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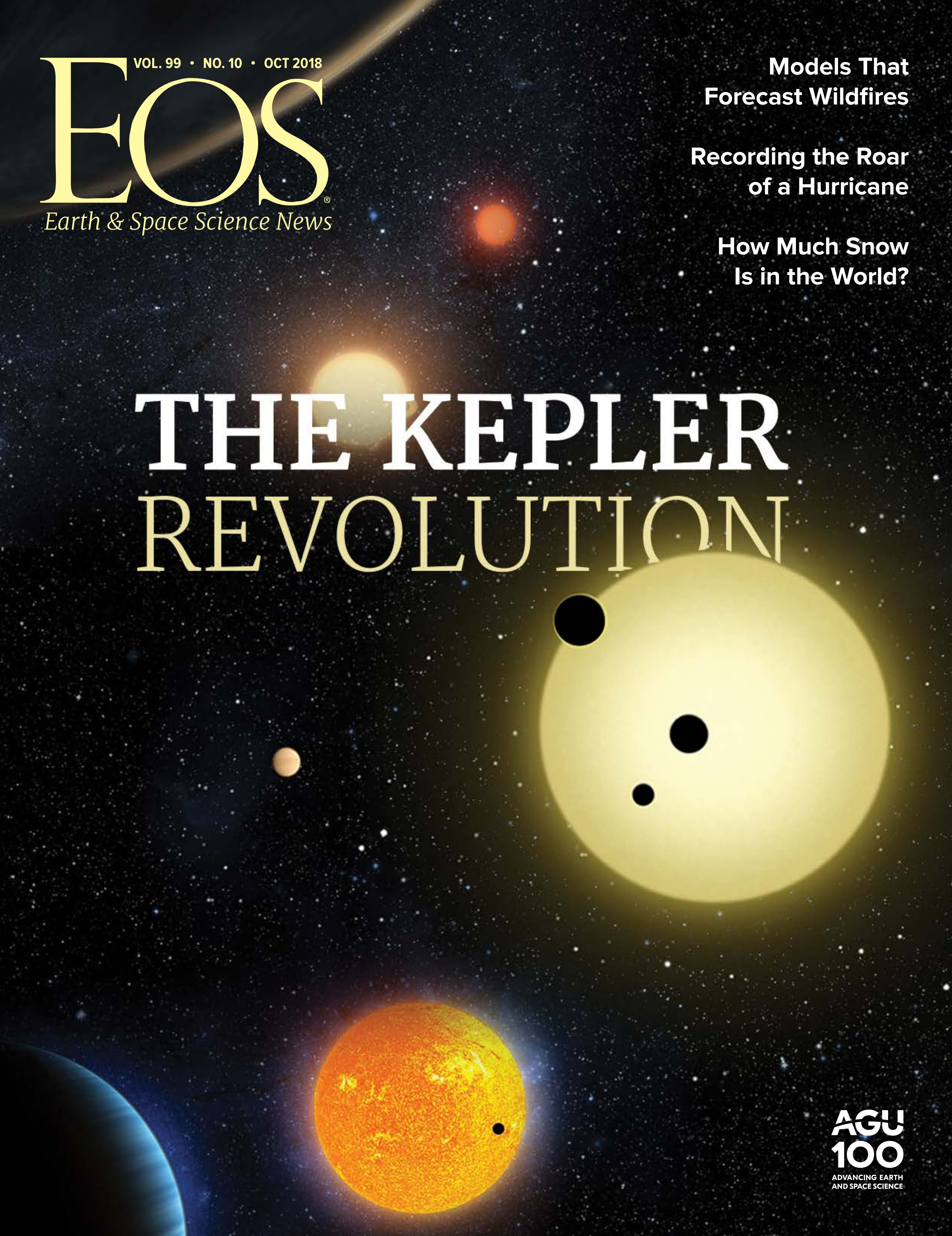

Models That Forecast Wildfires

Recording the Roar of a Hurricane

How Much Snow Is in the World?

THE KEPLER REVOLUTION

AGU 100
ADVANCING EARTH AND SPACE SCIENCE

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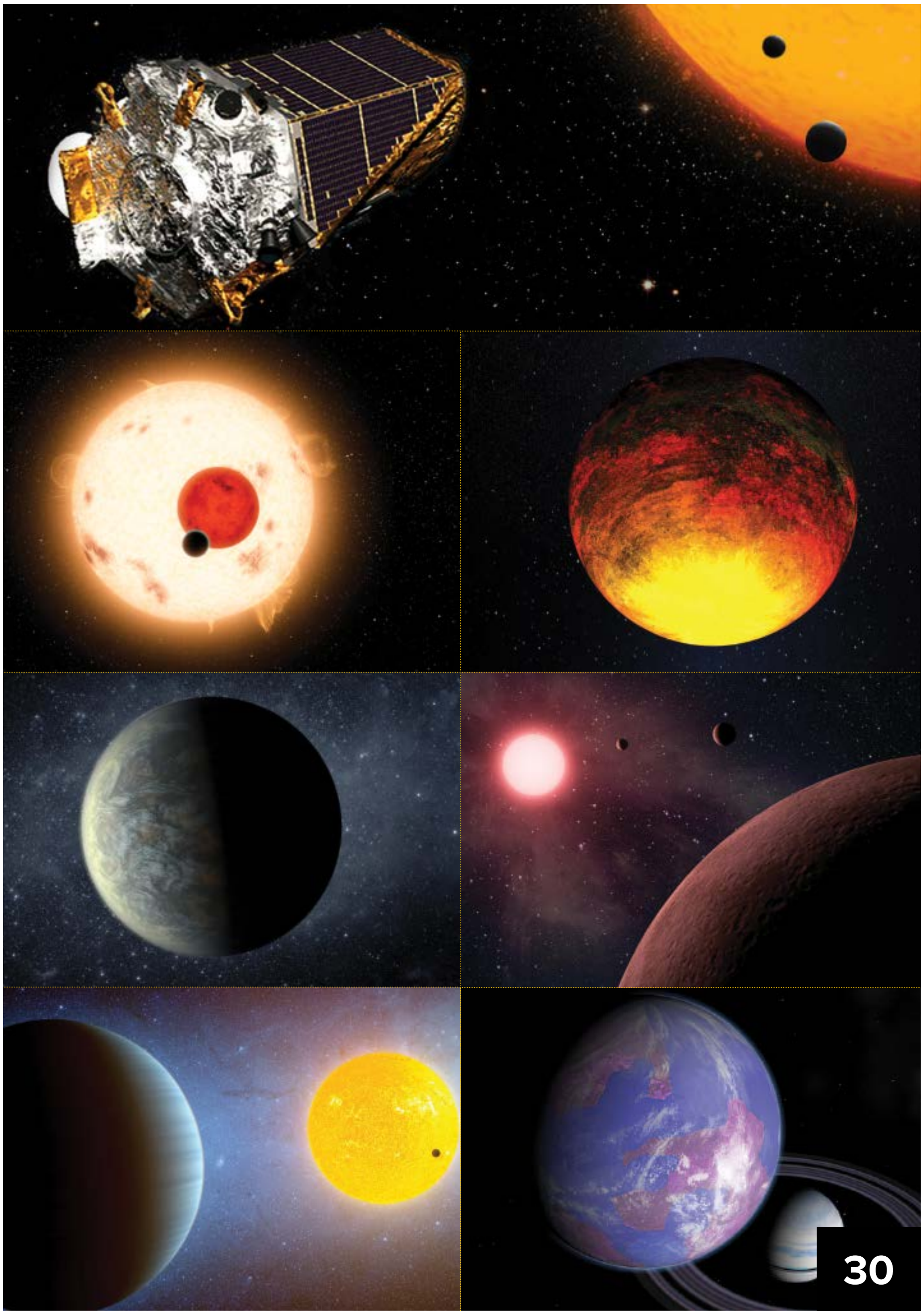

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A collage of artists' renditions of exoplanets discovered by the Kepler telescope. Credit: NASA

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Hail Causes the Most Storm Damage Costs Across North America

Gregg Cruger holds hailstones collected from a storm that damaged his family's home in Louisville, Colo., on 18 June. Cruger and his wife, Katy Human, witnessed the storm from their front porch. Credit: Helen H. Richardson/Contributor/Denver Post/Getty Images

On 18 June, Katy Human and her family watched as tiny chunks of ice fell from the sky.

At first, Human and her family, of Louisville, Colo., were delighted. "Hail is cool and relatively rare, so we all went out on the front porch to watch it," she said.

However, "Over the next 10 minutes, it got bigger and bigger." The family backed up, pressing against the wall of their house as golf- and tennis-ball-sized hailstones pummeled their yard.

"We have a garage, but both cars were out," she said. "It went from 'Oh, my God, isn't this beautiful' to 'Holy crap, this is doing a lot of damage.'"

Human's family was witness to something that people in the insurance industry have long known. Tornadoes and hurricanes may grab headlines, but when it comes to property damage, the biggest extreme weather culprit is an often overlooked weather phenomenon: hail.

Hailstorm destruction exceeds $10 billion each year across North America, accounting for almost 70% of the property damage in insurance claims from severe storms, said Ian Giammanco, lead research meteorologist at the Insurance Institute for Business and Home Safety's research center in Richburg, S.C. But, he said, funding for hail studies is limited, and the phenomenon is often treated by the public as a curiosity.

"It's the Rodney Dangerfield of perils," he said of hail. "It just doesn't get any respect."

"It's the Rodney Dangerfield of perils," he said of hail. "It just doesn't get any respect."

Giammanco spoke on a panel of scientists at the North American Workshop on Hail & Hailstorms. The mid-August 3-day symposium, the first of its kind in the United States, was hosted by the National Center for Atmospheric Research (NCAR) in Boulder, Colo. (http://bit.ly/Hail-Workshop).

Making Hail

The workshop occurred just a week after a severe hailstorm pelted Colorado Springs, about an hour's drive from Boulder, with hailstones reported to be as large as softballs. The storm caused millions of dollars in property damage, injured more than a dozen people, and killed five animals in the Cheyenne Mountain Zoo.

Colorado and the central United States are hot spots for hailstorms, explained panelist Andreas Prein, an NCAR project scientist who studies climate modeling with a focus on severe storms. Colloquially called hail alley, the area has the right conditions for severe thunderstorms that can produce large hailstones.

A severe hailstorm needs unstable air with a strong updraft, differing wind speeds and wind directions, air that's humid close to the ground and dry at higher altitudes, and a freezing point that's relatively close to the ground.

These conditions work together to form the largest hailstones by drawing moisture up from the ground and quickly cooling it into chunks of ice. The hailstones then circulate around and around within the storm, picking up more moisture and growing larger. Finally, the swirling hailstones have only a short distance to fall back to Earth; as a result, they don't melt on the way down, Prein said.

Climate Effects Unclear

Hail damage is expected to increase in coming years, largely driven by population growth and suburban sprawl. Sprawl means more buildings and thus "bigger targets for hailstorms to hit," Giammanco said.

But humans are also thought to be influencing hail itself, through climate change. The effect, however, isn't straightforward, influencing hail-forming conditions in varied and sometimes contradictory ways, Prein explained.

For example, climate change is expected to increase air buoyancy for strong updrafts, but at the same time it appears to be causing the freezing level to move higher above the ground. "The question is, How are these things interacting, and how are they affecting hail frequency?" Prein said.

He noted that whereas most of the country has seen hail decrease over the past 100 years, certain areas, including the central United States and the mid-Atlantic states, have seen it become more frequent and severe.

"We need more research on that to really understand how climate change and climate variability [are] changing hail hazard," Prein said.

Efforts to Study Hail

Hail expert and panelist Andrew Heymsfield, NCAR senior scientist and cochairman of the workshop, noted that a hailstorm-penetrating aircraft that had been used to gather important data since the 1970s had been decommissioned in 2003, leaving scientists without an important tool for research for the past 15 years.

Another panelist, Kristen Rasmussen, an atmospheric scientist at Colorado State University in Fort Collins, hopes to help reset the scales. She will travel to Argentina later this year to study one of the most hail-prone areas in the world.

Storms producing hail the size of oranges and grapefruits are a yearly occurrence in areas like Mendoza, and hail causes significant monetary damage to the region's many vineyards. But the area lacked any storm forecasting ground radar or warning systems—such as those provided by the National Weather Service in the United States—until about a year ago, she explained.

For her field project, funded by the National Science Foundation and the U.S. Department of Energy, Rasmussen plans to bring a suite of ground-based radars, hydrological gauges, lightning mapping instruments, and other equipment to learn more about the science of severe storms and hail formation. "We're trying to study the whole convective process from beginning to end," she said.

Extensive Damage

For Human, who works with storm researchers as communications director for the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder, the science of hail is now personal.

