance; CIR, Central Indian Ridge; RTJ, Rodriguez Triple Junction; SWIR, Southwest Indian Ridge; WA, Western Australia. The larger map shows details of the ocean depth mapping effort using multibeam echo sounder bathymetry data. Locations of Deep Sea Drilling Project (Leg 26) and Ocean Drilling Program (Legs 121 and 183) Sites 255, 752 to 755, 1141, and 1142 are also indicated, as are the locations of Figures 2, 3, and 4. Figure 4 can be found on Eos.org (http://bit.ly/Eos_MH370).*

roughly 2500 kilometers from the eastern flank of Batavia Seamount to the Geelvinck Fracture Zone (Figure 1). Aircraft debris found along the shores of the western Indian Ocean were consistent with drift modeling that indicates that the aircraft entered the sea in the search area (see http://bit.ly/MH370-search).

The data set that emerged from this search effort constitutes the largest high-resolution multibeam echo sounder mapping effort for the Indian Ocean, covering an area about the size of New Zealand. Previous ocean floor maps in this region had an average spatial resolution of more than 5 square kilometers, but the new maps resolve features smaller than 0.01 square kilometer (an area slightly larger than a soccer field). Crucially, the new data provided the geospatial framework for the last phase of the search, in which search teams deployed deepwater, high-resolution acoustic and optical imaging instruments with the ability to identify aircraft wreckage (see http://bit.ly/MH370-bathymetry).

A Sharper Focus on the Ocean Floor

The global ocean covers 71% of Earth's surface, yet the ocean floor remains poorly studied compared with the land surface. In particular, knowledge of ocean floor topography is sparse because light cannot penetrate the deep ocean and acoustic mapping techniques are relatively inefficient in mapping its floor. Most of the ocean floor (85%–90%) has been mapped indirectly using satellite-derived gravity data, which yield a spatial resolution of about 5 kilometers [*Weatherall et al.*, 2015]. By comparison, topographic maps of even the most remote land areas on Earth resolve features approximately 50 meters across, and topographic maps of the Moon, Mars, and Venus resolve 100-meter features [*Copley*, 2014].

Ship-mounted multibeam echo sounders that use sound waves that echo off the ocean floor provide much finer and more accurate topographic data for the deep ocean floor with a spatial resolution (as distinct from a vertical resolution) of at least 100 meters in 5000-meter water depths. However, only 10%–15% of the ocean basins have been mapped using multibeam echo sounders [*Weatherall et al.*, 2015].

This technique also records acoustic backscatter from the ocean floor, which can be used to distinguish between hard rock and soft sediment. Such fundamental spatial information is essential for characterizing the physical features of the ocean floor, for making inferences on geological and oceanographic processes, and for identifying the habitats of species that live on the ocean floor.

A Complex Region

Beyond the continental margins, toward the open sea, the floor of the Indian Ocean is a complex mosaic of normal oceanic crust (not associated with hot spots and other anomalies), submarine plateaus and ridges, seamounts, sea knolls, and microcontinents. Various processes, including seafloor spreading (including ridge jumps), flood and hot spot magmatism, and tectonism, produce a variety of features.

The MH370 search area includes all of the major elements of the mosaic, and it covers water depths between 635 and 6300 meters (Figure 1). The search teams mapped most of the area with a 30-kilohertz multibeam echo sounder system (Kongsberg EM302, M/V *Fugro Equator*), and they

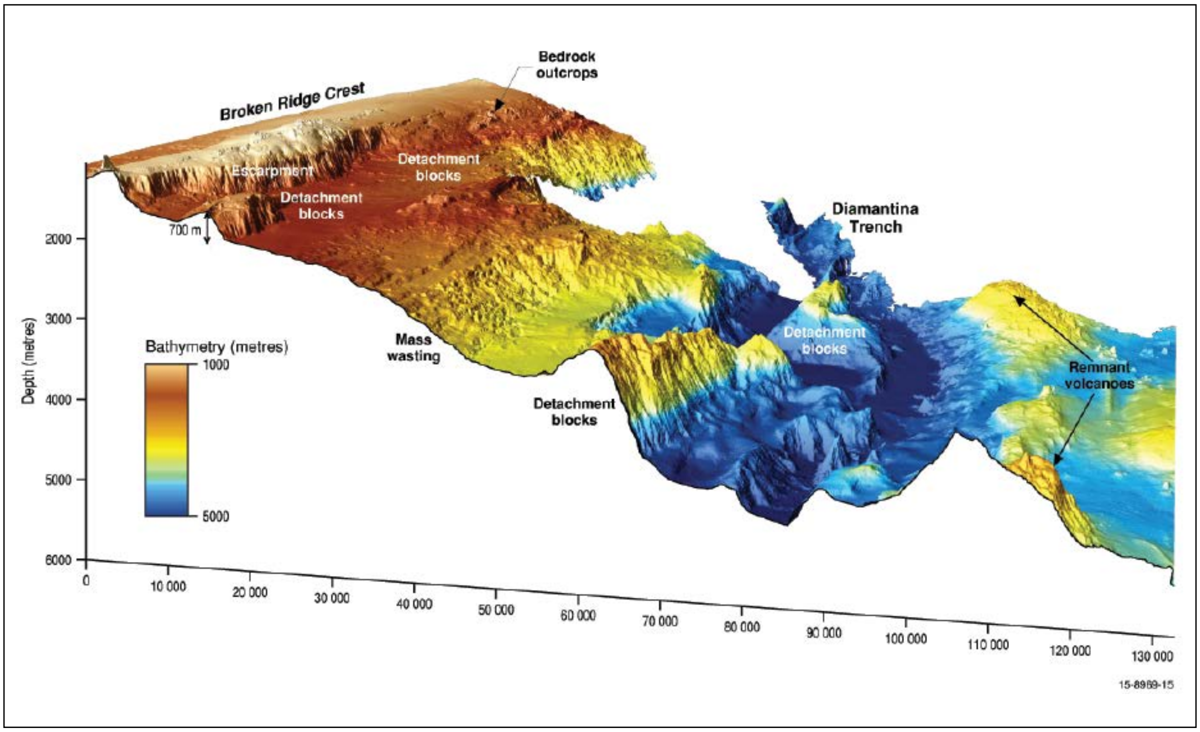


Fig. 2. Three-dimensional model looking east of the rifted southern flank of Broken Ridge (northern part of the rift valley) along the Diamantina Escarpment. Slopes commonly exceed 10°, and they increase to more than 35° along the margins of the Diamantina Trench. Large-scale ocean floor features include escarpments (as much as 1200 meters high), detachment blocks, grabens, and areas of planar floor within the trench as wide as 10 kilometers. High backscatter intensity and angular morphology indicate that bedrock is exposed, in a few places at and near the top of the ridge and on the flank down to depths of about 1350 meters. Parallel west-southwest to east-northeast lineations on some scarps, extending to water depths of about 2400 meters, most likely represent exposed, steeply dipping bedding planes. Mass wasting, a downslope movement of loose rocks and sediment during and after the rifting process, has incised the escarpment, and significant sediment has accumulated in the grabens and at the bottom of the Diamantina Trench (see Figure 1 for location).

mapped much smaller areas with 12-kilohertz systems, which can reach the deeper ocean floor (Kongsberg EM122, M/V *Fugro Supporter*; Reson SeaBat 8150, Chinese PLA Navy ship *Zhu Kezhen*).

Here we highlight three examples from this shipboard multibeam echo sounder data set that are helping to illuminate the geologic development of this portion of the Indian Ocean.

Submarine Plateau Rifting and Breakup

Broken Ridge and the Kerguelen Plateau formed mostly as a contiguous large igneous province in Cretaceous time [*Coffin et al.*, 2000]. They subsequently experienced rifting and were eventually separated by seafloor spreading along the Southeast Indian Ridge (SEIR) 43 million years ago [*Mutter and Cande*, 1983].

The southern flank of Broken Ridge, known as the Diamantina Escarpment, documents the rifting, plunging more than 5100 meters from its crest (638 meters of water depth) into a deep trough (5800 meters of water depth). This rifted flank includes escarpments rising more than 1000 meters above the ocean floor, slopes as steep as 67°, and fault blocks about 12 × 25 kilometers in size and rising more than 1200 meters above their base (Figure 2).

The new multibeam echo sounder data, integrated with preexisting seismic reflection and drilling data, illuminate exposed igneous basement rock, prerift sedimentary sections, and overlying sediment that accumulated on the ocean floor during (hemipelagic sediment) and after (pelagic sediment) rifting.

The morphology and seismic stratigraphy of the Diamantina Escarpment indicate that the mode of rifting resembled an orthogonal rift model, in which faults develop parallel to the axis of spreading. Between the faults, a series of elongated blocks of crustal material, grabens, step down into a deep trough and abut the spreading ridge volcanics [*Karner and Driscoll*, 1993].

Seafloor Erosion

North of its rifted southern flank, Broken Ridge generally has subtle relief, with igneous basement rocks overlain by

For an additional image of seafloor in the search area, view this article on Eos.org: http://bit.ly/Eos_MH370. For more about how much of the seafloor under commercial flight paths remains unmapped, see page 12.

A U.S. Navy helicopter carries supplies from the USNS Cesar Chavez *to the HMAS* Success *in April 2014, during the search in the Indian Ocean for Malaysia Airlines Flight MH370.*

sedimentary rock and pelagic sediment [e.g., *Coffin et al.*, 2000]. In places, slides and debris flows have reworked sediment downslope.

A large depression, about 90 kilometers in diameter and with about 500 meters of relief, lies some 70 kilometers northeast of the crest of Broken Ridge (Figure 3). Numerous crosscutting retrogressive slides (where the collapsing area extends progressively higher up the slope) and debris flows dissect the flanks of the depression, recording episodes of sediment flow, with

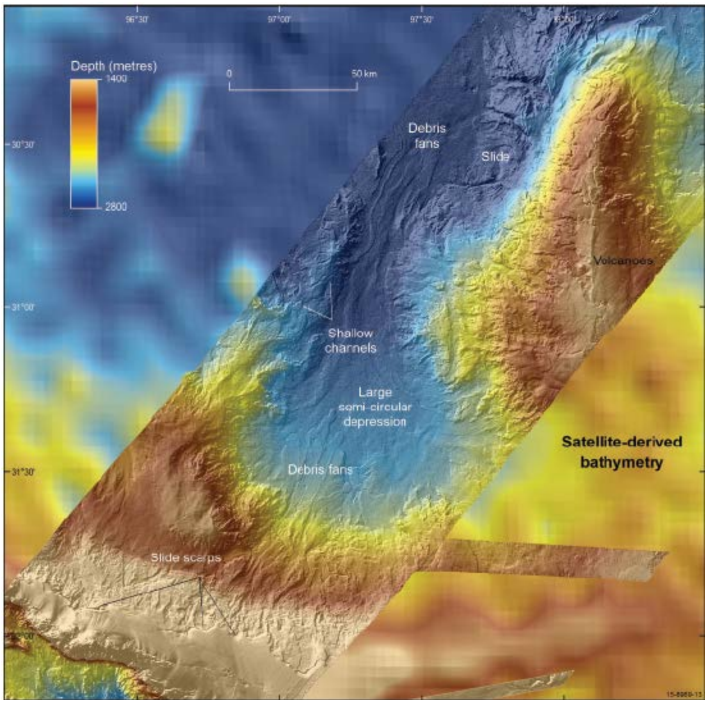


Fig. 3. The differences in resolution between multibeam and satellite-derived bathymetry data for the northern flank of Broken Ridge are apparent here. Numerous mass wasting features are evident, including slides and debris flows (delineated by their head scarps) that crosscut and run out as debris fans into the large semicircular depression (see Figure 1 for location).

slide scarps as much as 180 meters high and 10 kilometers wide and debris fans more than 150 kilometers long.

Tectonic Spreading Fabric

South of Broken Ridge, normal oceanic crust of the Australian-Antarctic Basin has formed along the SEIR at intermediate spreading rates of 59–75 millimeters per year [*Small et al.*, 1999; *Müller et al.*, 2008]. The shipboard multibeam echo sounder data swath traverses a region of crust north of the SEIR that is some 10 million to 40 million years old, obliquely cutting across tectonic seafloor spreading fabric consisting of elongated abyssal ridges and fracture zones (Figure 1).

Oceanic crust in this region, which lies in water depths of 2200 to 5000 meters, is characterized by SEIR and paleo-SEIR segments some 200 to 500 kilometers long (Figure 1) [*Small et al.*, 1999]. In the search area, fracture zone valleys are as much as 900 meters deep and 12 kilometers wide. The abyssal ridges have as much as 200 meters of relief and are more than 70 kilometers long (Figure 4 at http://bit.ly/Eos_MH370).

Discontinuities along the paleo-SEIR not associated with transform faults and more than 150 sea knolls and seamounts are also common. Volcanoes occur in isolation and in chains, forming semiconcentric structures, some as high as 1500 meters, with diameters of about 500 meters to more than 15 kilometers and slopes of about 10° to 30°.

Gaining Useful Knowledge from a Tragic Event

The new multibeam echo sounder data highlight the topographic complexity of the ocean floor and provided a framework for deploying deepwater instruments in the search for MH370 wreckage. The data also reveal details of the tectonic, sedimentary, and volcanic processes that formed this region of the ocean. This effort demonstrates the breadth and depth of knowledge that will be gained as the remaining 85% to 90% of the global ocean is mapped at similar resolution.