After the 18 June storm, she and her family stumbled out into the street; it was difficult to walk because they kept slipping on the smooth spheres of ice that littered the ground. There they joined their shocked neighbors in inspecting the damage. "Both cars were totaled," she recalled. Her home's solar panels were smashed and the roof was battered. Human later learned that the whole roof would have to be replaced. Human estimates the total damages at around $50,000, which will be covered by insurance.

Still, Human didn't lose her sense of wonder for hail. "They're beautiful when they crack open," she said. "There are these intricately layered concentric circles, like tree rings. They're gorgeous."

By **Ilima Loomis** (email: ilima@ilimaloomis.com; @iloomis), Freelance Journalist

Forecasting Models Are Changing the Way We Fight Fires

Firefighters stand silhouetted by the flames of the Ranch Fire, part of the Mendocino Complex fires in California. Credit: AP Photo/Noah Berger

Across the western United States, more than 100 fires burned through tinder-dry forests this summer. In California alone, one of the Mendocino Complex fires, the Ranch Fire, was the state's largest on record, and the Carr Fire may go down as the state's sixth most destructive fire by number of structures burned.

Even in places far from the flames, residents could feel the sting of wildfire smoke: In eastern Washington, for example, air quality in mid-August reached hazardous levels, with air quality indices of greater than 300. These levels prompted universities to cancel sports events and officials to caution everyone, regardless of age or health status, to avoid outside activities.

As the wildfires continued to blaze, scientists at the National Weather Service (NWS) turned to satellites and numerical models to aid firefighters on the ground. One of their latest tools was developed by NWS's parent body, the National Oceanic and Atmospheric Administration (NOAA). The model, created by scientists in the Office of Oceanic and Atmospheric Research's Global Systems Division, is a weather and smoke forecasting tool that helps communities downwind cope with soot-filled skies.

Eos spoke with one the people behind these tools: Andy Edman, chief of the Science and Technology Infusion Division of NWS's western region. The interview below has been condensed and lightly edited for flow and grammar.

Eos: *What is your role at the NWS?*

Andy Edman: I work in the western region headquarters here in Salt Lake City, Utah. Our group is responsible for the western third of the U.S. As researchers and academics come up with new ideas, my role is to take a hard look at them, and if it's appropriate, to infuse the new research into the services that we provide.

Eos: *How do you help communities fight fires?*

Edman: Over the last several years, there was a strong message from both fire managers and community managers, such as mayors, that we need better forecasts. If we wait till the fire is happening, it's too late to react. A city needs time to get ready.

Eos: *And that's where the NWS comes in?*

Edman: NWS is responsible for providing watches, warnings, and forecasts of the weather and hydrological events. Wildfires are particularly driven by the weather, so we provide a number of different services. We provide forecasts to both state and federal land agencies, saying, for example, "Here's what the weather is," or pointing out if conditions are ripe for a fire. The agencies can adjust their tactics accordingly.

One of the recent trends in the firefighting community is that they're getting much better about moving resources in anticipation of fire potential. If we've been having monsoon rains in Arizona or Utah, the agencies watching wildfire risk will start moving fire crews and repositioning them to, say, northern California, based on the forecast. About a week out, NWS will point to a region that's going to be hot, dry, and windy, and fire managers will begin to plan and pre-position resources in the general area before a fire even gets started. It takes time to move crews and equipment.

Eos: *The Carr Fire in California left in its wake a thousand buildings destroyed and resulted in at least eight deaths. How did the NWS assist the agencies fighting the Carr Fire?*

Edman: A week or two before the Carr Fire started, the NWS started highlighting to state and federal agencies in northern California that the atmosphere was warming up and that it was going to get spectacularly warm and dry there.

Once the fire got started, we sent briefings whenever the fire crews needed them. Knowing something about the wind direction and speed and how stable the atmosphere is makes a big difference. If the air is unstable, it can help support an updraft on the flames, and you'll see more dangerous fire activity. We also had an incident meteorologist, called an IMET, on the Carr Fire since almost day one.

Eos: *Has firefighting changed over the years, given that NWS now provides current and expected ground conditions and wind speeds?*

Edman: What's changed in the last 30 years is that the fire managers can be much smarter about where they put the crews. When I started at NWS, we had some incidents when we had fires burn over the fire crews, and we lost people. That doesn't happen very often these days. We're better at anticipating where fire activity is likely to increase and positioning the fire crews accordingly. The fire tactics are smarter.

"There has been a strong message from both fire managers and community managers, such as mayors, that we need better forecasts."

Eos: *Where do you get your data to advise fire crews? From planes? Satellites?*

Edman: It's a combination of observations, such as satellites, radar, and surface observations, as well as numerical modeling.

Eos: *You've been experimenting with a new model to predict where wildfire smoke will go. Even though it is still in its testing stages, the forecasting model, called High-Resolution Rapid Refresh–Smoke (HRRR-Smoke), has been providing fire managers and communities with valuable insights. What does it do?*

Edman: The model shows where the high levels of smoke concentrations are, and where they're headed. We start with an initial state of the atmosphere, and from there the model makes a forecast for the next 36 hours.

On 3 August 2018, European astronaut Alexander Gerst captured this image of smoke billowing from the Carr and Ferguson wildfires in California from aboard the International Space Station. Credit: NASA

Eos: *Other than making the sky hazy, what are the risks from wildfire smoke?*

Edman: It impacts where helicopters and airplanes can fly, because they have certain restrictions about when they can fly when the visibility gets too low, so they can't do target drops or move fire crews around.

In the communities close to the fires, smoke is a real health hazard. For example, Yosemite National Park closed for almost 3 weeks in August. The fire was physically outside of the park, but the smoke was blowing into the park. And the emissions were so high that park officials said that it was unhealthy for people to be there.

Eos: *How does HRRR-Smoke work? Where does it get the latest data about active wildfires?*

Edman: The HRRR model receives information about fire location and intensity from several polar orbiter instruments, such as the Joint Polar Satellite System (JPSS) and Moderate Resolution Imaging Spectroradiometer (MODIS). The instruments sense the heat signature of the fires using infrared light, and from that we get the fire location and intensity.

Once we get that information, the next step is to translate those data into an estimate of how much smoke is coming off the fires. That information is used by the high-resolution HRRR meteorological model to forecast where the smoke will go.

Eos: *Who has access to the HRRR-Smoke model output? Can we see it, or is it just for fire managers?*

Edman: We give it to the fire crews, and our western offices have been including it in our routine forecasts. Community leaders are paying attention to it. For example, there was a big bike race in Utah that's sort of the local version of the Tour de France. The organizers were worried about the smoke, so the NWS gave forecasts to the organizers.

Eos: *You've said that HRRR-Smoke is still in R&D. What could it do better?*

Edman: It's very much a work in progress. Every part of it needs to get better. We still struggle to model small fires and brand-new fires, because it takes time for the satellites to pick those up.

Eos: *What do we gain from this new technology?*

Edman: This is a great example of where we're going with science. It's no longer good enough to just observe something. For example, we can show you a pretty picture of a hurricane, but the first thing you're going to ask me is if it's going to hit your house.

Eos: *Does the Science and Technology Infusion Division have anything else new in the pipeline?*

Edman: The NOAA GOES-17 satellite was launched about 7 months ago. Once that's operational, we want to explore what we could do with those images too. What we have currently is GOES-15, but it is the older generation. It's close to 9 years old. Satellites are a little like cars; every generation gets better and better. GOES-17 can take imagery updates as quickly as every minute, whereas the other satellite can do it only every 5 minutes.

By **Jenessa Duncombe** (@jenessaduncombe), News Writing and Production Intern

U.S. Senate Reviews NASA's Science Priorities

Does life exist beyond Earth? Can we find it? What science should NASA prioritize in the near future? How will the agency reach its lofty exploration goals on time and within budget?

These were the central questions at a hearing in U.S. Senate offices on 1 August that focused on assessing the current priorities of NASA's Science Mission Directorate (SMD). During the hearing, senators heard testimony from scientists and administrators whose expertise covers the wide range of NASA's mission.

"As we look to draft a new NASA authorization act, hopefully this year, it is imperative that we continue to make progress answering [these questions]," said Sen. Ted Cruz (R-Texas), chairman of the Senate's Subcommittee on Space, Science, and Competitiveness, which convened the hearing.

During a previous hearing on 25 July, the subcommittee heard testimony about sending humans to Mars, a recent priority handed down from President Donald Trump. During the 1 August hearing, the subcommittee sought to assess NASA's science priorities ahead of Congress's reauthorization of NASA by the end of 2018. Congressional authorization is a regular process that confirms a federal program's continued operation, defines the scope of its mission, and allows it to receive appropriated funding.

> "The eventual success of [JWST] will be a source of national pride and a symbol of U.S. technical prowess."

Cruz stated that Congress must "also equip NASA with the capabilities that it needs to support science missions and priorities that will lead to discoveries across our solar system." He added, "This is a momentous time to be involved in space exploration."

What should NASA's science priorities be? Here are five key takeaways from the witnesses at the early August hearing.

1. Decadal Surveys Have Their Drawbacks

NASA currently sets its science priorities by following decadal surveys put together by the National Academies of Sciences, Engineering, and Medicine. These comprehensive overviews declare what the space science community believes to be the most important outstanding science questions and the missions needed to answer them.

The witnesses at the hearing, however, disagreed about how effective the decadal survey process is at deciding what's best for the space science community.

Sara Seager, a professor of astrophysics and planetary science at the Massachusetts Institute of Technology in Cambridge, explained that "the whole community feels that if they don't have one mission that the entire community buys into, that it will never get selected by the decadal survey." But getting that buy-in can lead to complex "all-in-one" missions, such as the delay-ridden James Webb Space Telescope, that may be too far beyond our technological capabilities to produce on time, she said.

There's also a generational issue, according to Seager. The scientists deciding what goes into a decadal survey are "the senior seed people who wouldn't necessarily vote the same way that the new generation would," she said.

The gold primary mirror of the James Webb Space Telescope, NASA's next flagship telescope mission. This photo was taken in April 2017 when the telescope mirrors were still at NASA Goddard Space Flight Center in Greenbelt, Md. Credit: NASA/Desiree Stover

Ellen Stofan, director of the Smithsonian's National Air and Space Museum in Washington, D. C., disagreed, arguing that the decadal process is effective as is. However, she believes that it could be more representative. "If we don't focus on increasing diversity in science, technology, engineering, and math," she said, "we are doing a disservice to our country because we are not tapping into the talent of all of our nation."

"It's really important that a diverse set of opinions are being listened to," added Thomas Zurbuchen, who is the associate administrator of

SMD, "because that's where good decisions come from: people with different backgrounds and different priorities."

2. James Webb Space Telescope Frustrates yet Excites

NASA's next flagship telescope, the James Webb Space Telescope (JWST), is currently under development and has undergone a frustrating set of delays and cost growths, witnesses attested.

"These large projects are challenging and require perseverance," said David Spergel, a professor of astronomy at Princeton University in Princeton, N.J. "JWST's delays are frustrating to all of us."

JWST, the successor to the aging Hubble Space Telescope, was originally estimated to cost $500 million and be launched in 2007. Its current cost estimate is $9.6 billion, and it is scheduled for launch in 2021.

"I think that if we went back in time," Spergel acknowledged, "we would have preferred to be able to build a 4-meter James Webb Space Telescope that would have launched for less money a decade ago and do other things."

But regardless of setbacks, the behemoth telescope will be worth the wait, the witnesses agreed.

"The exoplanet community remains tremendously enthusiastic," said Seager, "because the JWST will provide our first capability to study exoplanets in the search for life." Seager is an exoplanet researcher and has taken a lead role in many current and past exoplanet missions.

And the telescope will be a boon to more than just the science community, according to Spergel. "The eventual success of this complex engineering project will be a source of national pride and a symbol of U.S. technical prowess," he said.

3. Earth Science Should Not Be Left Behind

"One of the portfolios within NASA's Science Mission Directorate that is often overlooked, but is absolutely vital, is Earth science," Sen. Edward Markey (D-Mass.), the subcommittee's ranking member, said at the hearing. He cited such recent natural disasters as wildfires, 2017's devastating Atlantic hurricanes, and ongoing droughts around the world.

These disasters, Markey said, demonstrate that our Earth science investment "must be both abundant and unwavering."

Zurbuchen agreed. "There is no program in NASA science that has more direct impact to everyday life than our Earth science program," he said in his testimony. "Whether it is developing the tools to predict severe weather or drought, or whether it is to understand the complex interactions of the Earth system, what we learn here affects our lives."

The four expert witnesses who testified before the Senate Subcommittee on Space, Science, and Competitiveness on 1 August. From left to right are Thomas Zurbuchen, Ellen Stofan, David Spergel, and Sara Seager. Credit: C-SPAN

Zurbuchen added that NASA will remain committed to maintaining its current level of Earth science observation and research.

4. Private Sector Partnerships Will Lead to Rapid Progress

The witnesses agreed that the rise of commercial spaceflight companies in the past decade provides NASA with new avenues for streamlining its mission development and launch procedures.