Acknowledgments

We thank the Geoscience Australia team, especially Tanya Whiteway and Maggie Tran, for project management; Maggie Tran, Justy Siwabessy, Michele Spinoccia, Jonah Sullivan, and Jonathan Weales for data processing and mapping; and Silvio Mezzomo and David Arnold for the figures. We are thankful for insightful reviews by Scott Nichol and Ron Hackney of Geoscience Austrialia and two anonymous reviewers. The search for MH370 was managed by the Australian Transport Safety Bureau and the Joint Agency Coordination Centre for the Malaysian government. We thank the Fugro Survey Pty. Ltd. team from Perth, Australia, and the masters and crews of M/V *Fugro Equator*, M/V *Fugro Supporter*, and *Zhu Kezhen* for shipboard multibeam echo sounder data acquisition.

References

Argus, D. F., R. G. Gordon, and C. DeMets (2011), Geologically current motion of 56 plates relative to the no net rotation reference frame, *Geochem. Geophys. Geosyst., 12,* Q11001, https://doi.org/10.1029/2011GC003751.

Coffin, M. F., F. A. Frey, and P. J. Wallace (2000), *Proceedings of the Ocean Drilling Program, Initial Reports,* vol. 183, 101 pp., Ocean Drill. Program, College Station, Texas.

Copley, J. T. (2014), Just how little do we know about the ocean floor?, *Conversation,* 9 Oct. 2014, http://theconversation.com/just-how-little-do-we-know-about-the-ocean-floor-32751.

Karner, G. D., and N. W. Driscoll (1993), Rift flank topography and extensional basin architecture: Formation of Broken Ridge, southeast Indian Ocean, *An. Acad. Bras. Cienc., 65,* suppl. 2, 263–294.

Müller, R. D., M. Sdrolias, C. Gaina, and W. R. Roest (2008), Age, spreading rates, and spreading asymmetry of the world's ocean crust, *Geochem. Geophys. Geosyst., 9,* Q04006, https://doi.org/10.1029/2007GC001743.

Mutter, J. C., and S. C. Cande (1983), The early opening between Broken Ridge and the Kerguelen Plateau, *Earth Planet. Sci. Lett., 65,* 369–376, https://doi.org/10.1016/0012-821X(83)90174-7.

Sandwell, D. T., R. D. Müller, and W. H. F. Smith (2014), New global marine gravity model from Cryo-Sat-2 and Jason-1 reveals buried tectonic structure, *Science, 346,* 65–67, https://doi.org/10.1126/science.1258213.

Small, C., J. R. Cochran, J.-C. Sempéré, and D. Christie (1999), The structure and segmentation of the Southeast Indian Ridge, *Mar. Geol., 161,* 1–12, https://doi.org/10.1016/S0025-3227(99)00051-1.

Weatherall, P., K. M. Marks, and M. Jakobsson (2015), A new digital bathymetric model of the world's oceans, *Earth Space Sci., 2,* 331–345, https://doi.org/10.1002/2015EA000107.

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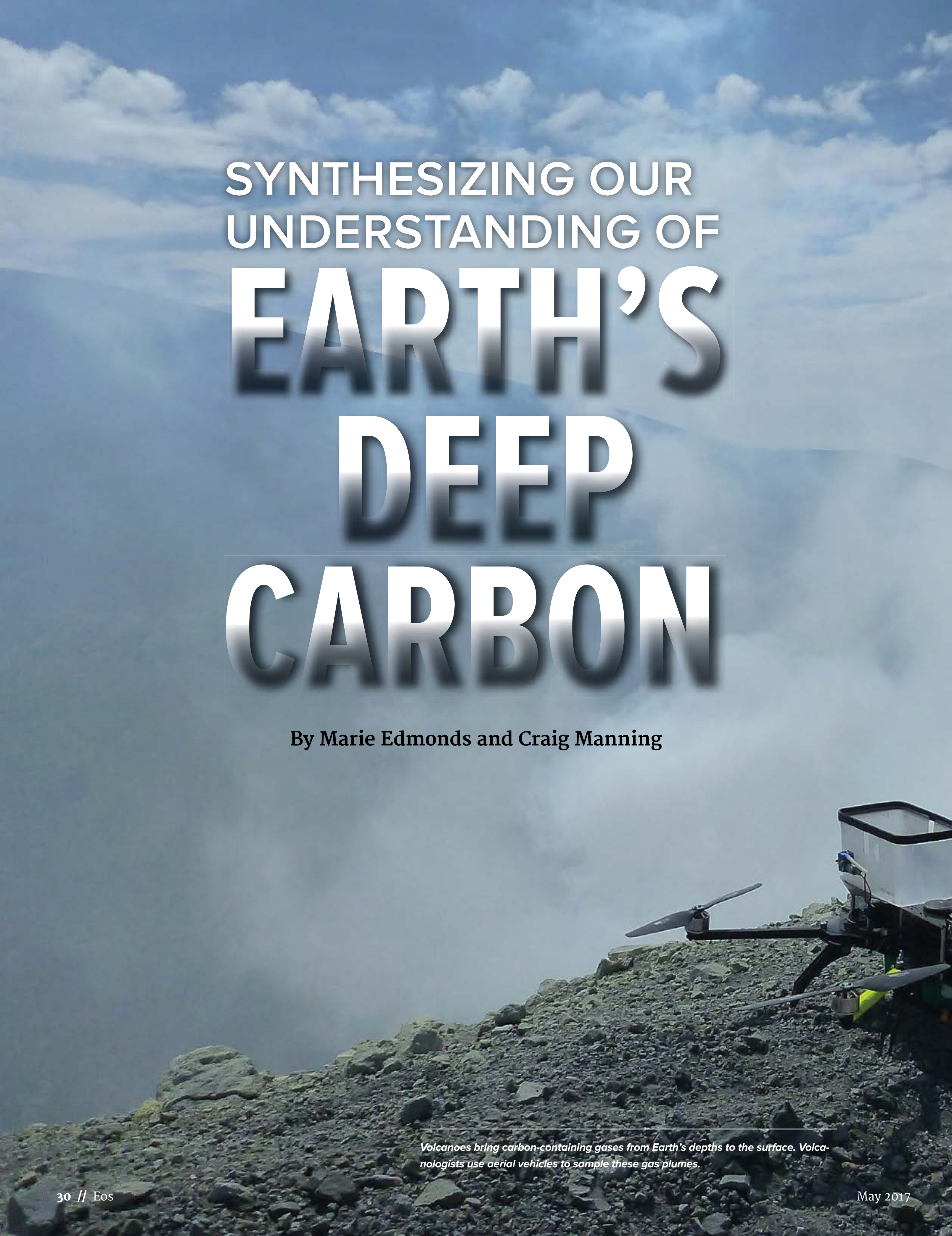
SYNTHESIZING OUR UNDERSTANDING OF EARTH'S DEEP CARBON

By Marie Edmonds and Craig Manning



Volcanoes bring carbon-containing gases from Earth's depths to the surface. Volcanologists use aerial vehicles to sample these gas plumes.

The Deep Carbon Observatory is entering a new phase in which it will integrate 10 years of discoveries into an overarching model to benefit the scientific community and a wider public.

Carbon is one of the most important elements on our planet; its distribution on and in Earth affects the global climate system, the origin and evolution of life, and the types and availability of energy resources. The geological cycling of carbon, driven by plate tectonics over long timescales, is the main factor influencing the size of Earth's shallow carbon reservoirs. Until recently, however, we had only a fragmented understanding of how much carbon resides in the deep Earth, its form, and how it moves between deep and shallow reservoirs.

Addressing these questions has been the core research goal of the Deep Carbon Observatory (DCO) program. Deep carbon science has emerged as a new scientific discipline, aimed at understanding the quantities, movements, forms, and origins of carbon in Earth's crust, mantle, and core, where we now know that more than 90% of Earth's carbon resides. The program has amassed 7 years' worth of dis-

Trail by Fire Team

Understanding how carbon cycles deep in Earth's crust, mantle, and core may inform scientists about how this element underpins a range of terrestrial processes, including diamond formation. Shown here is an aerial view of the Udachnaya pipe deposit diamond mine in Sakha Republic, Russia.

coveries about carbon in Earth's depths. Over the next 3 years, the program will integrate these discoveries into an overarching model of carbon in Earth and create legacies for the scientific community and wider public.

DCO's First 7 Years: A New Understanding of Deep Carbon

DCO research encompasses many related topics. How do subduction and volcanic and tectonic degassing cause carbon to cycle into and out of the mantle? What is the extent and diversity of the deep microbial biosphere? What forms and structures do carbon-bearing melts and minerals take in the mantle and core? What is the nature of deep sources of such carbon-based fluids as methane and higher hydrocarbons, and what processes control their formation [*Hazen et al.*, 2013a]?

One highlight of our research is the discovery of what happens when carbon is carried from Earth's crust into the mantle through subduction. For example, diamonds, which can contain geochemical signatures of organic material from Earth's surface, may form as a result of pH shifts in mantle fluids [*Sverjensky and Huang*, 2015]. Deeply subducted carbonate minerals transform to a novel structure that features carbon in tetrahedral coordination with oxygen, rather than the triangular coordination more typical of minerals near the surface [*Boulard et al.*, 2015].

Closer to the surface, the geosphere and biosphere show a complex linked evolution. The diversity and ecology of carbon-bearing minerals on Earth have histories that closely mirror such major events in Earth's history as the Great Oxidation Event, when biologically mediated free oxygen first appeared in our atmosphere, opening the way for the aerobic organisms we know today [*Hazen et al.*, 2013b].

Recent research has extended the known limits to microbial life; one study showed that microbes thrive as deep as 2.5 kilometers in the oceanic crust [*Inagaki et al.*, 2015]. Another study has identified unique microbial organisms that thrive as deep as 2 kilometers beneath the surface under the hot, highly saline conditions associated with the hydraulic fracturing of shale [*Daly et al.*, 2016].

We've also improved our understanding of the volcanic output of carbon into our atmosphere: Novel instrument networks reveal that volcanic flux of carbon dioxide is twice what researchers previously thought [*Burton et al.*, 2013].

Other studies measure the fluxes of reduced carbon (e.g., methane) in diverse crustal environments. Next-generation mass spectrometry allows scientists to precisely identify the isotopic makeup of methane molecules (isotopologues) to trace them back to their sources in the crust and mantle [*Young et al.*, 2016]. Still other studies have led to the discovery of "ancient water," more than a billion years old. This discovery provides evidence for the existence of early crustal environments perhaps capable of harboring life [*Holland et al.*, 2013].

Synthesizing a Decade of DCO Science

As the DCO completes its first decade of focused research, its emphasis is shifting toward scientific synthesis. For example, our workshops now center around unifying themes. Special publications and review articles will contain the underpinning science and discoveries that have emerged from the DCO and guide future scientific endeavors.

An important synthesis effort is the development of models and visualizations. We are developing models over a range of spatial and temporal scales to describe carbon mineralogy, carbon partitioning, fluxes between carbon reservoirs, and the extent and diversity of microbial life. Already, new models of the processes by which subduction causes Earth's mantle to take in and release gas suggest that subducting slabs transport carbon more efficiently toward Earth's surface than previously thought [*Kelemen and Manning*, 2015]. Scientists have attempted to extend such analyses back in time to the early Earth [*Dasgupta*, 2013].

*DCO researcher at Poás volcano, Costa Rica, using a multigas instrument [*Aiuppa et al., *2007] to measure carbon to sulfur molar ratios in the gas plume.*

Models of mantle melting beneath mid-ocean ridges [*Rosenthal et al.*, 2015; *Behn and Grove*, 2015] show that small amounts of carbonated melts and their reactive flow play critical roles in mantle dynamics [*Keller and Katz*, 2016]. Another key modeling effort focuses on the nature of carbon-bearing fluids by integrating existing thermodynamic models of magmas in the crust (MELTS; http://melts.ofm-research.org) [*Ghiorso and Sack*, 1995] and fluids in the mantle (Deep Earth Water (DEW); http://bit.ly/DEW-model) [*Sverjensky et al.*, 2014a, 2014b] to form a framework for modeling mass transfer of carbon and other elements.

Reaching a Broader Audience

DCO scientists are striving to share what they have learned about the global deep carbon cycle with fellow scientists, future students, and an interested public. We will share many of the findings through peer-reviewed publications, but DCO is also dedicating resources to creating films, infographics, and books. For more information, review DCO's midterm report (see http://bit.ly/DCO-Midterm) on the observatory's website (https://deepcarbon.net) and follow DCO on Twitter (@deepcarb) and Facebook (http://bit.ly/DCO-FB).

Acknowledgments

DCO distributes seed funding from the Alfred P. Sloan Foundation via four research communities to leverage scientific endeavors addressing DCO's goals. Robert Hazen, Craig Schiffries, Katie Pratt, and Darlene Trew Crist provided valuable input.

References

Aiuppa, A., et al. (2007), Forecasting Etna eruptions by real-time observation of volcanic gas composition, *Geology, 35*(12), 1115–1118, https://doi.org/10.1130/G24149A.1.

Behn, M. D., and T. L. Grove (2015), Melting systematics in mid-ocean ridge basalts: Application of a plagioclase-spinel melting model to global variations in major element chemistry and crustal thickness, *J. Geophys. Res. Solid Earth, 120*(7), 4863–4886, https://doi.org/10.1002/2015JB011885.

Boulard, E., et al. (2015), Tetrahedrally coordinated carbonates in Earth's lower mantle, *Nat. Commun., 6,* 6311, https://doi.org/10.1038/ncomms7311.