"It's not our intent, ever, to compete with the private sector," Zurbuchen said at the hearing. "Our intent is to grow that sector and benefit from positive partnerships, to really offload things that are possible there so we can focus on the bleeding edge [of science]."

Stofan put the situation simply. "It's really important for NASA to stay focused on what only NASA can do," she said.

"The ecosystem of potential partners has gotten much bigger," Spergel testified. "I think there's opportunity for NASA to partner not only with the Boeings and the SpaceXes but with the many small companies that are coming up in robotics, electronics, and machine learning."

Partnering with the private sector might even lead to quicker advancements. "The seat of innovation is the private commercial industry," Seager explained to the listening senators, "because they can afford to take risks that NASA cannot."

5. The Big Question of Our Time Is Whether Life Exists Beyond Earth

In its 2017 NASA reauthorization, Congress charged the agency with dedicating resources to searching for life in our solar system and beyond. Is there life elsewhere? asked Cruz at the hearing. If so, why should we prioritize finding it?

"We know that life is tenacious, diverse, and highly adaptable," Stofan replied. "Given the commonality of conditions here and elsewhere in the solar system, it is highly unlikely that life is unique to our planet."

The answer to whether life exists elsewhere will likely be a game changer. "I believe it's one of the big questions of all of humanity," Zurbuchen said at the hearing. "This will be one of those questions that, if answered, will be remembered forever. It will be a leap, not only in understanding more about nature but in learning about ourselves at a level that we've never had in the past."

And the hunt itself may have effects as wide reaching as the Apollo program's. "Most senior engineers today…were inspired by the Moon landings," said Seager. "And today the equivalent to that is the search for life. When we do discover it, it will inspire that next generation."

"Although we don't have evidence for life beyond Earth," she said, "we are the first generation with the capability to find it."

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

Two Active Volcanoes in Japan May Share a Magma Source

A single magma reservoir deep beneath Japan's Kyushu Island may feed two of its most active volcanoes. GPS measurements of Aira caldera show that its once steady inflation stalled while the nearby Shinmoedake volcano erupted in early 2011 and then resumed when the eruption stopped. This suggests that the two volcanic areas draw from a common magma source deep under Kyushu and that the two areas may interact before, during, and after eruptions.

"We observed a radical change in the behavior of Aira before and after the eruption of its neighbor," Elodie Brothelande, lead scientist on the study and a postdoctoral researcher at the Rosenstiel School of Marine and Atmospheric Science at the University of Miami in Florida, said in a press release. The only explanation for this interaction is "the existence of a connection between the two plumbing systems of the volcanoes at depth," she said.

Observations of interconnected volcanic systems like this one are rare, so finding and studying them may help forecasters improve their eruption prediction and hazard models, Brothelande told *Eos.* Her team published its results in late June in the journal *Scientific Reports* (http://bit.ly/Sharing-Magma).

An Underground Connection

Shinmoedake, part of the Kirishima volcanic group in southwestern Japan, began erupting in January 2011 and released more than 20 million tons of magma, ash, and pyroclastic rock.

To probe the possible connection between Shinmoedake and Aira, the researchers measured the vertical and horizontal displacements of the land in and around Aira caldera. They gathered daily GPS data from 32 stations on Kyushu spanning 2009–2013, 2 years before and after the Shinmoedake eruption. With these data, they calculated how Aira swelled and deflated in the time surrounding the eruption.

The researchers compared the caldera's behavior to models of how it would have reacted had it been responding only to geologic stress caused by Shinmoedake erupting. They found that Aira's behavior was inconsistent with having geologic stress as the primary cause: Its pattern of inflation and deflation was wrong, and the amount it deflated didn't match predictions.

However, the models showed that an underground magma reservoir in the mantle feeding both volcanoes could explain the caldera's behavior during the nearby eruption. Brothelande said that Aira and Shinmoedake are "good candidates" for this type of connection because they share the same active fault block and are relatively close to each other.

Here's how that scenario would have worked: In the period before Shinmoedake's eruption, the magma reservoir inflated both volcanoes. The eruption then rapidly drew magma up from the reservoir and caused a sudden drop in pressure underground. The reservoir, in turn, drew magma from Aira in response to the pressure drop, causing the observed caldera deflation. Once Shinmoedake finished erupting, the magma reservoir resumed filling both volcanoes.

Japan's Shinmoedake volcano on the island of Kyushu, erupting on 27 January 2011. Credit: Kyodo via AP Images

A Promising Step

"When a volcano enters a period of unrest or eruption, a common concern from communities and media is the chance of a neighboring volcano being 'triggered,'" said Janine Krippner, a volcanologist and postdoctoral researcher at Concord University in Athens, W.Va., who was not involved with the project.

"Research into the relationships between neighboring volcanic systems is important, but it is rare that evidence is found for systems affecting one another," she said. "This study is a step in the direction of understanding any links between neighboring volcanic systems."

Although the research is promising, more evidence is needed to solidify the ties between the two volcanoes, Krippner added. For example, repeat observations of the volcanoes during the time before and after an eruption, as well as geochemical analysis of the pair's eruption products, could help. "I would expect to see similarities in geochemistry trends—the magma 'genetics'—in eruption products like lavas, volcanic ash, and pyroclastic deposits if they have a common source," she said.

Past geochemical studies (http://bit.ly/Volcano-Isotopes-Japan) have shown that eruption products from the two volcanic systems have similar isotope ratios for strontium and neodymium, the paper notes. However, Brothelande told *Eos,* a "real comparative study is still required" to geochemically link Shinmoedake and Aira to a common source.

Improving Eruption Predictions

Shinmoedake and Aira's associated volcanic peak, Sakurajima, erupted in 2017, and each has seen ongoing intermittent activity throughout this year. The research team is planning to study the activity at Shinmoedake and Aira from the past 2 years to better understand their underground connection.

Brothelande pointed out that there are other volcanic systems in which similar hidden connections may cause a volcano to interact with its neighbor, for example, in Hawaii, Alaska, and Italy. This occurs even in smaller systems of lava domes and maars like those in France and Colorado. Models that calculate eruption probabilities, she said, likely need to include these interactions.

"External factors that have an impact on volcanic eruptions—triggering or delaying them—have been neglected for a long time," Brothelande said. But the findings at Shinmoedake and Aira open a new door, she added. "Nearby eruptions have to be included as well."

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

Just How Anomalous Is the Vast Baltic Sea Dead Zone?

An aerial view of the Archipelago Sea, a coastal region of the Baltic. Beneath these seemingly pristine waters lies a coastal ecosystem in crisis due to low oxygen levels. Credit: Kari Mattila, Archipelago Research Institute

Around the world, excess nutrients in coastal waters can lead to feeding frenzies for marine algae. Once the algae die and decompose, the water that's left behind may have little to no oxygen to support life.

These oxygen-starved waters are called dead zones. Fish and other marine life must flee them or reduce their habitats to avoid suffocating. In some cases, the unlucky faunas suffer mass die-offs.

Hot spots of dead zones around the world include the Gulf of Mexico, the Chesapeake Bay, and the Baltic Sea. The latter, a semienclosed body of water that lies between the Scandinavian Peninsula and continental Europe, has been called one of the largest dead zones in the world.

A study published in early July in the journal *Biogeosciences* describes a detailed 1,500-year history of low-oxygen conditions in the northern Baltic Sea (http://bit.ly/Baltic-Sea-Dead-Zone). The scientists pieced together this history using data from two finely layered sediment cores taken from near the coast of Finland.

The cores show a clear signal: "The oxygen deficiency in the last century is unprecedentedly strong," said coauthor Joonas Virtasalo of the Geological Survey of Finland.

A History of Dead Zones

The Baltic Sea is no stranger to dead zones. Low-oxygen conditions, often referred to as hypoxia, have cropped up throughout its history, even before humans came onto the scene. The dead zones are largely due to the Baltic's limited circulation and strong layering of water, which stop oxygen from replenishing bottom waters.

> "The oxygen deficiency in the last century is unprecedentedly strong."

Since the 1950s, nutrient pollution from fertilizer and sewage has caused hypoxia in the Baltic to surge. These nutrients fuel algae blooms that coat beaches in unappealing green slime and block out light for ocean plants. Dead zones often wipe out bottom-dwelling organisms, and the effect reverberates up the food chain: Fish miss out on 106,000 metric tons of carbon in fish food each year due to fewer bottom-dwelling critters, according to one study (http://bit.ly/Fish-Dead-Zone). Baltic cod, a commercially important species for the region, are more likely to be caught with empty stomachs near hypoxic zones.

Scientists have studied dead zones in the Baltic before, but they've focused largely on deep-sea locations rather than on coastal areas. Yet the two regions are not the same: Coastal waters typically experience dead zones during the summer months, whereas dead zones in deeper waters can last all year long. The coast can also act like a "filter" for nutrients coming from land: It is the first stop for nutrients traveling from farm fields and cities into the sea, and scientists don't know whether the coast can retain or chemically alter those nutrients before they reach the deeper sea.

Thus, examining past hypoxia in coastal areas and comparing those conditions with deep-sea hypoxia could help scientists better predict future expansion of dead zones for the rest of the Baltic Sea.

Secrets in the Sediment

To reconstruct past coastal conditions, the researchers started drilling. They collected two 4-meter-long sediment cores from the Archipelago Sea, a subregion of the Baltic near Finland. Because historical hypoxia can't be measured directly but instead is inferred by proxies, the study used a suite of chemical tests.

"Our study combined more proxies than usual in order to address all the mechanisms behind this complex phenomenon," Virtasalo said.

Molybdenum ions were among the dozen proxies examined. In normal seawater, these ions tend to stay unreactive. But in situations with little to no oxygen, molybdenum ions adhere to bottom sediments and become part of the sediment record. So when researchers find high concentrations of molybdenum in layers of mud, they can tell that the waters that once bathed the mud had oxygen levels close to nil.

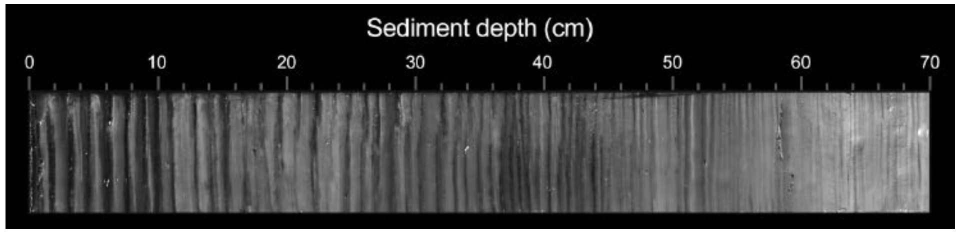
Another handy proxy was the clarity of the sediment layering itself. In times of ample oxygen, bottom-dwelling life thrives. These critters burrow into the seafloor and muck up the fine lineation of sediments. But in times of oxygen stress, the behavior of bottom dwellers "becomes simpler," and the sediment layering is left more intact, Virtasalo said. This proxy gives researchers an idea of when hypoxic conditions drove bottom-dwelling life away.

The Middle Ages Also Had Dead Zones

The researchers found evidence in the record of hypoxia during two different time periods. The first was during the Medieval Climate Anomaly between 900 and 1350 CE. Temperatures in Europe during the Middle Ages were unusually warm, and past research on deep Baltic Sea sediments has suggested that hypoxia was rampant.

The study showed evidence of coastal hypoxia, but unlike open-water records where hypoxia was "very pronounced," the coastal signal was "more muted," said Tom Jilbert, coauthor and assistant professor in the Department of Environmental Sciences at Finland's University of Helsinki. Sediments showed reduced levels of disruption, suggesting that waters at the seafloor had low oxygen but were not completely depleted.

Jilbert said that this is a "noteworthy insight" of the study because even though the climate was warmer, conditions were not sufficient to cause extreme hypoxia on the coast.