Burton, M. R., G. M. Sawyer, and D. Granieri (2013), Deep carbon emissions from volcanoes, *Rev. Mineral. Geochem., 75*(1), 323–354, https://doi.org/10.2138/rmg.2013.75.11.

Daly, R. A., et al. (2016), Microbial metabolisms in a 2.5-km-deep ecosystem created by hydraulic fracturing in shales, *Nat. Microbiol., 1,* 16146, https://doi.org/10.1038/nmicrobiol.2016.146.

Dasgupta, R. (2013), Ingassing, storage, and outgassing of terrestrial carbon through geologic time, *Rev. Mineral. Geochem., 75,* 183–229, https://doi.org/10.2138/rmg.2013.75.7.

Ghiorso, M., and R. Sack (1995), Chemical mass transfer in magmatic processes IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures, *Contrib. Mineral. Petrol., 119*(2–3), 197–212, https://doi.org/10.1007/BF00307281.

Hazen, R., A. Jones, and J. Baross (Eds.) (2013a), *Carbon in Earth, Rev. Mineral. Geochem., 75,* 698 pp.

Hazen, R. M., et al. (2013b), Carbon mineral evolution, *Rev. Mineral. Geochem., 75,* 79–107, https://doi.org/10.2138/rmg.2013.75.4.

Holland, G., et al. (2013), Deep fracture fluids isolated in the crust since the Precambrian era, *Nature, 497*(7449), 357–360, https://doi.org/10.1038/nature12127.

Inagaki, F., et al. (2015), Exploring deep microbial life in coal-bearing sediment down to ~2.5 km below the ocean floor, *Science, 349*(6246), 420–424, https://doi.org/10.1126/science.aaa6882.

Kelemen, P. B., and C. E. Manning (2015), Reevaluating carbon fluxes in subduction zones, what goes down, mostly comes up, *Proc. Natl. Acad. Sci. U. S. A., 112*(30), E3997–E4006, https://doi.org/10.1073/pnas.1507889112.

Keller, T., and R. F. Katz (2016), The role of volatiles in reactive melt transport in the asthenosphere, *J. Petrol., 57*(6), 1073–1108, https://doi.org/10.1093/petrology/egw030.

Rosenthal, A., E. Hauri, and M. Hirschmann (2015), Experimental determination of C, F, and H partitioning between mantle minerals and carbonated basalt, CO_2/Ba and CO_2/Nb systematics of partial melting, and the CO_2 contents of basaltic source regions, *Earth Planet. Sci. Lett., 412,* 77–87, https://doi.org/10.1016/j.epsl.2014.11.044.

Sverjensky, D. A., and F. Huang (2015), Diamond formation due to a pH drop during fluid-rock interactions, *Nat. Commun., 6,* 8702, https://doi.org/10.1038/ncomms9702.

Sverjensky, D. A., V. Stagno, and F. Huang (2014a), Important role for organic carbon in subduction-zone fluids in the deep carbon cycle, *Nat. Geosci., 7,* 909–913, https://doi.org/10.1038/ngeo2291.

Sverjensky, D. A., B. Harrison, and D. Azzolini (2014b), Water in the deep Earth: The dielectric constant and the solubilities of quartz and corundum to 60 kb and 1200° C, *Geochim. Cosmochim. Acta, 129,* 125–145, https://doi.org/10.1016/j.gca.2013.12.019.

Young, E. D., et al. (2016), A large-radius high-mass-resolution multiple-collector isotope ratio mass spectrometer for analysis of rare isotopologues of O_2, N_2, CH_4 and other gases, *Int. J. Mass Spectrom., 401,* 1–10, https://doi.org/10.1016/j.ijms.2016.01.006.

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Getting to Fair: Recognizing Implicit Bias and Easing Its Impact

Think of a nurse, and whom do you picture? Likely, it's a woman. Think of a scientist, and whom do you picture? Likely, it's a man. This may not seem like a very big deal, but under many circumstances—for instance, when evaluating someone's job performance or an application for honors or graduate school—social mores of which we are unaware may surface to direct our conscious thought. A number of studies have shown that conscious, willful thinking is only the tip of the iceberg as our brains process information leading to a decision. Around 2% of brain activity is conscious; the rest is below the level of consciousness, or implicit, often leading to unintended consequences.

Within a given cultural group, members share the same implicit thoughts and assumptions that are absorbed through life experience. If there is a bias in favor of women in the United States, nearly all of us in the country share it, without realizing it. If the bias is negative, we share that, too.

These implicit assumptions slant whom we nominate, whom we listen to, how qualified we think someone is for a job, and whether their qualifications seem to fit our ideas about the "ideal worker." Psychologist Virginia Valian of Hunter College calls this slight bias at each career step "the mountain made of molehills" that impedes women's careers (see http://bit.ly/unsaid-beliefs). For AGU publications, it leads to fewer women being suggested to review journal articles, a necessary activity for career advancement in science, technology, engineering, and mathematics (STEM) fields (see http://bit.ly/too-few-women-refs).

From Survival to Evaluation

It's important to emphasize that we are not making biased decisions on purpose. Nor do we make them to be mean or discriminatory or to maintain a particular status quo. Implicit thinking that makes use of preprogrammed schemas and assumptions is necessary to get through the day. We can't stop and think when a lion is racing toward us, "Is this one of the nice lions?" Folks who do that are gone from the gene pool! We don't face rampaging lions much anymore, yet the survival instincts we acquired in those bygone eras are still part of our nature. It therefore takes some effort to combat implicit bias—in other words, to be fair.

Dozens of studies have revealed the effects of implicit bias on evaluation outcomes. As members of AGU's Honors and Recognition Committee, we see those effects in the form of fewer women being nominated for or winning scientific awards and fewer being selected as Fellows. On the other hand, we see disproportionately more women receiving service and teaching awards. Among other impacts, we see disproportionately few people of color and women working in our scientific fields, and fewer people from outside the United States nominated for or winning awards.

Avoiding the Automatic

If this is how our brains work, what can we do to bypass this automatic mechanism? Research into solutions is ongoing and focuses for now on promoting awareness that this is how our brains work, that this seemingly small bias has a negative impact on our colleagues in certain underrepresented groups, and that taking more time (not feeling time pressure) helps to reduce this barrier.

A workshop hosted by our committee at the 2016 AGU Fall Meeting aimed to raise awareness about implicit bias in evaluations. We had hoped to reach at least 40 AGU members with our "Getting to Fair" event. To our delight, some 250 conference attendees registered for the workshop.

Tactics Against Implicit Bias

It was heartening to see such widespread interest in this important topic at the workshop. Below, we provide some additional information, starting with the following six tactics to reduce the impact of implicit bias in the geosciences:

- Build awareness of the scientific contributions made by women colleagues. Have they been nominated for awards for which they are qualified? Visit the AGU Honors website (http://bit.ly/aguhonors) and see the lists of awardees posted there; then think hard of women colleagues whose names are missing.
- Notice whether women in meetings are interrupted or their ideas are heard respectfully. Research demonstrates that when women in a mixed group speak for more than about 25% of the time, both men and women perceive that "women did all the talking" (see http://bit.ly/TalkBias).
- Look for telltale signs of bias in nomination and support letters. Many studies show that letters of nomination and recommendation written for men tend to be to be longer, have more superlatives, and directly address the curriculum vitae. Letters written for women, on the other hand, tend to be shorter, have more personal references (e.g., to marital status, motherhood, "nice" qualities), and have considerably less written about scholastic achievements and qualifications.

We write letters for men with more "agentic" terms (i.e., agents of effectiveness) and letters for women with more "communal" terms (gets along with people). It's nice to be described as agreeable and pleasant, but agentic attributes get us the job, get us noticed, get us nominated for awards (see http://bit.ly/recLetters).

Most recently, Kuheli Dutt of Lamont-Doherty Earth Observatory and her colleagues examined 1224 letters of recommendation for postdoctoral positions in the geosciences and found that women were only half as likely as men to have an excellent letter written for their applications (see http://bit.ly/LetterBias). If letters for a nominee are clearly biased in this manner, the AGU Honors Committee can ask that they be rewritten. A set of guidelines for writing good letters of nomination and of support and recommendation is provided on the AGU Honors website.

- Ensure that each section and focus group nomination committee has a canvassing committee charged with finding worthy nominees and colleagues to nominate them.
- Provide each selection committee (and any committee evaluating applicants for per-

formance) with a clearly written set of criteria for the award/selection before the nominations are submitted for review. We have all witnessed the phenomenon whereby one year we select a colleague on the basis of number of publications, and then the following year this evaluation criterion is less important and the letters of reference are elevated in importance. The committee's criteria should be consistent, clearly articulated, and arrived at by consensus.

- Step up, women colleagues, and nominate other women! Women are less likely to submit nominations (for men or women). Women need to be in the game before everyone plays fair.

Including Non-Majority Voices

In the long run, addressing inequity will require changing the culture of the system that trains new scientists. Some 65 academic institutions in the United States have received ADVANCE grants from the National Science Foundation. These are designed to increase the number of STEM women on the faculty by addressing ingrained, often unchallenged, gender-biased procedures, policies, and processes that determine who is on our faculty.

In the United States, many academic institutions require that some "nonmajority" person serve on each search committee for new faculty as well as on other selection committees. This process has backfired by overburdening women and faculty of color with extra service work.

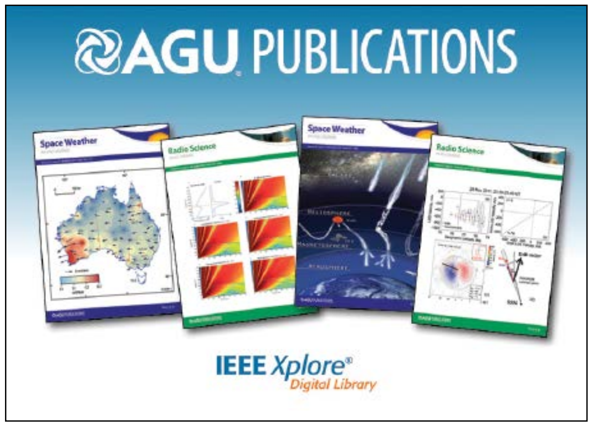
North Dakota State University, following the lead of the University of California, Irvine, and many other ADVANCE institutions, has created a "male advocates and allies" program, wherein men learn about implicit bias and how to combat it and serve as the "minority voice" on committees. AGU Honors committees could benefit by having at least one bias awareness–trained male advocate on each committee to help members learn about implicit bias and its impact and develop strategies to minimize that impact.

By **Mary Anne Holmes** (email: agu_unionhonors@agu.org), **Sam Mukasa** (chair), and **Donald Schwert**, Honors and Recognition Committee, AGU

Read more articles on Eos.org that address gender bias:

http://bit.ly/Eos_women-scientists
http://bit.ly/Eos_cryosphere-diversity
http://bit.ly/Eos_support-networks
http://bit.ly/Eos_gender-parity

Radio Science and *Space Weather* Now Available on IEEE *Xplore*



Users of the IEEE Xplore *database can now find articles from AGU's* Radio Science *and* Space Weather *journals.*

Two of AGU's journals, *Radio Science* and *Space Weather*, are now indexed in IEEE *Xplore*, a digital library of scholarly research focused on the topics of computer science and engineering (http://bit.ly/IEEE-Xplore).

Thousands of IEEE *Xplore* users worldwide will now be able to find more than 7000 articles from these two journals. Within this database of more than 4000 publication titles, users can perform full-text searches and use tools that refine results by title, author, affiliation, publication, publication date, and more.

Brooks Hanson, director of AGU Publications, noted, "Now that these articles are more discoverable by the broader engineering community, we are increasing the likelihood they will be read and cited. And we also hope that this cross-pollinates new relationships between engineers and Earth and space scientists."

By **Jamie Liu** (email: jliu@agu.org), Marketing Manager, AGU

Outstanding Student Paper Awards

The following AGU members received Outstanding Student Paper Awards at the 2016 Fall Meeting in San Francisco, Calif. Winners have individual pages on AGU's website (see http://bit.ly/Eos_OSPA).