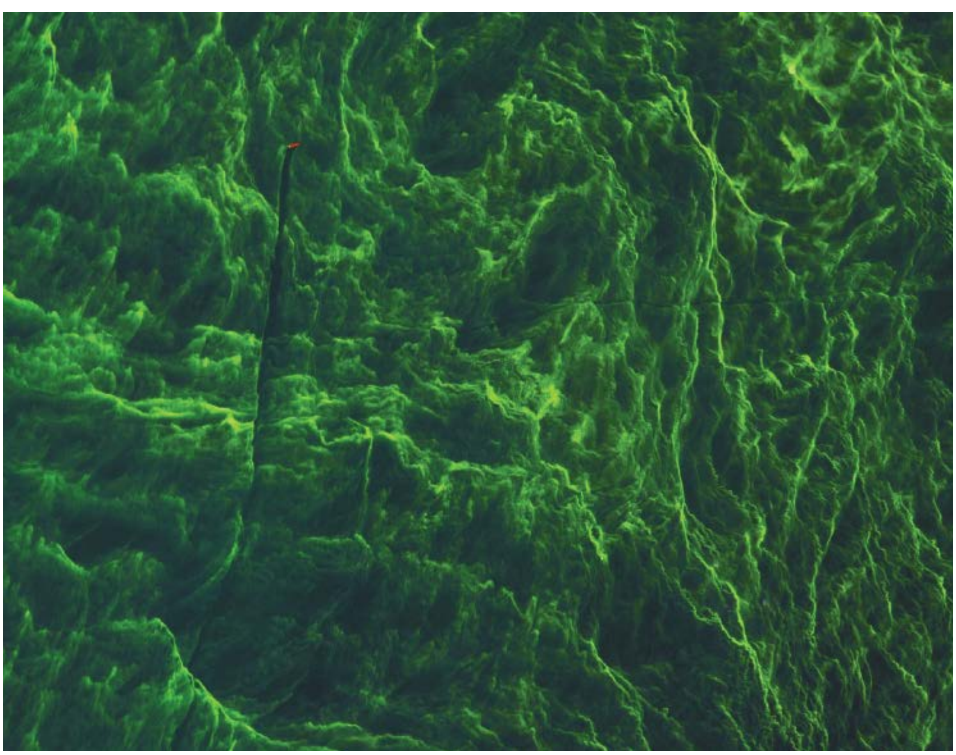
A segment of one of the study's sediment cores, used to reconstruct oxygen depletion in the Baltic Sea. The uppermost sediment layers at the left of the image are from the present day; those from the lowest layers (right) are from approximately 100 years ago. Finely preserved layers imply an absence of burrowing critters, suggesting that the seafloor has been devoid of life in recent years because of low oxygen levels. Credit: Sami Jokinen

Modern-Day Hypoxia

The second period of hypoxia in their sediment record began a little more than a century ago and continues seasonally through today. The study found that molybdenum levels in sediments slowly increased over the past century to reach the highest values tested, suggesting that waters at the seafloor are becoming increasingly hypoxic. The sediment layering was also wholly intact, meaning that for the first time in the record, the long-term residents of the seafloor, such as the crustacean *Saduria entomon* and the amphipods *Monoporeia affinis* and *Pontoporeia femorata*, were gone.

"The seafloor is completely devoid of macrofauna for the first time in our studied record," said Virtasalo. This statement is not just a reflection of what the researchers found in the core—field observations and monitoring at the study site also confirmed their findings. The authors note that nearby subbasins of the Archipelago still have enough oxygen to support life due to topographic differences. But they caution that the rise in hypoxia found in their sediment cores merely represents what is happening across the Archipelago Sea: Coastal bottom waters are losing oxygen.

Unlike Medieval Climate Anomaly dead zones, the study finds that modern-day hypoxia is driven by two main stressors: increased temperatures due to climate change and nutrient inputs from humans. "Only the higher temperatures combined with the excess nutrient levels were sufficient to cause the [seafloor] habitat loss of the last century," Virtasalo said. Together, these factors have made for levels of coastal hypoxia that are unparalleled in the sediment record.



A ship (red dot) cuts through algae swirling in the Baltic Sea, seen from space on 7 August 2015. Blooms like these are common in the Baltic and lead to low-oxygen conditions at the seafloor. Credit: Copernicus Sentinel data (2015)/ESA, CC BY-SA 3.0 IGO (http:// bit.ly/ccbysaigo3-0)

Still Hope for Shrinking Dead Zones

Despite the rise of hypoxia found in the study, Jilbert thinks that there's still time to stop the spread of dead zones. "It is definitively not too late," he said. "In fact, there have been substantial intergovernmental efforts already to reduce nutrient loading to the Baltic Sea."

He points to a modern-day success story: Waters around Stockholm, Sweden, had long suffered from human-caused dead zones but now show signs of rebounding after the city curtailed its nutrient pollution.

But the lead author of the study, Ph.D. candidate Sami Jokinen at the University of Turku, noted in a press release that future success may hinge on imposing even stricter measures: "To achieve good ecological status in coastal areas under the projected global warming, the required reduction in nutrient input might be higher than previously thought."

By **Jenessa Duncombe** (@jenessaduncombe), News Writing and Production Intern

Trump's Ocean Policy Order Draws Ire from Conservation Groups

Ocean conservation groups are up in arms over a new White House executive order on ocean policy that emphasizes the economy, national security, and resource development.

The order, which President Donald Trump issued on 19 June, revokes and veers sharply from an executive order implemented by President Barack Obama in 2010. That earlier order, issued in the wake of the 2010 Deepwater Horizon oil spill in the Gulf of Mexico, emphasized ocean stewardship, environmental sustainability, and human health.

The new executive order "unquestionably moves in the wrong direction," Janis Searles Jones, CEO of the Ocean Conservancy, a Washington, D. C.–based nonprofit, told *Eos*.

The order's "abandonment of sustainable use and conservation as a core tenet of U.S. ocean policy is alarming," she said. "With this order, we've lost the balance required to manage the ocean as an integrated and interdependent system."

The executive order refers to the nation's ocean, coastal, and Great Lakes waters as "foundational to the economy, security, global competitiveness, and well-being" of the country (see http://bit.ly/WH-Exec-Order-Oceans).

"Ocean industries employ millions of Americans and support a strong national economy," the document states. "Domestic energy production from Federal waters strengthens the Nation's security and reduces reliance on imported energy. Our Armed Forces protect our national interests in the ocean and along the Nation's coasts. Goods and materials that support our economy and quality of life flow through maritime commerce. Our fisheries resources help feed the Nation and present tremendous export opportunities."

Some Mentions of Science

The order includes some nods to science and technology and to environmental protection. For instance, "clean, healthy waters support fishing, boating, and other recreational opportunities for all Americans."

The order also states that the policy includes coordinating federal activities to manage ocean, coastal, and Great Lakes waters and "to provide economic, security, and environmental benefits for present and future generations of Americans." It says that the policy is to "advance ocean science and technology" and "modernize the acquisition, distribution, and use of the best available ocean-related science and knowledge" in partnership with stakeholders including marine industries and the ocean science and technology community.

Developing an Ocean Policy Committee

The order establishes an interagency Ocean Policy Committee (OPC) to ensure federal agency coordination on ocean-related matters. It calls for the committee to "coordinate and inform the ocean policy-making process and identify priority ocean research and technology needs," among other functions.

Deerin Babb-Brott, OSTP's principal assistant director for oceans and environment, will serve as OPC executive director, according to Gillfillan. Babb-Brott is a holdover from the Obama administration's OSTP, and he has served two stints as director of the National Ocean Council, which was established under Obama's executive order.

A bulk cargo ship docked under a port crane. Credit: iStock.com/unkas_photo

Questions About Whether the Science Language Goes Far Enough

Critics charge that the nods to science and the environment don't go far enough. "While the new policy includes language about data and science, it ignores that these are tools to support a healthy ocean ecosystem, not to maximize resources extraction," Jennifer Felt, ocean campaign director for the Boston-based Conservation Law Foundation, told *Eos.*

"This announcement comes on the heels of the administration's move to open up nearly all of America's ocean waters to dirty and destructive oil and gas drilling. It describes our oceans as resources to be mined, not places to responsibly manage and protect," she explained.

Margaret Spring, who was principal deputy undersecretary for oceans and atmosphere at the National Oceanic and Atmospheric Administration during the Obama administration, told *Eos* that the executive order does have some positive aspects. For example, the document appears to support state leadership in ocean policy and recognizes a need for science in decision-making.

"What's perplexing is that [the order] also deletes reference to scientific inquiry for understanding the ocean," she added. "We really don't know what that means. Is that sending a signal that there is going to be less support for science?"

Spring, who is the vice president of conservation science and chief conservation officer at the Monterey Bay Aquarium in California, said that the most important thing is how the order is implemented.

"Our major concern will be to get assurances that the focus isn't only on extraction and use, because that ignores the fact that you have got to take care of the oceans for future generations," Spring added.

"Misguided" Executive Order

"What really concerns me is that the [executive order] has a clear emphasis on use and exploitation as opposed to sustainability and resilience," said Whitley Saumweber, who served as associate director for ocean and coastal policy in the White House Council on Environmental Quality during the Obama administration.

Saumweber, an ocean policy consultant, speculated to *Eos* that Trump may have timed issuing the executive order for June to coincide with national ocean month. He said, "Maybe they wanted to do something related to oceans, misguided as it is."

By **Randy Showstack** (@RandyShowstack), Staff Writer

Training Early-Career Polar Weather and Climate Researchers

Polar Prediction School 2018
Abisko, Sweden, 17–27 April 2018

Weather and climate are changing faster in the polar regions than anywhere else on Earth. These changes are opening up new opportunities for shipping, energy extraction, and tourism, but they also expose these sensitive regions to increasing environmental hazards and pose major challenges to local communities. Limitations in our ability to predict polar weather and climate changes on scales from days to decades hamper our ability to make effective decisions regarding responses to these changes. Furthermore, our understanding of how changes in the polar regions may affect the midlatitudes, including their high-impact extreme events, is far from complete.

The polar prediction problem is inherently multidisciplinary and requires cooperation across a wide community. Thus, an international group of agencies specifically designed a 10-day training course to bring together a wide group of students and lecturers to cover important topics related to polar prediction.

The course combined theory lectures, practical exercises, and fieldwork, as well as a dedicated science communication program.

The course took place at the Abisko Scientific Research Station in Sweden.

Topics included satellite and conventional observation techniques; numerical modeling of the polar atmosphere, sea ice, and ocean; and data assimilation and model evaluation. The course included an innovative combination of theory lectures, practical exercises, and fieldwork, as well as a dedicated science communication program, each of which forms a crucial pillar of the prediction problem.

Micrometeorological observations and daily radio soundings provided hands-on training opportunities, and these data were directly used in the practical exercises. This experience allowed the students to investigate more thoroughly the topics discussed in the theoretical lectures. The data were also used in the daily weather briefings, exercises that encouraged the students to interpret and evaluate forecast models specifically for the context of a mountainous polar area. During the science communication sessions, which complemented the scientific program, the students produced brief, informative videos aimed at the general public.

In contrast to single-discipline courses designed to address a narrow topic, a course as diverse as this is unusual. However, this approach is necessary to help build and maintain the community needed to address the inherently multidisciplinary polar prediction problem. Student feedback showed that the school was well appreciated, and we propose this model for other disciplines in which cross-disciplinary links are crucial to progress.

The training school was organized under the auspices of the European Union Horizon 2020–funded Advanced Prediction in Polar Regions and Beyond (APPLICATE) project in cooperation with the Association of Polar Early Career Scientists (APECS) and the World Meteorological Organization's Polar Prediction Project on the occasion of the Year of Polar Prediction. Further sponsorship was provided by the Climate and Cryosphere project, International Arctic Science Committee, and Scientific Committee on Antarctic Research. More information about the school can be found on the APECS website (http://bit.ly/APECS-2018).

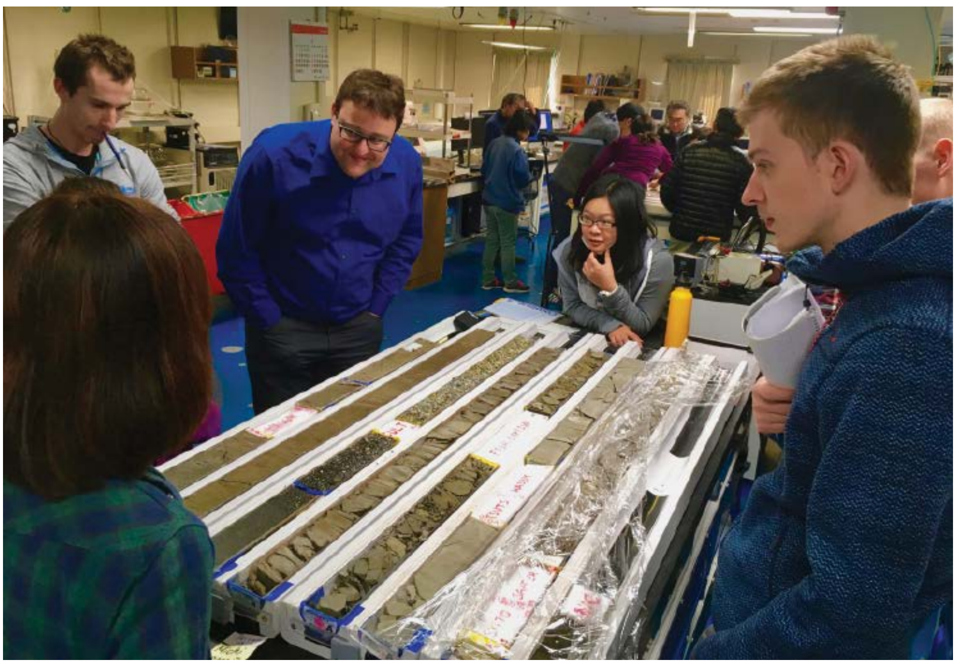
We thank all the school's lecturers—Ian Brooks, Matthieu Chevallier, Anna Fitch, Martin Hagman, Anna Hogg, Thomas Jung, Erik Kolstad, Linus Magnusson, Donald Perovich, Jessica Rohde, and Doug Smith—as well as the excellent team at the Abisko Scientific Research Station.

Students of Polar Prediction School 2018 set up a micrometeorological mast on Sweden's frozen Lake Torneträsk. Instruments on the mast provided data that the students used to study daily variations in the lower atmosphere and atmospheric turbulence and to evaluate atmospheric models. Credit: Fiona Tummon

By **Fiona Tummon** (email: fiona.s.tummon@uit.no), Arctic University of Norway, Tromsø; **Jonathan Day** (@jonny_day), European Centre for Medium-Range Weather Forecasts, Reading, U.K.; and **Gunilla Svensson,** Stockholm University, Stockholm, Sweden

At-Sea Workshop Advances Subduction Zone Research

International Ocean Discovery Program Core-Log-Seismic Integration at Sea (CLSI@Sea) Workshop
Nankai Trough, Philippine Sea, January–February 2018



Workshop participants and mentors discussing the sedimentology of cores C006 and C007, which were recovered from the Nankai Trough frontal prism, off the coast of southwestern Japan. Credit: Gael Lymer

Subduction plate boundaries are home to the world's largest-magnitude earthquakes and can generate tsunamis with catastrophic effects on populated coastal regions, like what occurred in 2004 in Sumatra and in 2011 in northeastern Japan. Recent recognition of seismic slip, which can breach the seafloor, and documentation of shallow slow slip and tremor have motivated new deep-sea drilling investigations and real-time monitoring of the in situ physical and chemical properties of subduction zone deformation.

However, existing archives of core and borehole log data from previous ocean drilling expeditions also provide a repository of data available to address new research questions with state-of-the-art analytical techniques. The first International Ocean Discovery Program (IODP) Core-Log-Seismic integration at Sea (CLSI@Sea; http://bit.ly/CLSI-at-Sea) workshop was motivated by the dual need to leverage these legacy data for future research and to train the next generation of early-career scientists in ocean drilling science.

The CLSI@Sea workshop focused on integrating IODP data from the southwestern Japan Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) to address the role of the frontal prism in tsunamigenic earthquakes and slow slip in the shallow portion of the subduction interface. Over the past decade, the NanTroSEIZE project has involved 2-D and 3-D seismic surveys, coring and logging, installation of long-term borehole monitoring systems (LTBMS), and connection to the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) across the Nankai accretionary prism. This combination has resulted in one of the best imaged and best monitored subduction systems in the world.

The CLSI@Sea workshop was organized on board the D/V *Chikyu* concurrent with IODP Expedition 380, allowing workshop participants to interact with expedition scientists installing an LTBMS observatory at the site where the workshop's research was focused. Well-preserved cores from across the prism toe were temporarily transported from the Kochi Core Center on board *Chikyu*, where they were made available for new description, sampling, and analysis. Logging data, drilling parameters, and seismic data were also available for use by workshop participants, who were granted access to *Chikyu* laboratory facilities and software to perform analyses at sea.

A core aspect of CLSI@Sea was to connect expert scientist mentors with early-career workshop participants from different backgrounds to work on common scientific questions. Multithematic presentations facilitated knowledge transfer between parties and field areas and highlighted the value of multidisciplinary collaboration that integrates processes across different spatiotemporal scales. Lively discussions in a cordial atmosphere and teamwork between mentors, participants, and IODP staff in a focused environment on board *Chikyu* were key components of efficient development of individual and collaborative research and publication plans.

This workshop led to the synthesis of data and formulation of key outstanding research questions in a summary report submitted to *Scientific Drilling*. Workshop participants have also planned postcruise meetings to enable continued international collaboration. The productivity of this workshop demonstrated the research and educational value of organizing a CLSI@Sea workshop. All scientific ocean drilling products are openly available for further scientific analyses, making similar workshops transportable to a variety of scientific disciplines and research focuses.

By **Christine Regalla** (email: cregalla@bu.edu; @Rengellia), Department of Earth and Environment, Boston University, Boston, Mass.; **Gael Lymer** (@GaelLymer), Dynamic Earth Research Group, University of Birmingham, Birmingham, U.K.; and **Rina Fukuchi** (@fukuchi_rina), Research and Development Center for Earthquake and Tsunami, Japan Agency for Marine-Earth Science and Technology, Kanagawa; now at Department of Ocean Floor Geoscience, Atmosphere and Ocean Research Institute, University of Tokyo, Chiba, Japan

Global Water Clarity: Continuing a Century-Long Monitoring

Aquatic systems worldwide are changing because of increasing climate variability and human activities. Yet it is difficult to capture such changes without standardized long-term observations.

Water transparency or clarity is commonly represented as Secchi depth (Z_{SD}), measured with a Secchi disk. Secchi depth is determined by lowering the disk into the water and recording the depth at which it is no longer visible to an observer at the surface.

The measurement provides a first-order indicator of water quality and ecosystem health. Unlike other optical parameters, Z_{SD} can be easily and cost-effectively measured in the field. It has been measured for more than a century in global seas and lakes (Figure 1). Furthermore, Z_{SD} can be estimated from satellite radiometry.

By combining historical and continued Z_{SD} with satellite products, scientists could produce a standardized global Z_{SD} product. Such a product would represent a unique, century-long Earth system data record that would enable researchers to assess changes in water clarity in global seas and lakes. With such data, scientists could improve their evaluations of changes to phytoplankton abundance, river sedimentation, fisheries productivity, agriculture's effect on downstream ecosystems, and more.

Going in Depth on Secchi Depth

The observation and recording of water clarity dates back more than 300 years. In an effort to understand the phenomena behind changing water clarity, Europeans started systematically documenting water clarity in the early 18th century with wooden boxes, colored plates, and white and red cloths. But it was the development of the Secchi disk by Pietro Angelo Secchi (1818–1878) [*Secchi,* 1864] that led to the standardized monitoring of water transparency from 1865 onward by scientists and interested citizens.

The standard Secchi disk is a circular white disk with a diameter of 0.30 meter (disks with diameters of 0.5 or 1 meter were also used when the water was extremely clear). The design has remained largely unchanged since it was first developed, although black-and-white disks are commonly used in monitoring lakes.

Studies have found that Secchi disk observations are remarkably insensitive to variability in observer technique, local meteorological conditions, or the solid white versus black-and-white disks (see http://bit.ly/Secchi-study). As a result, roughly 1 million Z_{SD} measurements across the world's marine and inland water bodies have been collected over the past 150+ years, all with similar uncertainties (~10%–15%).

Field Programs to Measure Z_{SD}

Because Z_{SD} measurements are quite observer independent and are easy and cost-effective to deploy, various government-supported and citizen science programs have been developed to collect water quality data via Secchi disks. These have significantly increased the breadth and length of data records.

For instance, the state of Wisconsin has estimated that citizen-collected Z_{SD} observations since 1986 have a monetary value of ~$4 million. These data are freely accessible and have been used to provide water clarity trends of more than 8,000 lakes in the state. The data also help educate and engage the public on the health of their lakes.

Broader programs also exist. The Secchi Dip-In program, which is administered by the North American Lake Management Society, now boasts more than 41,000 records on more than 7,000 separate water bodies in the United States and Canada. In parallel, the Secchi Disk, EyeOnWater, and Seen-Beobachtung Program projects initiated in Europe have accumulated tens of thousands of Z_{SD} observations from lakes to open oceans.

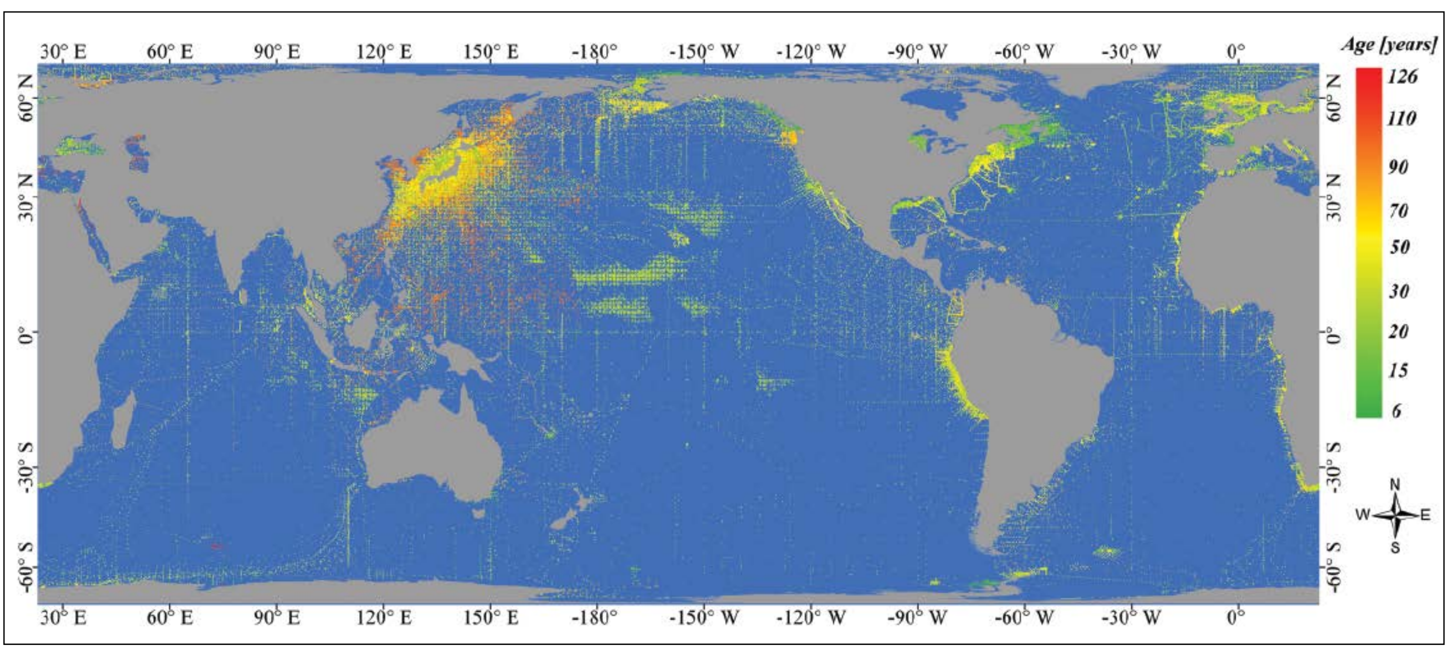


Fig. 1. Global map of some publicly available in situ Z_{SD} data. Colors depict the time series span (how long before 2016 the measurements were made) of available observations. Gray depicts landmasses, and blue depicts oceanic areas for which no in situ observations are available in our database.

Remote Sensing Approaches and Platforms to Estimate Z_{SD}

Z_{SD} can also be estimated from airborne or satellite radiometry, thus greatly increasing the geographic and temporal availability of water clarity observations. An early effort to collect such estimates started with empirical regressions that were used to relate multispectral Landsat signals to Z_{SD} in lakes (see http://bit.ly/Landsat-clarity).

Lower-resolution sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS) have also been effective in estimating Z_{SD} in estuaries and offshore marine waters. The combination of a series of Earth-observing satellite sensors, including the most recent Visible Infrared Imaging Radiometer Suite (VIIRS) and Sentinel-3, could enable the production of a near-daily record of global ocean color measurements now spanning nearly 2 decades.

Furthermore, Landsat 8 and Sentinel-2 have significantly improved radiometric precision and spectral sampling relative to their predecessors, making it possible to retrieve accurate water color at high spatial resolution for coastal waters and lakes. Thus, the research community is well on its way to providing Z_{SD} products at various spatial and temporal scales with sufficient accuracy through a combination of medium- and high-resolution satellite sensors, offering great potential for assessing water clarity changes on a routine basis at both local and global scales.

However, to date, there is no standardized Z_{SD} product from any of these satellite missions. The reason for this is, in part, a lack of community consensus on an appropriate algorithm to relate water color to Z_{SD} on the global scale. Recently, though, *Lee et al.* [2015] developed a new theory to interpret Z_{SD}. It has profound implications for Z_{SD} remote sensing, as it eliminates the need for local tuning as encountered in earlier estimations from satellite measurements. Examples of satellite-based Z_{SD} products are presented in Figure 2.

Tim Plude takes a Secchi reading on Wisconsin's Lake Tomahawk, October 2012. Credit: Laura Herman

Examples of Applications

If a standardized global Z_{SD} map at various time points could be created, opportunities for science studies would be manifold. Several realms could see significant scientific gains.