Atmospheric and Space Electricity

Coordinator: Morris Cohen

Gregory Bowers, University of California, Santa Cruz, *TGF ground observations from a winter thunderstorm in Japan: First ground observation of a multipulse TGF & evidence of neutron production from a TGF*

Vanna Chmielewski, Texas Tech University, *An analysis of small changes in environment which resulted in diverse charge structures on 4 June 2012 in West Texas*

Atmospheric Sciences

Coordinators: Shannon Capps, Ross Salawitch

Rachel Elizabeth Bartlett, University of Edinburgh, *Do differences in future sulfate emission pathways matter for near-term climate? A case study for the Asian monsoon*

Di Chen, State University of New York at Albany, *Dependence of estimated precipitation frequency and intensity on data resolution*

Hong Chen, University of Colorado, Boulder, *Using aircraft observations to improve passive remote sensing of clouds in the Arctic*

Eliza Dawson, University of Washington, *Variability of the Inter-Tropical Convergence Zone related to changes in interhemispheric dust load*

Amanda Giang, Massachusetts Institute of Technology, *Implications of climate variability for monitoring the effectiveness of global mercury policy*

Alexander Hegedus, University of Michigan, *Simulating 3D spacecraft constellations for low frequency radio imaging*

Stephanie Henderson, Colorado State University, *The extratropical influence of the Madden–Julian Oscillation on wintertime blocking*

Huancui Hu, University of Illinois at Urbana-Champaign, *Introducing water tracers in the Noah-MP land surface model*

Xiaomeng Jin, Columbia University in the City of New York, *Evaluating a space-based indicator of surface ozone sensitivity to emissions of NO_x vs. NMVOC over major northern mid-latitude source regions*

Richie Kaur, University of California, Davis, *Aqueous reactions of triplet excited states with allylic compounds*

Feiyu Lu, University of Wisconsin–Madison, *Understanding the control of extratropical atmospheric variability on ENSO using regional coupled data assimilation*

Erin McDuffie, University of Colorado, Boulder, *The wintertime fate of N_2O_5: Observations and box model analysis for the 2015 WINTER Aircraft Campaign*

Elin McIlhattan, University of Wisconsin–Madison, *Every day is a snow day: Leveraging A-Train observations to evaluate Arctic liquid containing cloud processes in the Community Earth System Model*

Alexis Shusterman, University of California, Berkeley, *The Berkeley Atmospheric CO_2 Observation Network: Design, calibration, and initial evaluation of a high-density CO_2 surface network*

Jennifer Walker, California Institute of Technology, *Onset and withdrawal of the large-scale South Asian monsoon: A dynamical definition using change point detection*

Simon Wild, University of Birmingham, *Extra-tropical cyclones and windstorms in seasonal prediction models*

Brandon Wolding, Colorado State University, *Destabilization of the Madden–Julian Oscillation in present and future climates*

Xiyue Zhang, California Institute of Technology, *Arctic mixed-phase clouds in large-eddy simulations and a mixed-layer model*

Biogeosciences

Coordinators: Noel Aloysious, Justin Dodd, Maggie Lau, Sue Natali, Kunwar Singh

Jotautas Baronas, University of Southern California, *Mixing as a driver of temporal variations in river hydrochemistry: Concentration-runoff dynamics in the Andes-Amazon*

Zichong Chen, University of Minnesota, Twin Cities, *Partitioning N_2O emissions within the US corn belt using an inverse modeling approach*

Amber Churchill, University of Colorado, Boulder, *Alpine plant community controls on ecosystem N pools under the influence of N deposition using an enriched ^{15}N tracer experiment*

Alison Hoyt, Massachusetts Institute of Technology, *Methane oxidation in a tropical peatland*

Malcolm Itter, Michigan State University, *A model-based approach to infer shifts in regional fire regimes over time using sediment charcoal records*

Yanlan Liu, Duke University, *Increasing atmospheric humidity and CO_2 concentration alleviate forest mortality risk*

Lauren Lowman, Duke University, *Predicting phenologic response to water stress and implications for carbon uptake across the Southeast U.S.*

Lynsay Spafford, Saint Francis Xavier University, *Temporally-resolved study of atmosphere-lake net CO_2 exchange at Lochaber Lake, Nova Scotia, Canada*

Begum D. Topcuoglu, University of Massachusetts, *Methanogenic hydrogen syntrophy among thermophiles: A model of metabolism, adaptation and survival in the subsurface*

Ellen Ward, Stanford University, *Strategy to conduct quantitative ecohydrologic analysis of a UNESCO World Heritage Site: The Peace-Athabasca Delta, Canada*

Cryosphere

Coordinators: Ellyn Enderlin, Dan McGrath, Lucas Zoet

Cenlin He, University of California, Los Angeles, *A physically-based parameterization for BC-snow interaction with application to snow albedo reduction over the Tibetan Plateau*

Keith Jennings, University of Colorado, Boulder, *Assessing the climate sensitivity of cold content and snowmelt in seasonal alpine and subalpine snowpacks*

Emily Kane, University of California, Irvine, *Measuring short term velocity changes of Kangilerngata Sermia, West Greenland, using a gamma portable radar interferometer*

Christian Kienholz, University of Alaska Fairbanks, *Integrating in-situ observations, remote sensing and modeling to constrain the mass balance evolution of Black Rapids Glacier, Alaska, 1980–2015–2100*

Aaron Mohammed, University of Calgary, *Vadose zone dynamics governing snowmelt infiltration and groundwater recharge in a seasonally frozen, semi-arid landscape*

Kira Olsen, Columbia University in the City of New York, *Regional and local glacial-earthquake patterns in Greenland*

Kevin Schiele, Ulster University, *Offshore–onshore correlations refining the glacial history of western Ireland*

Earth and Planetary Surface Processes

Coordinator: Roman DiBiase

William Jesse Hahm, University of California, Berkeley, *Ecohydrological consequences of Critical Zone structure in the Franciscan Formation, northern California Coast Ranges*

Alexander Horton, Cardiff University, *Modification of river meandering caused by tropical deforestation along the Kinabatangan River, Borneo*

Katherine Lininger, Colorado State University, *Geomorphic controls on floodplain organic carbon storage in sediment along five rivers in interior Alaska*

Virginia Marcon, Pennsylvania State University, *Evaluating the effect of lithology on porosity development in ridgetops in the Appalachian Piedmont*

Ryan Sincavage, Vanderbilt University, *Patterns of downstream fining and facies change reflecting differing modes of mid-Holocene sediment disperal across the Ganges-Brahmaputra-Meghna Delta*

Alexandra Skrivanek, University of Florida, *Evidence for tectonism based on differential uplift of the Falmouth Formation of Jamaica*

Earth and Space Science Informatics

Coordinators: Mohamed Aly, Anita Dewaard, Sudhir Shrestha, Brad Zavodsky

Ankit Rai, University of Illinois at Urbana-Champaign, *Identifying green infrastructure from social media and crowdsourcing—An image based machine-learning approach*

Education

Coordinator: Stacie Bender

Sean Czarnecki, Angelo State University, *New mapping in the Sand Springs Range of western Nevada clarifies and constrains regional deformation sequences of the Lining-Fencemaker thrust belt*

Yi-Ling Hwong, University of New South Wales, *What makes you tick? An empirical study of space science related social media communications using machine learning*

Geodesy

Coordinators: Yuning Fu, Emily Montgomery-Brown, Bob Wang

Mary Grace Bato, Institut des Sciences de la Terre, *Volcano deformation and eruption forecasting using data assimilation: Building the strategy*

Priyamvada Nanjundiah, Nanyang Technological University, *Tectonic and geomorphic setting of the Pamir Plateau—Insights from InSAR, seismic and optical data for the 2015 M_w 7.2 Darwas-Karakoram earthquake*

Talib Oliver, University of Miami, *Detection of sinkhole activity in centra Florida using high-spatial-resolution InSAR time series observations*

Geomagnetism, Paleomagnetism, and Electromagnetism

Coordinator: Julie Bowles

Stanislava Akimova, Institut de Physique du Globe de Paris, *New archeointensity data from late Neolithic Yarim Tepe 1 and 2 settlements (northern Iraq) dated from the pre-Halaf and Halaf periods (7th–6th Millennia BC)*

Lydian Boschman, Utrecht University, *On the enigmatic birth of the Pacific plate within the Panthalassa Ocean*

Pauline Le Maire, University of Strasbourg, *2D potential theory using complex algebra: New perspectives for interpretation of aeromagnetic data*

Daniel Maxbauer, University of Minnesota, *Magnetic minerals in soils across the forest–prairie ecotone in NW Minnesota*

Global Environmental Change

Coordinators: Pierre Gentine, Lucy Hutyra, Dan Li, Wenhong Li, Hui Su

Stephen Decina, Boston University, *Patterns and drivers of inorganic and organic nitrogen and phosphorus deposition, cycling, and loss throughout a metropolitan area*

Kira Hoffman, University of Victoria, *Ecological legacies of indigenous fire management in high-latitude coastal temperate rainforests, Canada*

Richard Vachula, Brown University, *A comprehensive reconstruction of Alaskan Arctic fire history over the last 30,000 years as inferred from a novel multi-proxy suite of organic geochemical and paleoecological methodology*

Hydrology

Coordinators: Terri Hogue, Rolf Hut, Alicia Kinoshita, Kolja Rotzoll

Jane Barlow, University of Arizona, *Assessing hydrologic impacts of future land cover change scenarios in the South Platte River Basin (CO, WY, & NE) and the San Pedro River Basin (U.S./Mexico)*

Rachel Baum, University of North Carolina at Chapel Hill, *Tradeoffs in risk and return of financial hedging solutions to mitigate drought-related financial risks for water utilities*

Danielle Boshers, University of Connecticut, *Oxygen isotope composition of nitrate produced by freshwater nitrification*

Bernardo Carvalho Trindade, Cornell University, *Time evolving multi-city dependencies and robustness tradeoffs for risk-based portfolios of conservation, transfers, and cooperative water supply infrastructure development pathways*

Levon Demirdjian, University of California, Los Angeles, *Improving the statistical modeling of the TRMM Extreme Precipitation Monitoring System*

Johanna Engstrom, University of Florida, *Hydropower in southeastern United States—A hydroclimatological perspective*

Sarah Fletcher, Massachusetts Institute of Technology, *Uncertainty categorization, modeling, and management for water supply planning*

Margaret Garcia, Tufts University, *Modelling per capita water demand change to support system planning*

Lidiia Iavorivska, Pennsylvania State University, *Inputs of organic carbon to watersheds via atmospheric deposition: Variation across spatial and temporal scales*

Cyndi Kelly, Stanford University, *Back-projection imaging of extended pre-, co-, and post-eruptive seismic sources through multiple eruption cycles at Jefe geyser, El Tatio geyser field, Chile*

Xiuyuan Li, Lehigh University, *Assessing the influence of climate variables on the past floods in continental USA*

Theodore C. Lim, University of Pennsylvania, *Beyond imperviousness: A statistical approach to identifying functional differences between development morphologies on variable source area-type response in urbanized watersheds*

Nathaniel Looker, University of Minnesota, Twin Cities, *Effects of land use/cover and landform on upper soil physical properties in the highlands of Veracruz, Mexico*

Kimberly Manago, Colorado School of Mines, *Evaluating relationships between urban land cover composition and evapotranspiration in semi-arid regions*

Stephen Maples, University of California, Davis, *How to recharge a confined alluvial aquifer system*

Christopher Marsh, University of Saskatchewan, *The Canadian Hydrological Model (CHM): A multi-scale, variable-complexity hydrological model for cold regions*

Natalie Nelson, University of Florida, *Uncovering cyanobacteria ecological networks from long-term monitoring data using Granger causality analysis*

Preston Pound, Georgia Southern University, *Bacterial flux by net precipitation from the phyllosphere to the forest floor*

Daniel Wilusz, Johns Hopkins University, *Can a simple lumped parameter model simulate complex transit time distributions? Benchmarking experiments in a virtual watershed*

Margaret Zimmer, Duke University, *Shallow and deep groundwater contributions to ephemeral streamflow generation*

Mineral and Rock Physics

Coordinator: Heather Watson

John A. Krantz, Brown University, *Noble gas recycling: Experimental constraints on Ar, Kr, and Xe solubility in serpentinite*

Kathryn Kumamoto, Stanford University, *Olivine strength in the low-temperature plasticity regime measured via spherical nanoindentation*

Ryan J. McCarty, Stanford University, *NMR technique for determining transition metal cation distribution at low concentrations demonstrated using periclase (MgO) and CaO*

Roberto Emanuele Rizzo, University of Aberdeen, *Riding the right wavelet: Detecting fracture and fault orientation scale transitions using Morlet wavelets*

Natural Hazards

Coordinators: Naresh Devineni, Phu Nguyen, Yadu Pokhrel, Armin Sorooshian

Maya Buchanan, Princeton University, *Amplification of flood frequencies with local sea-level rise and emerging flood regimes*

Karoline Messenzehl, University of Bonn, *Structural and thermal controls on the frequency and magnitude of small-size rockfall events (European Swiss Alps)*

Katherine Serafin, Oregon State University, *Location, location, location! Regional differences in morphologic and hydrodynamic controls on extreme total water levels along the West Coast of the United States*

Near-Surface Geophysics

Coordinators: Xavier Comas, Fred Day-Lewis, Sarah Kruse, George Tsoflias

Daniel Blatter, University of California, San Diego, *Bayesian inversion of 2D models from airborne transient EM data*

Chao Gao, University of Maryland, *Quantifying the uncertainties and multi-parameter trade-offs in joint inversion of receiver functions and surface wave velocity and ellipticity*

Samuel B. Kachuck, Cornell University, *Sloppy inversion and optimal experiment design for Last Glacial Maximum Barents Sea ice sheet configuration*

Farzaneh Mahmood Poor Dehkordy, University of Connecticut, *Studying exchange with less-mobile porosity at the laboratory scale: Experimentation and multiphysics simulations*

Adam Nielson, Colorado State University, *Using synthetic forward seismic models of channelized deep-water slope deposits to inform stratigraphic interpretation, Tres Pasos Formation, Magallanes Basin, Chile*

Kirk Scanlan, University of Alberta, *Difficulties in interpreting ballast degradation level estimates from synthetic ground-penetrating radar data*

Nonlinear Geophysics

Coordinators: Joern Davidsen, Steven Fletcher

Sahani Pathiraja, University of New South Wales, *Improving forecasts through realistic uncertainty estimates: A novel data driven method for model uncertainty quantification in data assimilation*

Ocean Sciences

Coordinators: James Dykes, Donya Frank, Chris Hayes, Stephan Howden, Heidi Sosik

Dylan Anderson, Oregon State University, *Instantaneous sediment bed level response to wave-induced pore-pressure gradients on a surfzone sandbar*