Evaluation of long-term changes in phytoplankton. A prerequisite to understanding the state of the world's waterways is obtaining standardized long-term measurements. For example, studies report that 40–60 years of standardized observations are required to reliably estimate time trends in phytoplankton concentration (see http://bit.ly/standard-time-trends), and a lack of such data may be responsible for conflicting reports of time-dependent changes in phytoplankton biomass. Coastal seas and inland waters often show a decline in water clarity, with some of these changes driven by pollution or climate change, whereas other areas show increases in transparency due to remediation. Scientists could achieve increased confidence in long-term changes in water clarity with standardized Z_{SD} products because of their direct representation and long-term data record (1865 to present).

Ecosystem monitoring. Scientists have found that Z_{SD} data are very valuable for consistent and systematic monitoring of ecosystems. Not only is Z_{SD} a good indicator of suspended particulate matter, but also it has been used as a trophic indicator for coral reef and overall

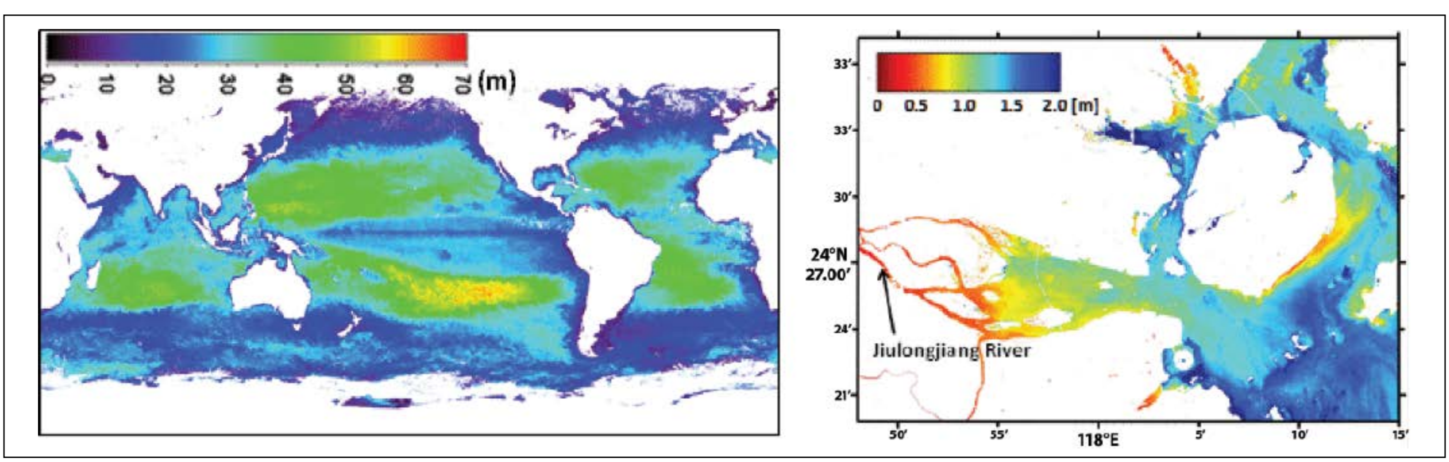


*Fig. 2. Global- to fine-scale Z_{SD} data derived from satellite measurements. (left) Global Z_{SD} derived from MODIS data (in autumn 2008); (right) Z_{SD} in the Jiulongjiang River estuary derived from Landsat 8 data collected on 4 August 2013. Credit: MODIS/Landsat/*Lee et al. *[2016]*

estuarine ecosystem status. Lake managers have used the metric to assess the status of lakes, where a lake's trophic state and algal biomass are related to Z_{SD}. Also, euphotic zone depth, an important indicator of ecosystem state, can be predicted from Z_{SD}.

Fisheries. Phytoplankton biomass production sets the carrying capacity of marine ecosystems and is highly correlated with commercial fishery landings, making Z_{SD} a valuable indicator of a fishery's productivity. Over most of the global ocean, where phytoplankton plays a dominant role in modulating water clarity, phytoplankton chlorophyll or primary production can be reasonably estimated from Z_{SD} measurements. Using such an approach, Z_{SD} observations could be used to explore changes in ocean ecosystems to support fisheries and to anticipate critical transitions in fish productivity. Separately, water clarity affects the predation dynamics within aquatic ecosystems, particularly for highly visual predators, which may affect ecosystem structure and fisheries.

Other users. Secchi disk and Z_{SD} products are also valuable for many other applications, such as coastal recreation and valuation of waterfront properties. For example, the U.S. Navy has used Z_{SD} products for many applications, including diver visibility and water mass classification.

Decades ago, a Secchi depth atlas was developed for the world's coastlines for waters less than 500 meters deep [*Arnone et al.,* 1985] as an initial effort to define coastal water optics for hydrographic charting systems that are constrained by water clarity. With advancements in both remote sensing algorithms and satellite sensors, a significantly revised atlas with improved spatial coverage, resolution, and accuracy will better meet many users' needs.

More broadly, variations in the attenuation of visible radiation in the upper ocean, which directly relate to changes in Z_{SD}, alter local heating and consequently have an effect on the thermal and fluid dynamical processes for the ocean-atmosphere system. Thus, a global, time-varying Z_{SD} product would provide a convenient way to measure local heating for inclusion in weather and climate models.

Z_{SD} in the Future

Understanding how aquatic environments will respond to ongoing human- and climate-related changes requires long-term time series. Although satellite measurements are spatially extensive, their coverage across time is limited (currently 1978–1986 and 1997–2017), making it difficult to differentiate trends driven by natural variability from those that are directed. The archive of Z_{SD} over the past century provides one of the longest-running (1865 to present) and most spatially extensive (global) standardized records to monitor Earth's aquatic environment.

Through careful calibration, historical Z_{SD} observations can and have been combined with new measurements and satellite products to greatly increase the spatial and temporal scales at which ocean changes are considered [e.g., *Boyce et al.,* 2017]. This database can also serve a critical need: to gauge the response of aquatic environments to a changing climate.

To date, however, Z_{SD} has not been a standard product of satellite missions. Although expanding the product suite of ocean color satellite missions to include Z_{SD} might be relatively easy because these contemporary sensors are well characterized and monitored, dedicated efforts are required to systematically evaluate Z_{SD} products from Landsat 8– and Sentinel-2-type land-targeted sensors to achieve sound monitoring on finer spatial scales.

Bridging Past and Future

Because of the deployment of advanced optical-electronic systems to measure inherent optical properties of waters, there is a tendency for reduced field measurements of Z_{SD} in contemporary oceanic surveys. Although the optical data provide more details about water constituents, the measurement systems are not yet mature, and the collections will never match the time span of the historical data record of Z_{SD}.

It is therefore critically important to continue monitoring Z_{SD} in both marine and freshwater environments to bridge the past and the future. With more than 150 years of global shipboard Z_{SD} records and synoptic Z_{SD} products of past (Coastal Zone Color Scanner (CZCS)) and future satellite sensors, the research community will not only obtain a clear picture of the current status of water clarity of the world's water bodies but also develop a more complete understanding of how and why water clarity is changing globally.

Acknowledgments

We dedicate this article to our coauthor Marcel Wernand, who recently passed away. Marcel was a pioneering researcher on the color and clarity of the sea. We are indebted to all scientists and citizens who provided the long record of Z_{SD} for community use, and we thank Xianfu Liu (South China Sea Marine Engineering and Environment Institute) for creating Figure 1 and Yonghong Li (Xiamen University) for creating Figure 2. The views expressed in this paper are those of the authors and do not represent the views or policies of the U.S. Environmental Protection Agency, the National Oceanic and Atmospheric Administration, or NASA.

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Editor's Note: Additional figures and hyperlinks to various studies discussed in this article can be found in its online version (http://bit.ly/Eos-Secchi-Depth).

Explore Your Inner Child by Painting Science with Pixels

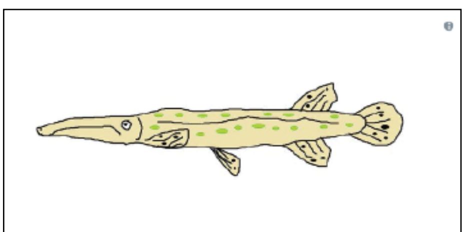
A boldly colored painting of a stream cutting through the Sonoran Desert from one aquatic ecologist tweeting to #MSPaintYourScience. Credit: Kathrine Kemmitt (@kkmmtt01)

Need a break from slogging through revision requests on your latest paper? Are lab results making you want to bang your head against a wall? Going in circles trying to fund your research?

If so, you need the latest science art challenge making its way around Twitter: #MSPaintYourScience (see http://bit.ly/MSPYS).

This Internet trend challenges scientists in all disciplines to sketch the topic of their current research project using whatever basic drawing software, like Microsoft Paint, is installed on their computer. There's a catch, though: The picture must be drawn with the scientist's nondominant hand.

The trend started with one aquatic geologist taking a lighthearted break from writing to draw a picture of a garfish:



Dr. Solomon David @SolomonRDavid

To answer your question, no it's not easy for a left-handed person to draw a gar in MS Paint (using a mouse). But it was a nice break from writing! #sciart

5:03 PM - Jul 31, 2018

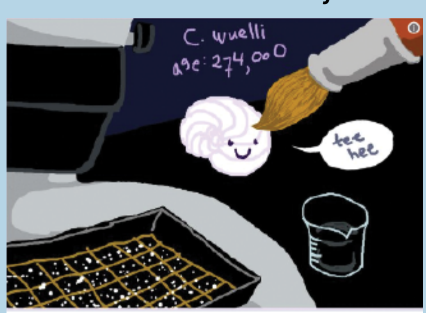
254 · 34 people are talking about this

That one fish sparked a wave of scientists' procrastinating on their research to create more science art.

And there have been dozens of tweets so far, from the exceedingly beautiful (presumably made by artistic and ambidextrous people) to cute pictures reminiscent of when your kindergarten teacher looked at your drawing and said, "That's very imaginative. Can you tell me about it?"

We'll let you judge. Check out these creative Earth and space science computer drawings.

This Foram Tickles Our Fancy



Katie Harazin @_katiezin

This is my submission to #MSPaintYourScience showing the process of picking #foraminifera shells with a paintbrush for paleoclimate reconstruction #forams #paleoceanography #sciart

I title this masterpiece: "tickling the swirly boiz" feat. mad lad C. wuellerstorfi

4:40 PM - Aug 2, 2018

86 · See Katie Harazin's other Tweets

Of Course the Sun Wears a Hat

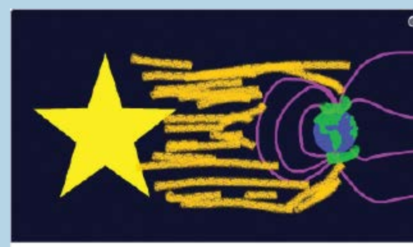
Andy Emery @AndyDoggerBank

Well, why not? #MSPaintYourScience

8:57 AM - Aug 3, 2018

30 · See Andy Emery's other Tweets

Don't Cross the (Solar Wind) Streams



Tony Iampietro @lamtony_97

I don't know why I'm a science major when clearly I'm destined to be an art major #MSPaintYourScience

11:48 AM - Aug 3, 2018

25 · See Tony Iampietro's other Tweets

Even Federal Agencies Are Getting Their Paint On

NOAA Sea Grant @SeaGrant

We couldn't choose just one part of our work to highlight, so we chose them all! All 33 programs across the country are doing really great science and helping their local communities #MSPaintYourScience seagrant.noaa.gov

12:17 PM - Aug 1, 2018

93 · 26 people are talking about this

Healthy Wetlands Make for Happy Fish

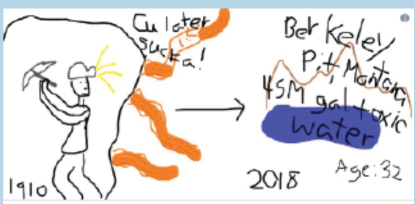
Katherine O'Reilly
@DrKatfish

#GreatLakes coastal wetlands provide a critically important habitat for fish like yellow perch - all that food and refuge really puts a smile on their face! #GreatLakesSci #MSPaintYourScience

9:39 AM - Aug 1, 2018

137 24 people are talking about this

We “C” What “U” Did There…



Kelley Christensen
@kjhchristensen

I study the effects of extraction on communities and how communities work with government agencies clean up the problem. #MSPaintYourScience (The true nerds will get the elemental joke.) #thisiswhatascientistlookslike #SocialSciences

10:16 PM - Aug 1, 2018

15 See Kelley Christensen's other Tweets

Minerals Sold Separately

Daveedo ⛏
@daveedoburrito

A fun time down in the mines! (Wulfenite not included)#MSPaintYourScience

12:43 AM - Aug 3, 2018

19 See Daveedo ⛏'s other Tweets

Ah, Ah, Ah, Ah! Stayin’ Alive…in Space!