Katie Bigham, University of Washington, *Interpretation of the relationship between benthic fauna, geologic distributions, and methane seeps at Southern Hydrate Ridge, Oregon Continental Margin*

Julius Busecke, Columbia University in the City of New York, *Time variable eddy mixing in the global sea surface salinity maxima*

Yassir Eddebbar, University of California, San Diego, *Impacts of ENSO on air–sea oxygen exchange: Observations and mechanisms*

Marcel Kleinherenbrink, Delft University of Technology, *Separating steric sea level and ocean bottom pressure in the tropical Asian seas*

Lauren Kuntz, Harvard University, *The Pacificventilated thermocline and its impact on global temperatures*

Tianjia Liu, Columbia University in the City of New York, *Global salinity predictors of western United States precipitation*

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Ajda Savarin, University of Miami, *Diurnal cycle of convection and air–sea–land interaction associated with MJO over the Maritime Continent*

Meghan Shea, Stanford University, *Use of a land-based, dual-parameter analyzer for tracking ocean acidification in nearshore coastal habitats*

Elizabeth Weidner, University of New Hampshire, *Quantification of methane gas flux and bubble fate on the eastern Siberian Arctic shelf utilizing calibrated split-beam echosounder data*

Paleoceanography and Paleoclimatology

Coordinator: Matt Kirby

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Danielle P. Santiago Ramos, Princeton University, *Paired measurements of K and Mg isotopes and clay authigenesis in marine sediments*

Karen Vyverberg, University of Florida, *New constraints from the Seychelles on the timing and magnitude of peak global mean sea level during the Last Interglacial*

Maayan Yehudai, Columbia University in the City of New York, *Changes in equatorial Atlantic Ocean thermohaline circulation across the mid-Pleistocene transition*

Planetary Sciences

Coordinators: Nathan Bridges, Rosaly Lopes

Michael E. Evans, Texas A&M University, *Stepped acid extractions of CO_2 from ancient carbonates in Martian nakhlites (MIL 03346, 090030, 090032, 090036) show distinct $\delta^{18}O$ and $\delta^{13}C$ isotopic values compared to secondary terrestrial carbonates formed on ordinary chondrites (OC) collected from Antarctica*

Daniel D. B. Koll, University of Chicago, *Interpreting atmospheric circulations of rocky exoplanets as heat engines*

Joseph O'Rourke, California Institute of Technology, *Sustaining a global magnetic field on Earth but not Venus with mantle dynamics*

Peiyun Zhu, University of Michigan, *The influence of ice–ocean interactions on Europa's overturning circulation*

Public Affairs

Coordinators: Denise Hills, Linda Rowan

Marshaun Montgomery, University of Illinois at Urbana-Champaign, *A framework for using rural markets to analyze local food shortage resilience and mitigation potential in sub-Saharan Africa based on evidence from Zambia*

Amanda Sorensen, Rutgers, The State University of New Jersey, *A case study of framing and project design impacts on participant identity, views, and trust of science in a phenology public participatory program*

Seismology

Coordinators: Miaki Ishii, Eric Kiser

Michael Afanasiev, Swiss Federal Institute of Technology, Zurich, *Salvus: A flexible open-source package for waveform modelling and inversion from laboratory to global scales*

Yaochieh Chen, National Taiwan Normal University, *Research of repeating earthquakes and fault character in Chihshang Fault, Taiwan*

Wenyuan Fan, University of California, San Diego, *Back-projection of large earthquakes: Advances and caveats*

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Kathryn Materna, University of California, Berkeley, *Measuring aseismic slip through characteristically repeating earthquakes at the Mendocino Triple Junction, Northern California*

Yajun Peng, Princeton University, *Investigating complex slow slip evolution with high-resolution tremor catalogs and numerical simulations*

Lukas Preiswerk, Swiss Federal Institute of Technology, Zurich, *Monitoring unstable glaciers with seismic noise interferometry*

Kathrin Spieker, University of Bergen, *Fine-scale crustal structure of the Azores Islands from teleseismic receiver functions*

Ruijia Wang, University of Alberta, *An integrated investigation of the induced seismicity near Crooked Lake, Alberta, Canada, in 2016*

Space Physics and Aeronomy

Coordinators: Lindsay Glesener, Betsey Mitchell, Allan Weathermax

Jeffrey Broll, University of Texas at San Antonio, *Observations and simulations of specularly reflected He++ at Earth's quasiperpendicular bow shock*

Sebastian De Pascuale, University of Iowa, *Determining core plasmaspheric electron densities with the Van Allen probes*

Katherine Goodrich, University of Colorado, Boulder, *Classifying large-amplitude parallel electric fields along the magnetopause and their effect on magnetic reconnection*

Nils Peter Janitzek, University of Kiel, *Differential streaming at 1 AU observed with SOHO/CELIAS/CTOF and ACE/SWICS*

Zixu Liu, University of California, Los Angeles, *Observations of a new foreshock region upstream of a foreshock bubble's shock*

Andrew Marsh, University of California, Santa Cruz, *Hard X-ray detectability of small-scale coronal heating events*

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Sam Schonfeld, New Mexico State University, *Correcting* $F_{10.7}$ *for use in ionospheric models*

Akshay Suresh, Indian Institute of Science Education and Research Pune, *Wavelet based characterization of low radio frequency solar emissions*

Keith Wood, Auburn University, *Field aligned currents derived from pressure profiles obtained from TWINS ENA images for geomagnetic storms that occurred on 01 June 2013 and 17 March 2015*

Study of the Earth's Deep Interior

Coordinator: Laurent Montesi

Eugenia Hyung, Harvard University, *^{142}Nd/^{144}Nd heterogeneity in the Proterozoic to Phanerozoic mantle and implications for mantle mixing*

Kuangdai Leng, University of Oxford, *AxiSEM3D: A new fast method for global wave propagation in 3-D Earth models with undulating discontinuities*

Tectonophysics

Coordinators: Kristin Morell, Julia Morgan

Susie Boote, University of South Carolina, *Precambrian origin of the Brunswick magnetic anomaly: New insights from the revised extent of the Suwannee Basin offshore*

Jorge Alberto Castillo Castellanos, California Institute of Technology, *Transition of the slab geometry at the eastern end of the Trans-Mexican Volcanic Belt from ambient noise and earthquake surface waves*

Helen A. Janiszewski, Columbia University in the City of New York, *Shoreline-crossing shear-velocity structure of the Juan de Fuca plate and Cascadia Subduction Zone from surface waves and receiver functions*

Hannah Mark, Massachusetts Institute of Technology, *Seismic coupling at divergent plate boundaries from rate-and-state friction models*

Daniel Evan Portner, University of Arizona, *New finite-frequency teleseismic* P*-wave tomography of the Anatolian sub-continent and the fate of the subducted Cyprean slab*

Daniel Rasmussen, Columbia University in the City of New York, *Run-up to the 1999 sub-Plinian eruption of Shishaldin volcano unveiled using petrologic and seismic approaches*

Florian Schmid, Alfred Wegener Institute, *Microseismicity reveals extreme types of oceanic lithosphere, deep reaching fluid circulation and active diking at the Southwest Indian Ridge*

Brandon Shuck, University of Texas at Austin, *Evolution of the upper lithosphere in the ENAM area from 3-D wide-angle seismic data*

Nicholas Stewart, University of Nice Sophia Antipolis, *A new MATLAB code to automatically measure lateral and vertical fault offsets in topographic data*

Matthew Tarling, University of Otago, *Slip dynamics and the effects of metasomatism on fault rheology in ultramafic rocks, the Livingstone Fault, New Zealand*

Volcanology, Geochemistry, and Petrology

Coordinators: Eric Brown, Sarah Brownlee, Brian Dreyer, Nick Dygert, Brian Jicha, Sarah Lambart, Noah McLean, Sean Mulcahy, Wendy Nelson, Tyrone Rooney

Chelsea Allison, Arizona State University, *Improved understanding of H_2O–CO_2 solubility in alkali basalts at mid-crustal pressures*

Robert Bogue, Occidental College, *Simultaneous in situ CO_2 soil flux and isotopic analysis in a high CO_2 flux environment at Mammoth Mountain, CA*

Kara Brugman, Arizona State University, *Clinopyroxene diffusion chronometry of the Scaup Lake rhyolite, Yellowstone Caldera, WY*

Clare Donaldson, University of Cambridge, *Relative seismic velocity variations correlate with deformation at Kīlauea volcano*

Melissa Drignon, Oregon State University, *Modeling the re-equilibration processes between melt inclusions and their host plagioclase megacrysts in plagioclase ultraphyric basalts*

Erin Fitch, University of Hawaii at Manoa, *The mechanisms and dynamics of high-energy lava–water explosions*

Elisabeth Gallant, University of South Florida, *Terrestrial radar survey of Momotombo volcano, Nicaragua*

Josefine A. M. Nanne, Durham University, *Osmium stable isotope composition of chondrites and iron meteorites: Implications for planetary core formation*

Joey Nelson, Stanford University, *Effects of crystallinity on Zn isotope fractionation during adsorption onto silica surfaces*

RESEARCH SPOTLIGHT

Polar Interlopers in the Aurora

Alexander Gerst/NASA

Several times a day, the edges of Earth's auroral rings brighten and arc toward the poles in events called poleward boundary intensifications, which a new paper suggests are caused by ionospheric polarization and flows of plasma from polar regions into the auroral oval.

Earth's aurora appears as a ring of high conductance around each pole, shifting and undulating as the hours go by. The poleward edge of this auroral oval also marks a conductance boundary, often coinciding with the boundary of the polar cap, where the topology of Earth's magnetic field lines changes from closed loops at lower latitudes to open to the solar wind at higher latitudes.

Many times every day, the edge of the aurora brightens in a poleward boundary intensification (PBI). PBIs have been studied extensively for decades, but researchers have not yet conclusively determined their source. Here *Ohtani and Yoshikawa* present an explanation of how PBIs may be caused by ionospheric convection, rather than the popular idea that they could be caused by magnetic reconnection far from Earth in the magnetosphere.

Fast polar cap flows, which transport ionospheric plasma from the dayside to nightside auroral oval across the polar cap, are strongly correlated to PBIs: The two occur together about 90% of the time. When these flows make contact with the auroral oval, the polarization of the ionosphere at the edge of the auroral oval causes a field-aligned current (FAC), a current of electrons that stream along Earth's magnetic field lines. The authors hypothesize that FACs, if directed upward, are accompanied by enhanced electron precipitation, which would cause auroral intensification, in other words, a PBI.

This idea is supported by a number of characteristics of PBIs. For one, PBIs start immediately when a polar cap flow touches the auroral oval and have the same duration as the polar cap flow, which can be explained by the instantaneous nature of ionospheric polarization. For another, PBIs last as long as the polar cap flow is touching the auroral oval, a correlation that is difficult to explain if they are caused by distant reconnection.

PBIs are also wider than polar cap flows: If PBIs were caused by distant reconnection, the reconnection would have to be inexplicably triggered simultaneously inside and outside the flow channel. Finally, PBIs are often followed by the movement toward the equator of the open-close boundary marking the edge of the polar cap, connecting PBIs to the enhanced polar cap convection.

These statistical characteristics, when considered together, suggest that the vast majority of PBIs are caused by ionospheric polarization. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1002/2016JA023143, 2016) **—Leah Crane, Freelance Writer**

After Decades, High-Altitude Observations Revived at Jicamarca

When the Jicamarca Radio Observatory made its first observations of Earth's ionosphere in the early 1960s, it was one of the most impressive facilities in the nascent field of space physics. Its massive square array of dipole antennas was laid out in the Peruvian desert east of Lima, nearly 300 meters on each side. The enormous radar facility was designed to probe the ionosphere directly above Earth's equator; electrons in the ionosphere scatter the radar beams, but a faint return signal gives an indication of their density.

In its initial observing runs, scientists included measurements at very high altitudes, an exercise meant to map out the space surrounding Earth. They also pushed the facility to its limits, requiring powerful radar pulses from all four of its transmitters and many people to operate them. Soon, however, high-altitude operations were canceled; the last runs occurred in 1965.

As the facility began to focus on more popular areas of research, the unpublished high-altitude records languished. Many were lost. The details of the observations and analysis—such as which filtering methods, if any, were used—faded away, limiting the surviving data's usefulness. Eventually, the capability to reproduce them was lost, as transmitters fell offline and Jicamarca focused on targets closer to the ground.

Today, more than 50 years later, interest in high-altitude observations is on the rise, this time driven by a desire to understand how plasma behaves during geomagnetic storms. Jicamarca remains one of the most important space physics radar facilities, and fortunately, recent upgrades have restored the facility's ability to carry out high-altitude observations. On 31 May 2016, Jicamarca fired up its transmitters and focused its antennas on high-altitude incoherent scatter in a study conducted by *Hysell et al.*

In a 24-hour period of observations, the team found that Jicamarca could profile the electron density up to an altitude of roughly 6300 kilometers. That's high enough to usefully overlap with data from ground-based magnetometers, which can cover a range from roughly 3000 kilometers to 16,000 kilometers. The data analysis also revealed that different filtering methods did not change the results much, which makes it easier to interpret historical data.

The authors used just two of Jicamarca's four transmitters, all of which have been restored to operational status. Even with only two transmitters, the data quality was similar to that of the 1965 data, with a slightly better dynamic range. The team notes that future observations using all four transmitters will be more sensitive and should push the observatory's range occasionally up to 10,000 kilometers. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1002/2016JA023569, 2017) **—Mark Zastrow, Freelance Writer**

Alastair Philip Wiper/VIEW

Dipoles of the telescope at Jicamarca Radio Observatory near Lima, Peru. Construction of the observatory was completed in 1962, around the time this photo was taken.

River's Rise Linked to Oklahoma's Largest Earthquake

Earthquakes do much more than literally make the earth quake. The shifting of massive sheets of rock has an effect on all sorts of hydrogeological processes, affecting groundwater and surface water like rivers, lakes, and reservoirs.

Some of this activity, however, is not natural. For example, geologists have extensively documented that when wastewater is injected deep into the Earth, as a means of disposal, it can induce seismic activity, which could, in turn, have hydrogeological effects. As overall induced seismic activity has increased in frequency in recent years, scientists seek to learn more about the secondary and potentially residual impacts of human-induced quakes.

A recent study by *Manga et al.* is the first documented instance in which an earthquake that was most likely induced by wastewater injection had a visible effect on surface water.

In early September 2016, an earthquake reaching 5.8 moment magnitude (an earthquake rating scale used for the largest quakes) struck Pawnee, Okla., setting a state record. If it was indeed a wastewater-induced quake, it would be the largest such earthquake on record. The team of researchers concluded that the quake was most likely triggered by one or more of the 26 wastewater disposal wells within a 20-kilometer radius, given that it was a strike-slip event, the type of earthquake most commonly associated with induced quakes in Oklahoma, and had several other telltale physical characteristics.

Several hours into the Pawnee quake, the U.S. Geological Survey stream gauge nearest the epicenter, located at Black Bear Creek, began recording rising water levels. The increase continued for a full week, until heavy rains obscured the data. The pattern of data collected is reminiscent of water level fluctuations following past earthquakes.

The amount of extra water recorded is just a fraction of the area's annual water budget and will not affect residents' water supply, the researchers say. But the Black Bear Creek case is important in that it proves that this method of wastewater disposal has an impact on groundwater systems. Furthermore, if the number of induced earthquakes continues to increase as it has, events like this are likely to become more widespread. To track this progress, the researchers hope to continue to monitor and expand the existing network of stream gauges. (*Geophysical Research Letters*, https://doi.org/10.1002/2016GL071268, 2016) **—Sarah Witman, Freelance Writer**

What Proportion of River Nutrients Reaches the Open Sea?

Although it is widely recognized that the world's rivers deliver substantial amounts of dissolved nitrogen and phosphorus to coastal waters each year, the proportion of important nutrients that ultimately reaches the open ocean is not presently known. Such estimates are crucial to understanding how anthropogenic activity and global climate change may affect global biogeochemical cycles.

Most current nutrient cycling models unrealistically assume that all or none of the rivers' loads of dissolved nitrogen and phosphorus reach the open sea. To improve upon this all-or-nothing approach, *Sharples et al.* have developed a new method for estimating the proportion of nutrients that reaches the open ocean following biogeochemical processing along the continental shelf.

Using a mechanistic model that uses our knowledge of how plumes of fresh river water behave after entering the sea, the team created a worldwide map of the average length of time a given nutrient lingers within shelf ecosystems. The researchers then combined these average durations with information about nutrient cycling in aquatic systems and a database of nutrient loads for more than 6000 rivers to develop geographically based estimates of nutrient delivery.

Their results suggest that 75% of nitrogen and 80% of phosphorus cross the continental shelves, delivering a total of 17 teragrams of nitrogen and 1.2 teragrams of phosphorus from rivers to the open ocean each year. These supplies, however, vary depending upon several factors, including the width of the continental shelf, each river's nutrient load, and latitude. Latitude's effect on nutrient export varies between 70% and 80% for nitrogen and between 70% and 90% for phosphorus.

Liam Gumley, Space Science and Engineering Center, University of Wisconsin-Madison and the MODIS science team

Every year rivers deliver 55 million tons of nutrients to coastal seas. In a new study, researchers assess just how much of this river nutrient supply ends up in the open ocean.

Because these results ignore nutrient processing within estuaries, a parameter that is more difficult to estimate, these numbers should be considered upper limits, according to the team. Despite this limitation, the study is an important step forward in our understanding of the spatial variability of nutrient processing on continental shelves. This improved understanding needs to be incorporated into global geochemical models to realistically project the response of coastal and oceanic ecosystems to future warming. (*Global Biogeochemical Cycles*, https://doi.org/10.1002/2016GB005483, 2017) **—Terri Cook, Freelance Writer**

Radar Method Shows Promise in Aquifer

The fine-scale structure of an aquifer is difficult to determine, posing challenges for scientists trying to predict underground water flow and transport. In a new paper, *Gueting et al.* demonstrate the potential for recent advances in ground-penetrating radar (GPR) to image aquifer structure in unprecedented detail.

The researchers used a new approach to a method known as cross-borehole GPR. In this technique, a transmitter placed in a borehole emits an electromagnetic wave that travels to a receiver in another borehole several meters away. Underground features disrupt the wave as it travels, so the altered wave picked up by the receiver contains information about the structure of these features. Analysis of the wave data can then reveal these structures.

Traditional GPR data analysis uses a mathematical method that strongly simplifies the presumed path of the wave through the ground, limiting the clarity of perceived underground features. In the newer approach used by the team, a technique called full-waveform inversion more accurately reconstructs the wave's path, allowing for improved resolution.

The researchers used full-waveform inversion of cross-borehole GPR data to investigate underground water dynamics at an alluvial aquifer near Cologne, Germany. Using several densely spaced boreholes, they took measurements along cross sections that were 50 meters long and 10 meters deep. Repeated measurements with the transmitter and receiver placed in slightly different positions allowed them to construct images of the aquifer structure with a resolution at the scale of decimeters.

To determine the true benefit of the full-waveform inversion technique, the scientists then compared its output with data gathered using standard hydrogeological methods, as well as the output of traditional GPR analysis. Overall, full-waveform inversion analysis showed a strong correspondence with the hydrogeological data.

In one hydrogeological experiment, a tracer injected into a borehole flowed downstream, where its concentration was detected at various points. Full-waveform inversion analysis suggested the presence of a thin layer of sand that would explain the observed tracer concentrations. This sand layer was not detected using traditional GPR data analysis, demonstrating the strength of full-waveform inversion.

Currently, this study is one of just a few that have investigated GPR full-waveform inversion. The scientists hope that their results will encourage a growing number of researchers to use the new technique. (*Water Resources Research*, https://doi.org/10.1002/2016WR019498, 2017) **—Sarah Stanley, Freelance Writer**

When Income Goes Up, Does Pollution Go Down?

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Does economic development always damage water quality, or does increased income actually help decrease pollution? Researchers have been studying the question for a long time, and its answer may help communities or countries better predict their environmental future.

One hypothesis is that for a time, a region's environmental degradation will increase as wealth increases, but at a certain income level the environment will start to recover. For water quality and air quality, scientists have found data supporting this idea in research at the country level, in both developed and developing countries. The bell-shaped environmental Kuznets curve (EKC) graphs a hypothetical relationship between pollution and the average income earned per person in a given area.

In a recent study, *Pandit and Paudel* used models to look at the relationship between water pollutants in watersheds and income in the state of Louisiana to see whether an EKC exists that shows eventual water quality recovery due to increased incomes in the state.

The scientists focused on nitrogen, phosphorus, dissolved oxygen, and mercury to test water quality. So-called flow pollutants like nitrogen and phosphorus (typically associated with agricultural pollution) can be absorbed back into the environment. These types of pollutants contrast with "stock pollutants" such as mercury, which, once put into the environment, will not disappear or be absorbed. Instead, they will continue to cause damage and cycle through the environment forever. Mercury is usually locked away in rocks and coal but is released into the environment when coal is burned to produce electricity or when burning hazardous waste.

The authors used watershed data (including data on water pollution) covering 53 counties in Louisiana over a 21-year period, from 1985 to 2006. Over the same period, they used economic growth with per capita income, available from the U.S. Bureau of Economic Analysis.

Because the researchers were looking at multiple pollutants, they decided to use a seemingly unrelated partially linear model (SUPLM) for the study. This model is often used in economics to combine multiple equations that are related only through their errors.

The results indicated that nitrogen did follow a Kuznets curve, as did dissolved oxygen, meaning that water quality in Louisiana improved with increased wealth. Phosphorus and mercury both told a different story: Although phosphorus pollution did decrease when state per capita income rose to $14,000, the pollution increased again after a per capita income of $17,000. A similar problem happened with mercury, indicating that mercury pollution rose the second time perhaps because of the increased demand for power and energy.

The mixed results show that the factors that fix pollution are complicated, but some pollutants, like nitrogen, could be reduced by economic growth. What this study does not answer, as the authors point out, is whether this pollution automatically fell with income growth or whether it was the result of environmentally protective policies in the state. The authors suggest that a combination of these factors likely had some relation to improvement in water quality.

This research did not find that economic growth will naturally solve pollution and water quality issues, but this growing area of research will be of interest to both environmentalists and economists investigating the connection between industrial development and water pollution. (*Water Resources Research*, https://doi.org/10.1002/2016WR018655, 2016) **—Alexandra Branscombe, Freelance Writer**

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- *Eos* accepts employment and open position advertisements from governments, individuals, organizations, and academic institutions. We reserve the right to accept or reject ads at our discretion.
- *Eos* is not responsible for typographical errors.

* Print-only recruitment ads will only be allowed for those whose requirements include that positions must be advertised in a printed/paper medium.

Atmospheric Sciences

Postdoctoral Research Associate, Princeton University

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), seeks a postdoctoral or a more senior scientist to conduct frontier studies on the predictability and genesis mechanisms of severe convective storms over the continental Unites States using available satellite and radar observations to validate a newly-developed global cloud-resolving model (supported by the Next Generation Global Prediction System project) with two-way global-to-regional nested grid capability, with the ultimate goal of transitioning the prediction capability into operational forecasting.

The selected candidate will have a Ph.D. in meteorology, atmospheric sciences, or a related field. The candidates should have substantial backgrounds in observations, theory, and/or modeling in tropical meteorology (e.g., tropical cyclones), convective-scale storms (e.g., supercell thunderstorms and derechoes), and associated analysis skill, to develop tools to aid model developers in building a next generation multi-scale prediction system for high-impact weather events.

The positions are for one year renewable for up to three years pending satisfactory progress and continued funding. The positions are subject to Princeton University's background check policy.

Applicants must apply online and submit a CV, publication list, contact information for at least 3 references, and a one-to-two page statement of research interests should be submitted to https://www.princeton.edu/acad-positions/position/1261. For additional information contact Shian-Jiann Lin (shian-jiann.lin@noaa.gov) and/or Lucas Harris (lucas.harris@noaa.gov).

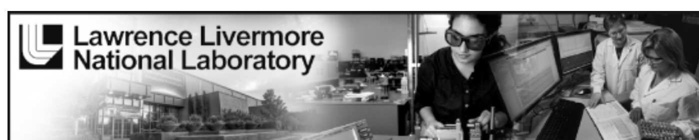
Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status,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

Geochemistry

Part-Time Lecturer, Tufts University–Mineralogy and Petrology

Tufts University invites applications for a one-year appointment as part-time lecturer in the Department of Earth and Ocean Sciences (EOS) to teach a 2-semester sequence in Mineralogy (Fall 2017) and Igneous and Metamorphic Petrology (Spring 2018). The successful candidate will be expected to teach these courses along with their labs to mostly undergraduate Geology and Geological Sciences majors. The EOS Department is well-equipped for undergraduate study in mineralogy and petrology with a teaching lab that has petrographic microscopes, a comprehensive collection of minerals and igneous and metamorphic rocks, rock saws, thin section preparation equipment, and a scanning electron microscope with EDS capability. Tufts University is located in the Boston area and is near a diverse array of different igneous and metamorphic rock terrains conducive to field trips in New England.

Preferred qualifications include a Ph.D. in mineralogy or petrology and teaching experience in these disciplines. All application materials must be submitted via Interfolio at https://apply.interfolio.com/40440. Please



Project Leader, Program for Climate Model Diagnosis and Intercomparison (PCMDI)

We have an opening for the Project Leader and Principal Investigator of the Program for Climate Model Diagnosis and Intercomparison (PCMDI), a major research activity funded by the DOE Office of Science. You will direct an internationally-recognized research effort in climate science, including climate model diagnostics, model performance metrics, and climate change detection and attribution research, and you will provide leadership and community support for international climate modeling activities. This position is in the Atmospheric, Earth and Energy Division.

To apply, visit http://apptrkr.com/980466

LLNL is an affirmative action/ equal opportunity employer.

submit the following: 1) a letter of application including a statement of teaching philosophy and experience in both teaching and research or practice in mineralogy and petrology, 2) a curriculum vitae, and 3) the names (with contact addresses) of three references. Questions about the position can be directed to Professor Jack Ridge, Chair, Department of Earth and Ocean Sciences, at jack.ridge@tufts.edu. Review of applications will begin on March 10, 2017 and will continue until the position is filled.