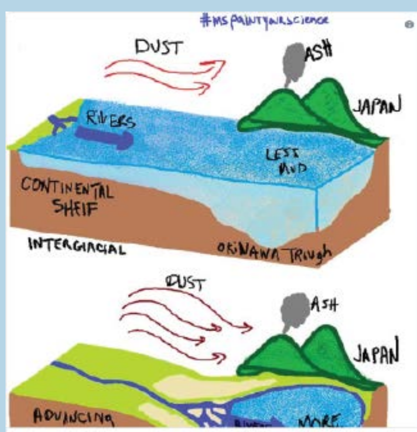
Nicol Caplin
@NCaplin_PhD

So #MSPaintYourScience is brilliant. Here's my #exobiology contribution 🛰 @esa #space #biology

10:41 AM - Aug 2, 2018 · Noordwijk, Nederland

29 See Nicol Caplin's other Tweets

Coming Soon to a Science Journal Near You



Chloe Anderson #goldschmidt2018
@chloerophyll_a

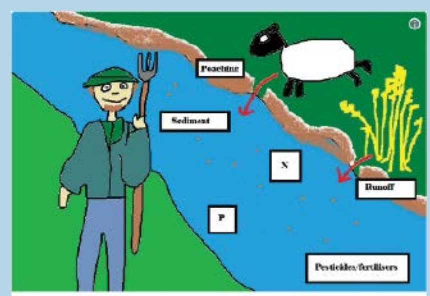
I tried. #MSPaintYourScience

Unofficial Fig. 7 for my recently accepted sediment reconstruction in the Okinawa Trough (bit.ly/2veHRoC). Advancing river mouths in glacials transport lots of mud out to sea and make it difficult to look for #dust from the #monsoon!

10:27 AM - Aug 3, 2018

14 See Chloe Anderson #goldschmidt2018's other Tweets

We See Shades of *American Gothic* Here



Charlotte Chivers 🚜
@cachivers

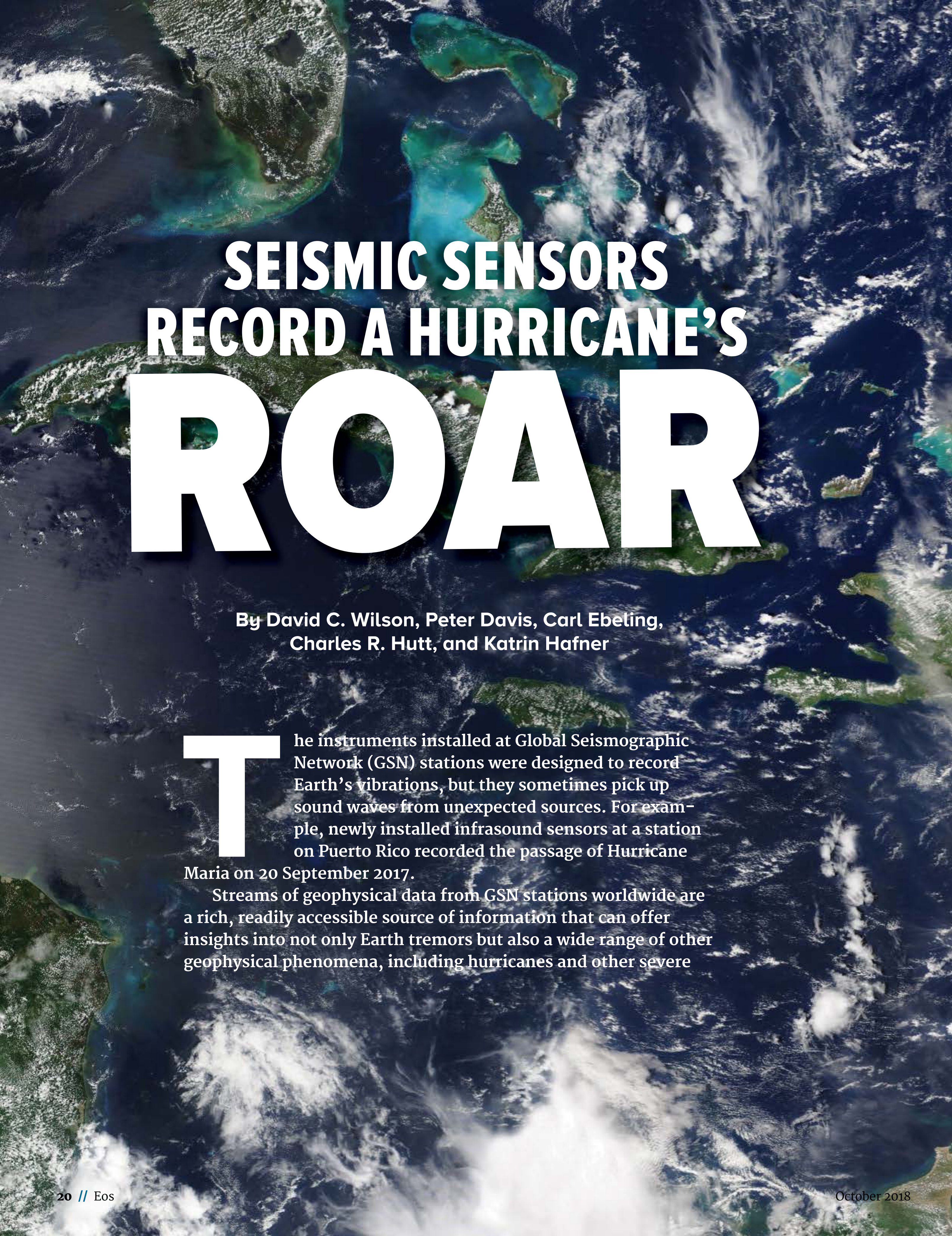
I'm studying water pollution from agriculture for my PhD! #MSpaintyourscience #phdlife

12:54 PM - Aug 1, 2018

9 See Charlotte Chivers 🚜's other Tweets

Do you have exciting science to share? Open up your computer’s paint program and sketch away! Don’t worry—your research can wait.

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



SEISMIC SENSORS RECORD A HURRICANE'S ROAR

By David C. Wilson, Peter Davis, Carl Ebeling, Charles R. Hutt, and Katrin Hafner

The instruments installed at Global Seismographic Network (GSN) stations were designed to record Earth's vibrations, but they sometimes pick up sound waves from unexpected sources. For example, newly installed infrasound sensors at a station on Puerto Rico recorded the passage of Hurricane Maria on 20 September 2017.

Streams of geophysical data from GSN stations worldwide are a rich, readily accessible source of information that can offer insights into not only Earth tremors but also a wide range of other geophysical phenomena, including hurricanes and other severe

Hurricane Maria makes landfall in Puerto Rica in September 2017. Elements of this image furnished by NASA. Credit: lavizzara/Shutterstock

Hurricane Maria damaged the SJG observatory in Cayey, Puerto Rico, although the instruments at the observatory survived and recorded the event. In this photo, taken 25 September 2017, the bunker containing the seismic station is visible in the hillside in the background. During the hurricane, the once lush hillside was stripped of vegetation. Credit: Miguel Lopez, USGS

weather events. This is particularly useful in remote areas, where data from other sources may be scarce.

Just how useful are the instruments at GSN stations to scientists who seek to expand our information on hurricanes? Data from Hurricane Maria suggest some untapped potential.

Detecting Earth Vibrations

The GSN is a permanent digital network of more than 150 modern stations in more than 80 countries. The primary sensors of the GSN are broadband seismometers with high dynamic ranges that respond to vibrations over a wide range of frequencies.

These instruments can record the strong ground shaking of a large earthquake with high fidelity, but they are also extremely sensitive to very small signals. The seismometers can detect Earth's tides with periods of tens of thousands of seconds. They can pick up signals generated by ocean swells (recorded as 6- to 18-second microseisms). These signals can be detected across the entire planet, regardless of distance from the ocean.

Other sensors—such as microbarographs, anemometers, magnetometers, and GPS receivers—are commonly installed alongside GSN seismometers to help identify other sources of noise that may mask seismic signals of interest. But these instruments may gather useful data in their own right. So in effect, these stations serve as geophysical observatories.

Monitoring the Low Rumbles

In 2016, the GSN began installing infrasound sensors at selected stations. These sensors respond to sound waves with frequencies below the lower limit of human audibility (typically about 20 hertz). As of June 2018, 13 GSN stations had infrasound sensors.

The new instruments have several scientific purposes. One is to gain a better understanding of the infrasonic wavefield (which are generated by a variety of natural and human sources) that may couple with the ground at GSN sites and leak unwanted signals into the seismic wavefield.

A second purpose is to improve monitoring of natural events, such as volcanic eruptions, meteor explosions, landslides, and severe storms. Scientists are also keen to learn more about man-made signal sources, such as rocket launches and detonations. The instruments can detect these events in remote parts of the world where there is limited geophysical scientific infrastructure to record them.

A third is to use infrasound recordings across the broad geographic coverage of the GSN. This information can improve our understanding of global atmospheric dynamics.

The infrasound sensors deployed in the GSN are most sensitive in the 0.02- to 15-hertz range. To suppress wind noise, infrasound sensors are usually deployed with a rosette-style spatial filter with a 10-meter aperture. The design of this noise-reducing system is flexible enough that it can be configured to meet spatial constraints unique to individual GSN stations.

Hurricane Maria Arrives

An unexpected opportunity to observe the monitoring capability of these new sensors presented itself on 20 September 2017 when the eye of Hurricane Maria passed near GSN station IU-SJG (see https://on.doi.gov/2nHHsa4),

Installation of an infrasound sensor at GSN station IU-SJG in Puerto Rico. The sensor can detect sound waves at frequencies of less than 20 hertz, below the threshold of human hearing. Credit: Ted Kromer, USGS

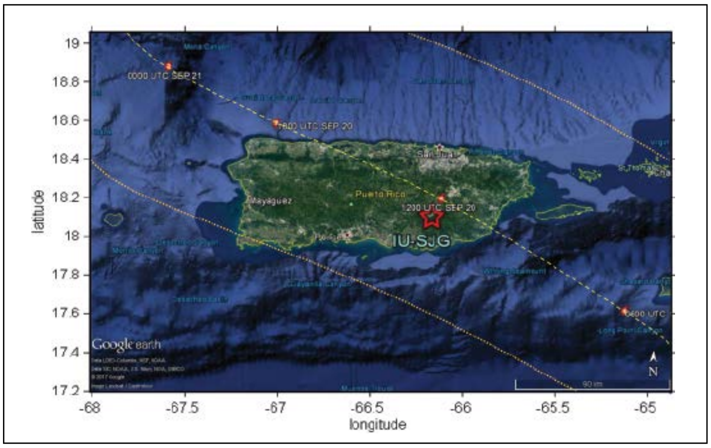


Fig. 1. Map of Puerto Rico showing the path (dashed line) of the eye of Hurricane Maria on 20 September 2017. The red star indicates the location of GSN station IU-SJG, which detected the hurricane. The dotted lines indicate the width of the region that experienced hurricane-force winds (greater than 118 kilometers per hour). Source: National Hurricane Center

Instruments on the surface and underground at station IU-SJG of the GSN recorded the passage of Hurricane Maria near the coast of Puerto Rico on 20 September 2017. Credit: Ted Kromer, USGS

where an infrasound sensor had fortuitously been deployed only a few weeks before (Figure 1).

Maria, formally identified as a tropical storm on 16 September, had intensified rapidly, earning recognition as a hurricane within 1 day and as a major hurricane within 2 days. Maria made landfall in Puerto Rico near Yabucoa, about 63 kilometers east of the GSN station, around 6:35 a.m. Atlantic standard time (10:35 a.m. UTC) on 20 September.

At the time of landfall, a sustained wind of 96 kilometers per hour, with wind gusts of up to 182 kilometers per hour, was reported at Yabucoa Harbor. Approximately 90 minutes later, the center of Maria's eye came within about 11 kilometers of station SJG, and the National Oceanic and Atmospheric Administration's National Hurricane Center recorded a minimum central pressure of 921 millibars (0.909 atmosphere).