Tufts University, founded in 1852, prioritizes quality teaching, highly competitive basic and applied research and a commitment to active citizenship locally, regionally and globally. Tufts University also prides itself on creating a diverse, equitable, and inclusive community. Current and prospective employees of the university are expected to have and continuously develop skill in, and disposition for, positively engaging with a diverse population of faculty, staff, and students. Tufts University is an Equal Opportunity/ Affirmative Action Employer. We are committed to increasing the diversity of our faculty and staff and fostering their success when hired. Members of underrepresented groups are welcome and strongly encouraged to apply. If you are an applicant with a disability who is unable to use our online tools to search and apply for jobs, please contact us by calling Johny Laine in the Office of Equal Opportunity (OEO) at 617.627.3298 or at Johny.Laine@tufts.edu. Applicants can learn more about requesting reasonable accommodations at http://oeo.tufts.edu.

Hydrology

Multiple Post-doctoral Positions in Water Sciences, Hohai University

Established in 1915, Hohai University (HHU) is the leader of innovation and development of higher education in hydraulic engineering and water sciences in China. HHU is located at Nanjing, Jiangsu, China. Nanjing is the internationally recognized capital of Jiangsu province, one of the largest cities in China.

The College of Hydrology and Water Resources (CHWR) at HHU invites applications for multiple post-doctoral positions in water sciences, to start as early as March 2017. The positions are open until filled, including (1) 3 positions in watershed hydrological simulation, (2) 3 positions in water resources management, water resources planning, water resources utilization and protection, or water resource policy, and (3) 3 positions in atmospheric-hydrological coupled modeling system, land surface model, or ecohydrology.

The successful candidates will conduct independent, externally funded research programs in their field of expertise. Support for developing an active research agenda is provided through departmental support. CHWR will provide strong supports to the successful candidates to apply for national and provincial research grants.

All candidates must hold a Ph.D. in hydrology, water resources, ecology, and other related fields. The candidates should demonstrate a strong publication potential in hydrology, water resources, and other related fields (at least 2 first-author papers published in internationally recognized journals).

Total income is up to 210,000 RMB/year (appx. 30,000USD/Year) and commensurate with research outputs. Review of applications will begin upon receipt until the position is filled. Materials should be sent to: tao.yang@hhu.edu.cn.

Post-Doctoral Opportunity – Uncertainty in Climate Change Modeling, University of Manitoba

We are seeking a highly motivated post-doctoral researcher with strong academic experience in hydrologic modeling and statistical analyses to examine the impacts of regulation and climate change on freshwater inputs to Hudson Bay. The successful candidate for this position will be working with the freshwater systems team of the BaySys project (an NSERC-funded collaborative research project) to quantify the relative contributions to changes in magnitude and timing from climate change, model uncertainty, and regulation of the Nelson and La Grande Rivers. Candidates will work in close collaboration with industry (Manitoba Hydro, Hydro Quebec) and will be expected to contribute to presentations for the industrial partners, and author peer-reviewed publications.

Applicants should have a strong background in the areas of hydrologic modeling and statistical analyses specifically related to uncertainty assessment, and preferably have experience with climate change simulation. Special consideration will be given to those candidates who have had exposure to programming in R, Matlab, and Fortran.

The successful candidate will study jointly within the Faculty of Engineering (Department of Civil Engineering) and Centre for Earth Observation Science (CEOS) at the University of Manitoba, Winnipeg MB, Canada. Housed within the Clayton H. Riddell Faculty of Environment Earth and Resources, CEOS is home to 15 full time faculty, and approximately 70 other students and staff devoted to the study of Arctic marine science. The Centre is located in the newly developed Nellie Cournoyea Arctic Research Facility. Graduate students have access to state-of-the-art field and laboratory facilities. CEOS is a founding member of the new international Arctic Science Partnership.

Applications should be emailed Dr. Trish Stadnyk (Tricia.Stadnyk@umanitoba.ca)

Please include in your application a CV, transcripts, a short statement of relevant research experience and interests, and the contact information for two referees. Send all documentation in 1 PDF file please.

Interdisciplinary

Assistant/Associate/Full Professors-Physical and biological Oceanography, marine geophysics/geology, The Southern University of Science and Technology

The department of oceanography at the Southern University of Science and Technology of China (SUSTech) invites applications for tenure-track (or tenured) faculty positions at the ranks of Assistant, Associate, and Full Professors. Applicants must have earned doctoral degrees in marine geophysics/geology, physical oceanography, biological oceanography and ocean engineering or closely related fields. Successful applicants will be expected to establish a robust, externally funded research program and demonstrate strong commitment to undergraduate and graduate teaching, student mentoring, and professional services. These positions will remain open until filled.

SUSTech is a young university at Shenzhen, China (next to Hong Kong) since 2010 which is set to become a world-leading research university, to lead the higher education reform in China, to serve the needs of innovation-oriented national development and the needs of building Shenzhen into a modern, international and innovative metropolitan. These positions are created with a significant development to establish a vigorous research program in oceanography at SUSTech to serve the national call for China's important role in deep sea research and resource-oriented exploration in the world oceans.

To apply send a cover letter, complete vitae with list of publications, and three names of references to hiring@sustc.edu.cn, or to Dr. Y. John Chen, Chair Professor at Department of Oceanography, Southern University of Science and Technology, No 1088, Xueyuan Rd., Xili, Nanshan District, Shenzhen, Guangdong, China 518055.

Cluster Hiring in Geo-Bioinformatics/Environmental Genomics and Organic Biogeochemistry, The Southern University of Science and Technology

The Southern University of Science and Technology (known as SUSTech or SUSTC) (http://www.sustc.edu.cn/en) was founded in 2011 with public funding from Shenzhen, a dynamic city

Ocean Prediction Postdoctoral Positions Naval Research Laboratory, Stennis Space Center, MS

U.S. NAVAL RESEARCH LABORATORY

The Naval Research Laboratory is seeking postdoctoral researchers to push forward the frontiers of ocean forecasting. The work covers a wide scope of physics including surface waves, thermohaline circulation, nearshore circulation, and ocean/atmosphere coupling from global to nearshore scales. This challenging work includes processing and analysis of satellite and in water observations, construction of numerical model systems on high performance computing systems and assimilation for predicting the ocean environment. For a quick overview of some of the research work within the NRL oceanography division at Stennis Space Center, visit the web site:
https://www7320.nrlssc.navy.mil/pubs.php

Applicants must be a US citizen or permanent resident at time of application. Applications will be accepted until positions are filled. Please e-mail a resume and description of research interests:

Gregg Jacobs: gregg.jacobs@nrlssc.navy.mil

Tenure-Track Faculty Solid Earth Geochemistry/Petrology

The Department of Geosciences at The Pennsylvania State University invites applications for a tenure-track faculty position at the Assistant Professor level in Solid Earth Geochemistry. We seek a colleague who creatively uses theoretical, observational, analytical and/or experimental approaches to address fundamental problems related to the mineralogy, petrology, and geochemistry of the solid Earth. Candidates with expertise in planets and meteorites will also be considered. Successful applicants will be expected to contribute to a diverse research and teaching community in the Department of Geosciences through the development of a vigorous, internationally recognized and externally funded research program, and through teaching courses in their discipline at the undergraduate and graduate levels. The Department of Geosciences is part of the College of Earth and Mineral Sciences, and houses research programs and state-of-the-art analytical facilities spanning a broad spectrum of Earth Science disciplines (further information is available at: http://www.geosc.psu.edu). Applicants must have a Ph.D. in geosciences or a related field at the time of appointment. Applicants should submit a cover letter, curriculum vitae, a statement of professional interests (research and teaching), and the names and contact information of three references. These materials must be submitted online. Appointment may begin as early as July 1, 2018. Review of applications will begin on September 1, 2017, and continue until the position is filled. For further information or questions, please contact Jim Kasting, Chair of the Search Committee at jfk4@psu.edu.

Apply online at **http://apptrkr.com/977649**

CAMPUS SECURITY CRIME STATISTICS: For more about safety at Penn State, and to review the Annual Security Report which contains information about crime statistics and other safety and security matters, please go to http://www.police.psu.edu/clery/, which will also provide you with detail on how to request a hard copy of the Annual Security Report.

Penn State is an equal opportunity, affirmative action employer, and is committed to providing employment opportunities to all qualified applicants without regard to race, color, religion, age, sex, sexual orientation, gender identity, national origin, disability or protected veteran status.

that has been viewed as the vanguard of China's development in science and technology. The goal of SUSTech is to become a top-tier international university that excels in interdisciplinary research, talent development and knowledge discovery.

Siting at the mouth of the Pearl River flowing to the South China Sea, the newly born (2015) Department of Ocean Science and Engineering at SUSTech aims to become a major player in education and research in ocean sciences in China. It will be housed in a brand new building on the beautiful SUSTech campus, with ample laboratory space that is equipped with the latest technology for conducting cutting edge research. The 5000 ton R/V Shenzhen is in the planning stage of construction, which is expected to be built by 2022.

The Institute for Geo-Omics Research (TIGOR) at SUSTech aims to become an open platform for world class research in microbial oceanography and geomicrobiology, and an inviting home for domestic and overseas scientists to exchange ideas and together advance the field of ocean sciences. In the early stage of TIGOR's growth, the priority will be to build two research strengths: Geo-Bioinformatics/Environmental Genomics and Organic Biogeochemistry. The integration of these strengths will allow us to study systematically the evolution of life on early Earth, microbial ecology impacted by human activity, mechanisms of bio-organic interactions in the deep ocean, and fundamentals of biogeochemistry (e.g. lipid biosynthesis and bio-fractionation of isotopes of life-essential elements).

In Geo-Bioinformatics/Environmental Genomics hiring, we seek highly qualified candidates (at the assistant or associate professor levels) who are able to apply bioinformatics techniques (metagenomics, multi-omic integrative analysis, in silico lead discovery from microbial metabolites and computational biology algorithm/server development) to analyze data from the next-generation sequencing and other high-throughput sequence profiling to address fundamental questions mentioned above. Candidates with strong ecological backgrounds are particularly encouraged to apply.

In Organic Biogeochemistry hiring, we seek highly qualified candidates (at the assistant, associate or full professor levels) with strong skills in mass spectrometry and isotope geochemistry. The candidates are expected to apply GC-MS, LC-MS (Orbitrap or ion mobility Q-TOF), FT-ICR MS, or AMS to address questions mentioned above.

Highly competitive salaries and benefit packages will be provided to the hired candidates, who may also be eligible for additional government support such as the Shenzhen City's Peacock Program and the Chinese Government's One Thousand Talents Program (http://www.sustc.edu.cn/en/faculty_en).

Applicants are required to have a Ph.D. degree in earth sciences, biology, chemistry, computer science, or related disciplines. Post-doctoral experiences are preferred but not required. Candidates must have a proven and consistent track record of high-quality scientific publications and good communication skills. Chinese and English are required languages for teaching. To apply, please submit the following material electronically to wangy9@sustc.edu.cn: 1) Cover letter; 2) Curriculum vitae (with a complete list of publications); 3) Statement of research and teaching interests; 4) Reprints of three recent papers; and 5) Names and contact information for three references. All positions remain open until filled.

Faculty Positions available in the School of Environmental Science and Engineering, The Southern University of Science and Technology

The Southern University of Science and Technology (known as SUSTech or SUSTC) (http://www.sustc.edu.cn/en) was founded in 2011 with public funding from Shenzhen City. A thriving metropolis of 20 million people bordering Hong Kong, Shenzhen has often been referred to as the "Silicon Valley of China" with strong telecommunication, biotechnology and pharmaceutical sectors. The goal of SUSTech is to become a top-tier international university that excels in interdisciplinary research, talent development and knowledge discovery. English is the language of instruction.

The School of Environmental Science and Engineering at SUSTech was established in May 2015 to provide a new platform for performing cutting-edge research and for training a new generation of environmental scientists, engineers and managers who are interdisciplinary, innovative and global-thinking. Currently the school has 18 full time faculty members (http://ese.sustc.edu.cn/en/) with 30 or more tenure-track/tenured positions to be filled. In addition to a generous startup package to each tenured or tenure track faculty position, the school was recently awarded a 3-year grant of 50 million RMB (~7 million USD) to strengthen its 5 core areas of research. Moreover, the school is in line to receive 120 million RMB (~18 million USD) for research instrument capability development.

Applications are invited for faculty positions at all ranks. Areas of interest include, but are not limited to, water pollution and treatment, environmental (soil, groundwater, ecosystem) remediation and restoration, hydrology and water resources engineering, biogeochemistry, environmental microbiology, atmospheric chemistry, air pollution control, air quality engineering, solid waste treatment and utilization, environmental health risk assessment, environmental health interventions, remote sensing of the environment, global change, and environmental management. Highly competitive salaries and benefit packages will be provided to tenure-track/tenured faculty. New hires may be eligible for additional government support such as the Shenzhen City's Peacock Program and the Chinese Government's One Thousand Talents Program (http://www.sustc.edu.cn/en/faculty_en).

Applicants are required to have a Ph.D. degree in environmental science and engineering, earth and atmospheric sciences, or related disciplines. Post-doctoral experiences are preferred but not required. Candidates must have a proven and consistent track record of high-quality scientific publications and good communication skills. Chinese language skill is a plus but not required. To apply, submit the following materials electronically to iese@sustc.edu.cn: 1) Cover Letter; 2) Curriculum Vitae (with a complete list of publications); 3) Statement of research and teaching interest; 4) Selected reprints of three recent papers; and 5) Names and contact information for five references. All positions remain open until filled. For additional information, contact Xiaoli Wang, Email: wangxl@sustc.edu.cn, phone: +86-755-8801-0821.

Graduate Student Research and Teaching Assistantships- Env, Earth & Atmos Sciences, University of Massachusetts, Lowell

The Department of Environmental, Earth, and Atmospheric Sciences (EEAS) at the University of Massachusetts Lowell (www.uml.edu/sciences/eeas) offers several graduate research and teaching assistantships for motivated students for the Fall 2017 semester. Several positions are currently open, including in: Geochronology and Isotope Geochemistry (Prof. Richard Gaschnig), Extreme Precipitation in the Northeast US (Prof. Mathew Barlow), Arctic Greenhouse Gas Cycling (Prof. Daniel Obrist), Climatology of Snow Squalls in the Eastern U.S. (Prof. Frank Colby), Buried Ice in Antarctica (Prof. Kate Swanger), and Environmental Mercury Cycling (Prof. Daniel Obrist). Further information about these positions can be found on our webpage.

The University of Massachusetts Lowell (also known as UMass Lowell) is an urban public research university in Lowell, Massachusetts, with nearly 1,150 faculty members and 18,058 students. EEAS offers unique interdisciplinary study programs encompassing Geosciences, Meteorology, Hydrology, and Environmental Chemistry. EEAS offers undergraduate and graduate degrees in Environmental Sciences, with concentrations in Environmental Studies, Geosciences, and Atmospheric Sciences. Graduate School admission policies are found under https://www.uml.edu/grad/.

Hydrographic Science Faculty Position, University of Southern Mississippi

The University of Southern Mississippi's School of Ocean Science and Technology (SOST), Division of Marine Science (DMS; http://www.usm.edu/marine/) at the NASA John C. Stennis Space Center (SSC) is offering a position in hydrographic science at the tenure-track, Assistant or Associate Professor level. Applicants should hold a Ph.D. in a hydrographic science, marine science, geomatics engineering, ocean engineering, or closely related field. Applicants will have demonstrated field and research experience in acoustic and LIDAR-based hydrographic and bathymetric surveying, and precise positioning at sea. Proficiency in commercial software packages used to collect and process hydrographic data is expected. Also desirable is an interest in applying hydrographic technologies to collaborative opportunities in marine science, including biological, chemical, physical, geological and fisheries oceanography. A nationally recognized record of publication, demonstrated successful grantsmanship, and at least 5 years service at a degree-granting institution or equivalent service at a non-degree granting institution are needed at the Associate-level. A successful candidate is expected to conduct an active research program and participate in the hydrographic science master's program, which is recognized at the Category-A (Cat-A) level by the International Hydrographic Organization. The latter efforts include curricula review, delivery and development of the program, and faculty experience in delivering a Cat-A hydrographic science curricula are highly desirable. The development of courses for a new hydrography emphasis in the undergraduate Marine Science degree program is also expected.

Along with DMS, SOST integrates the Gulf Coast Research Laboratory, the Division of Coastal Sciences, and the University's fleet of five research vessels, to form a regionally, nationally and internationally recognized leader in marine science. DMS is home to an interdisciplinary program of graduate and undergraduate study and research in marine environments. Seventeen on-site faculty conduct research and teach courses in biological oceanography, marine chemistry, geological oceanography, physical oceanography, remote sensing, numerical modeling, and hydrography to ~50 full-time graduate students at SSC and ~40 undergraduates at the USM Gulf Park campus. The Division offers Marine Science B.S., M.S. and Ph.D. degrees and a Hydrographic Science M.S. Located at SSC, Marine Science is strategically situated at the single largest concentration of oceanographers and hydrographers in the world. Faculty interact with research

METER

METER Group, Inc. USA is seeking a Product Development Scientist (Product Owner) at the M.S. or Ph.D. level with some micrometeorology or atmospheric science field instrumentation experience and optimally also plant science expertise. This individual will work with a dedicated team of engineers and scientists to develop new instrumentation for Environmental/Ag/Atmospheric/Plant Science researchers.

Responsibilities:

- Provide product ownership of METER's ATMOS and PHYTOS product lines, which include atmospheric and plant measurements
- Lead dedicated product development team, acting as the subject matter expert
- Regularly interact with customers at tradeshows, customer sites, etc., to develop product vision and allow development team to iterate and make better products

Minimum Qualifications include:

- M.S. or Ph.D. with research/coursework in Environmental Biophysics, Atmospheric Science, Climatology, Micrometeorology, or related field
- Field instrumentation experience during research program
- Plant science coursework or research
- Excellent verbal and written communication skills
- General knowledge of current research and monitoring needs in these areas and willingness to routinely communicate with researchers to learn more
- Ability to travel as much as 3 weeks/quarter
- Ability to manage complex projects from start to finish, often with competing priorities
- Background check results satisfactory to METER
- At least three professional or academic references will be required during the interview process

scientists at government agencies located on site and at the Joint Airborne Lidar Bathymet y Center of Excellence (JALBTCX) including the Naval Oceanographic Office, Naval Meteorology and Oceanography Command (CNMOC), Naval Research Laboratory (NRL-SSC), USACE, NOAA, USGS, and NASA.

Applicants should submit a letter of interest outlining their qualifications for the position, including a research plan, teaching philosophy with a curricular plan, a curriculum vitae, and names and contact information of at least four references. Applications must be submitted online at https://jobs.usm.edu. For inquiries about the position, contact Stephan Howden, Chair of the Search Committee, at 1-228-688-5284 or stephan.howden@usm.edu. Review of applications begins 1 February 2017 and continues until the position is filled, with an anticipated start date of August 2017.

AA/EOE/ADAI

Postdoctoral Research Associate in Understanding Cryosphere-Aerosol Interactions Over High Mountain Asia, Princeton University

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), seeks a postdoctoral or more senior candidate for research related to how cryosphere-aerosol interactions affect hydroclimate variability over High Mountain Asia. A key focus will require comparing observations and high-resolution global climate model output to understand hydroclimate variability over High Mountain Asia with a particular emphasis on the cryosphere-aerosol interactions and related processes. This will include an assessment of presently available and future developmental satellite-based data products and other regional observational or model-based reanalyses. This will also include an assessment of aerosol-climate interactions in the region and targeted analysis to better understand how aerosol deposition and its variability may affect regional hydroclimate in both the historical record and the future. The research will also examine how the cryosphere and hydroclimate respond to natural variability and radiative forcing changes over the next 100 years. This position will provide the opportunity for collaboration within GFDL and Princeton University, as well as with members of the NASA High Mountain Asia Team at various institutions. Travel to meet with collaborators will be encouraged, but not required.

The selected candidate will have one or more of the following attributes: (a) a strong background in hydroclimate, climate dynamics, snow hydrology, cryosphere science, or a closely related field; (b) experience using and analyzing advanced climate models and observational datasets (including remote sensing data); (c) strong diagnostic skills in analyzing large data sets.

Candidate must have a PhD. Initial appointment is for one year with the possibility of renewal subject to satisfactory performance and available funding.

Complete applications, including a CV, publication list, at least 3 letters of recommendation, and a short statement of research interests should be submitted by May 5, 2017 for full consideration.

Applicants must apply online to https://www.princeton.edu/acad-positions/position/1221. For additional information, you may contact Dr. Sarah Kapnick (sarah.kapnick@noaa.gov) or Dr. Paul Ginoux (paul.ginoux@noaa.gov).

This position is subject to the University's background check policy.

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

Ocean Sciences

Postdoctoral Investigator, Woods Hole Oceanographic Institution

As part of a project funded by the National Science Foundation, a position for a Postdoctoral Investigator is available in the Department of Geology and Geophysics at Woods Hole Oceanographic Institution. We invite applications for the position to investigate abrupt changes in ocean circulation during the last glacial cycle. The initial appointment is for one year with the possibility of an extension based on funding and performance. Review of applications will begin immediately and continue until the position is filled. The start date is flexible, but preference will be given to qualified candidates who are available to begin by August 1, 2017.

The institution has a top-rated postdoctoral program that supports a dynamic postdoctoral community with formal mentoring and career guidance programs. While the primary focus of the work will be in research, the postdoctoral investigator will have an opportunity to participate in educational and outreach activities associated with the project. (www.whoi.edu/postdoctoral/)

Desired education and experience: Recent Ph.D. in Earth or Ocean Sciences or related disciplines, experience with trace element analytical techniques as applied to marine microfossils from sediment cores and with demonstrated accomplishments in related research areas. Please apply at http://www.whoi.edu/jobs.

Planetary Sciences

Research Scientist–Mars Science, Jet Propulsion Laboratory (JPL)

The Planetary Science section at the Jet Propulsion Laboratory (JPL) in Pasadena, CA is looking to fill a position for a researcher in areas relevant to future planetary sample return missions.

The position is to conduct Mars-related scientific research within one of the following fields: Geology, Geochemistry, Geomorphology, Astrobiology, and Petrology. The candidate should have a PhD in planetary science, or related scientific discipline, along with demonstrated experience in conceiving, defining, and conducting independent scientific research, with a strong interest in applying those efforts to problems related to the origin, evolution and/or habitability of Mars including the study of results from orbital and in situ Martian measurements and/or extraterrestrial samples.

It is expected that the successful candidate will pursue new mission and/or instrument opportunities focusing on Martian exploration through advocacy and outreach within the scientific and stakeholder community. This pursuit will involve working closely with science and engineering teams at JPL to design solar system sample return and Martian exploration missions and instrumentation.

The candidate is also expected to participate in long-lead activities related to humans-to-Mars being coordinated by the Mars Program Office. This may involve participating in engineering-led planning teams, interaction with personnel involved in similar efforts at other NASA locations, helping to play a coordination role with the interested external community, participation in relevant committees, involvement in subject conferences, and maintaining external visibility through publication.

The position may include a significant start up funding package.

To view the full job description and apply to the position, please visit:

www.jpl.nasa.gov/opportunities/, (see Requisition # 2017-7983). Candidates should submit a CV that includes a list of publications and an introductory cover letter (no more than 2 pages) that includes research, research goals and the names and contact information of references.

JPL is a Federally-Funded Research and Development Center operated by the California Institute of Technology for NASA. JPL/Caltech is an equal opportunity/affirmative action employer.

Postcards from the Field

Hi, Folks.

Artist Mike Carroll and I went to Mount Erebus in Antarctica, under the auspices of the National Science Foundation's Writers and Artists Program, to do a book comparing landscapes on Erebus with those on icy moons. Here I am (in red) descending into Hut Cave on the slopes of Erebus, aided by mountaineer Evan Miller (in blue). These ice caves are truly otherworldly features, and we can imagine that they might exist on Europa or Enceladus.

—**Rosaly Lopes,** Jet Propulsion Laboratory, Pasadena, Calif.

View more postcards at *http://americangeophysicalunion.tumblr.com/tagged/postcards-from-the-field.*

AGU PUBLICATIONS

Editors in Chief Needed

Reviews of Geophysics

AN AGU JOURNAL

Global Biogeochemical Cycles

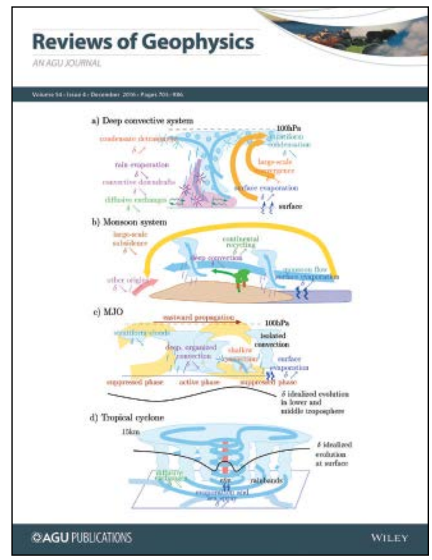
AN AGU JOURNAL

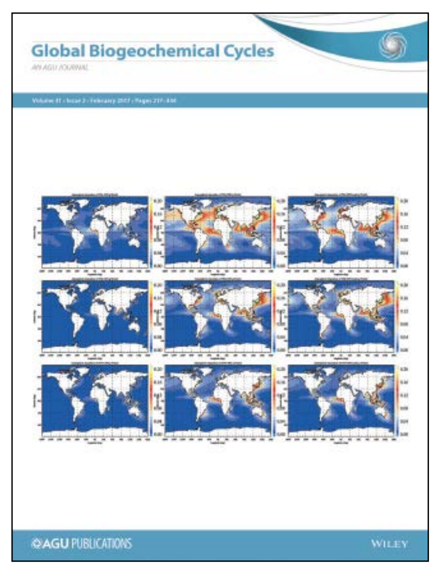
AGU is looking for two dynamic, well-organized scientists with high editorial standards and strong leadership skills to serve a 4-year term as editor in chief (EIC) for *Reviews of Geophysics* or *Global Biogeochemical Cycles*.

The EIC is the principal architect of the scientific content of the journal. The EIC is an active scientist, well-known and well-regarded in his/her discipline, and must be active in soliciting the best science from the best scientists to be published in the journal. Working with the other editors and AGU staff, the EIC is the arbiter of the content of the journal. Among other functions, the EIC is responsible for:

- **Act as an ambassador to the author/editor/reviewer/scientist community.**
- **Set the strategy for the journal.**
- **Lead the editor selection process.**
- **Assign and balance review work load.**
- **Decisions of ethics.**
- **Review and contribute to periodic monitoring reports.**
- **Conduct and attend meetings.**

If you would like to be considered, send your CV with a letter of interest via email to pubmatters@agu.org. If you would like to nominate a highly qualified colleague, send a letter of recommendation to the same email address. **Please make sure to include the name of the journal in the subject line.**





Application Deadline: 15 May 2017