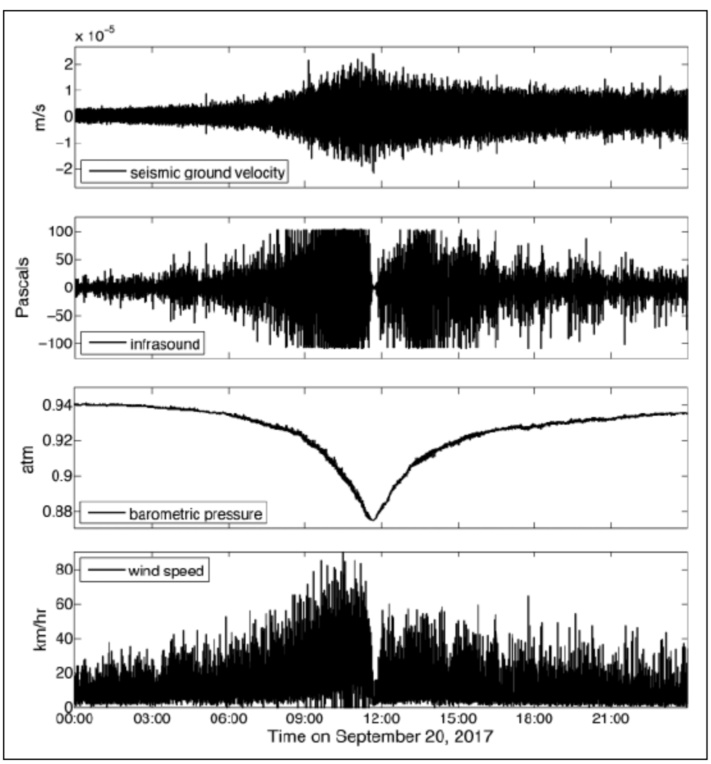


Fig. 2. Geophysical data from GSN station IU-SJG in Cayey, Puerto Rico, for 20 September 2017. The four plots, from top to bottom, show seismic data, infrasound data, barometric pressure, and wind speed. The data cover 1 day, and a power failure took the station offline shortly afterward. Note the dip in infrasound signal and wind speed at about noon, when the eye of the hurricane passed overhead.

Detecting the Storm

Instruments at station SJG recorded a variety of geophysical signals—ground shaking, barometric pressure and wind speed, and infrasound intensity—on 20 September as Maria approached and receded (Figure 2).

Data from the microbarograph at SJG show that the atmospheric pressure dropped from about 0.94 atmosphere (952 millibars) to just below 0.88 atmosphere (892 millibars) as the hurricane approached. The station is located 420 meters above sea level, so the measured pressure is lower than what would have been observed at sea level.

The infrasonic pressure and wind speed steadily increased until around the time that the eye was nearest the station. Amplitudes of both stayed low for several minutes during the calm conditions within the hurricane's eye.

As the eye of the storm passed, the barometric pressure rose again, and the wind and infrasound increased as well, but not to the extent experienced during the storm's approach. The infrasound signal, which was caused most likely by local wind turbulence, did not reach the levels seen while the eye was approaching because the wind speeds were not as great as the eye moved away.

A photo of the destruction to the road just outside the SJG observatory in Cayey, taken 27 September 2017. The community of Cayey suffered widespread damage, and many transportation routes were cut off. Credit: Miguel Lopez, USGS

Storm Damage

The maximum wind speed recorded at the station was 90.4 kilometers per hour (25.1 meters per second). However, the wind sensor at IU-SJG is mounted only about 2 meters above the ground and is flanked by high topography that would have protected it from the hurricane-force winds, which exceeded 118 kilometers per hour in that region (Figure 1).

The infrasonic signal reached the upper limit of the instrument's recording capability: The instrument records pressure changes as large as ±100 pascals. This sound level is in the range of the noise that a jet engine produces at a distance of 100 meters (although in a different frequency range).

The instrumentation at station SJG survived the storm even though there was widespread destruction in Puerto Rico. Power outages took the station offline for a few days, but our local contacts were able to restore station power within 1 week using generators. (It took more than a month to restore the power in their community.)

Seismic Stations as Geophysical Observatories

The measurements made at GSN station IU-SJG during Hurricane Maria provide a striking example of the role that such stations can play as geophysical observatories, not just for seismic studies but also in investigations of atmospheric dynamics and other geophysical processes, particularly in remote areas. In this example, researchers need finely detailed data on barometric pressure and wind speeds on the ground across a hurricane's width so that they can better track a storm's evolution and ground truth any models of the storm's progress. GSN stations, through the suite of instruments they contain, could provide such data.

Infrasound sensors have now been installed at 13 GSN stations around the world. All GSN data are freely available to the public and to scientists around the world from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (see http://bit.ly/IRIS-data). We look forward to the scientific community's finding new ways to use all of the various geophysical channels of the GSN.

Acknowledgments

The Global Seismographic Network was formed as a partnership involving the U.S. Geological Survey (USGS), the National Science Foundation, and IRIS (a university consortium). The network, which is operated by the USGS Albuquerque Seismological Laboratory and the University of California, San Diego's Project IDA with a subaward from IRIS, serves as a multiuse scientific facility and societal resource for monitoring, research, and education.

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Lars Johansson / stock.adobe.com

HOW CAN WE FIND OUT HOW MUCH SNOW IS IN THE WORLD?

By Edward Kim

Seasonal snow cover extends over 46 million square kilometers, or about 31% of Earth's land area, each year. This snow is a critical source of water, and it has major positive and negative economic effects. Not only does it support agriculture, recreation, and other aspects of local economies, but as a natural hazard it can also cause great harm.

Satellite remote sensing, with its potential for global coverage and frequent measurements, is highly suited to studying Earth's dynamic seasonal snow cover. Although many remote techniques for mapping snow cover extent are well established (e.g., efforts led by NASA and the U.S. National Ice Center), more accurate measurement of global snow water equivalent (SWE), which is the volume of water contained in the world's snowpacks, is at the top of the wish list. Current global SWE products are challenged, for example, by areas with forests or complex terrain.

Snow remote sensing experts agree that no single remote sensing technique can accurately measure SWE under the wide variety of conditions found across the globe. However, multiple techniques, using sensors that detect radiation in different parts of the electromagnetic spectrum, from the visible to the microwave, are sensitive to SWE. Thus, a combination of sensing techniques coupled with in situ measurements and

The first year of the SnowEx project tackled the challenging problem of using remote sensing techniques to measure snow water content in forested areas. Credit: NASA Goddard Space Flight Center

modeling is a promising approach to monitoring SWE globally.

NASA has embarked on a multiyear project called SnowEx (see https://go.nasa.gov/2MR7i6i) to inform the design of a space mission to improve global measurement of SWE.

As much as half of global snow-covered areas are forested, and forests have confounded our measurement attempts of SWE for decades. Thus, the focus of SnowEx in year 1 (2016–2017) was the collection of airborne and ground-based observations in forested areas. We used these observations to challenge the accuracy of various sensing techniques to measure snow in the presence of forest cover. The campaign was designed to quantify when and why each technique reached its limit.

Motivation and Strategy

The societal impacts of seasonal snow cover are immense. In California, for example, snowmelt supports an agricultural industry worth billions of dollars each year. In the western United States, snow-related recreation is also a multibillion-dollar-per-year business. The climatological significance of snow cover is truly far reaching: Because of its highly reflective nature, snow cover modulates the land surface energy balance on local to planetary scales and is also an indicator of climate change.

To assess existing capabilities for measuring SWE in forested areas, researchers selected two forested areas in Colorado to examine thoroughly during the first year of the SnowEx project. The primary study site, Grand Mesa in western Colorado (Figure 1), offered excellent conditions for the year 1 forest challenge: The site offers a variety of forested and open terrains, and the forest density and the SWE follow natural gradients. The secondary site, Senator Beck Basin in southwestern Colorado, was added to obtain data from a well-defined watershed to help address energy balance questions. As a bonus, it also featured complex terrain.

Snowy Fieldwork

Nearly 100 people, including students and senior scientists, participated in data collection in situ at the two selected sites during a February 2017 field campaign. U.S. government researchers from NASA, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Forest Ser-

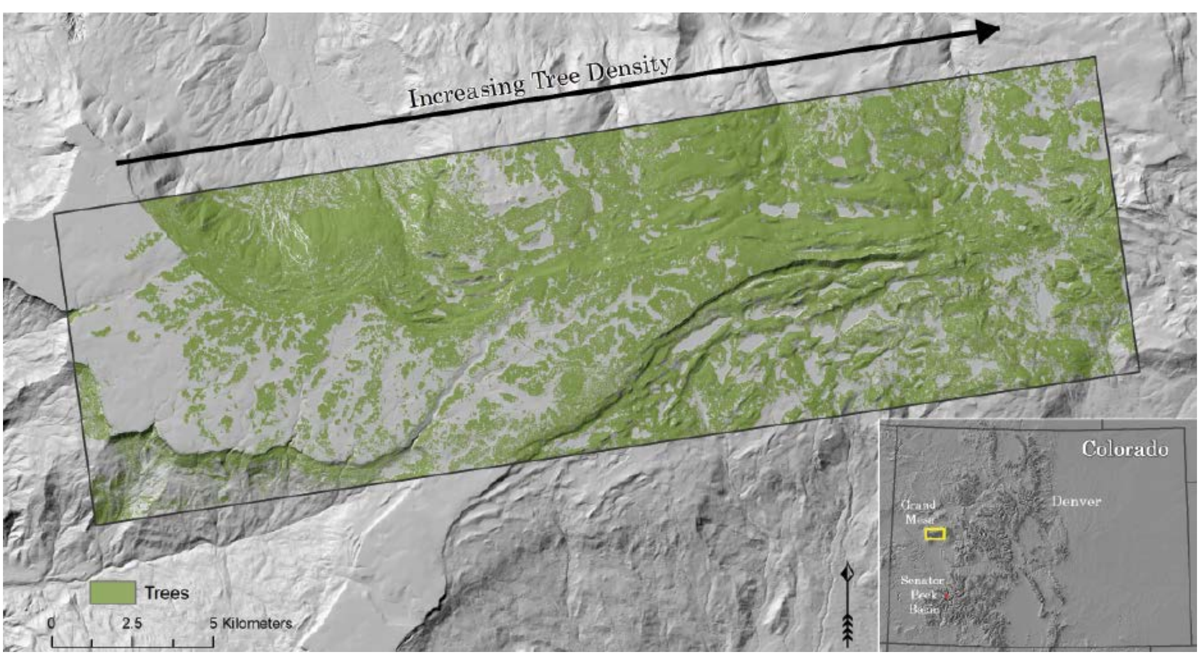

Fig. 1. The Grand Mesa site (rectangle outlined in black) in Colorado contains a natural west-to-east gradient of increasing forest density (green). Airborne and ground data were collected within the rectangle. The inset map shows locations of the primary Grand Mesa and secondary Senator Beck sites in Colorado. Credit: Chris Hiemstra/CRREL

vice, and the U.S. Army Cold Regions Research and Engineering Laboratory were joined by researchers from 25 universities, some of whom hailed from outside the United States.

After a day of safety training and to learn consistent measurement techniques, study personnel made rigorously controlled measurements during each week of fieldwork. About 40 individuals took coordinated ground measurements each week in a variety of weather conditions during an intensive 3-week observation period that extended from 6 through 26 February.

In conjunction with the SnowEx deployment, NASA, NOAA, and university researchers conducted the Great Lakes Winter Experiment 2017 (GLAWEX'17; https://go.nasa.gov/2nFcEGW) in Wisconsin and the Upper Peninsula of Michigan from 26 February through 2 March.

GLAWEX'17 researchers made detailed lake ice measurements in small lakes in Michigan and on Lake Michigan in Green Bay, Wis., to investigate remote sensing signatures of snow on land versus snow on lakes. The measurements were designed to help validate and support lake ice classification algorithms dependent on satellite synthetic aperture radar (SAR) data.


In the SnowEx effort of February 2017, nearly 100 snow researchers made rigorously controlled measurements of snow characteristics in western Colorado over a period of 3 weeks, using a wide variety of instruments. Credit: Zach Uhlmann/Boise State University

Aircraft Remote Sensing

Five instrumented aircraft flew over the Colorado study sites during the intensive observation period, with nine different sensors operating in different parts of the electromagnetic spectrum, from the visible/near-infrared and thermal infrared to the microwave regions. Instruments included SARs, lidar, multispectral and hyperspectral imagers, and infrared and video cameras.

Lidar and SAR were used to measure snow depth and SWE for comparison with ground measurements acquired before and after snowfall. The thermal infrared camera provided snow and forest canopy surface temperature. The visible/near-infrared sensors measured bidirectional reflectance and albedo needed for accurate energy balance modeling.

In Situ Measurements and Modeling

Overall, more than 30 instruments were deployed on the ground, including radars, microwave radiometers, spectrometers, lidar systems, GPS interferometric reflection systems, time-lapse cameras, and devices to characterize precipitation.

Approximately 100 ground measurement sites were distributed across the Grand Mesa and Senator Beck Basin study areas to capture a range of snow characteristics in varying canopies and snow depths/SWE across varying gradients.

Seven specialized weather stations provided surface weather, radiation, soil moisture, snow depth, and snow/soil temperatures. Snow pit measurements included full profiles of snow density, wetness, temperature, grain characteristics, specific surface area, and stratigraphy.

To support model development, SnowEx also included distributed observations of the snowpack energy balance, snowpack temperature profiles, and airborne and space-based observations of albedo and snow surface temperature.

Next Steps

The year 1 campaign kicked off NASA's SnowEx project by collecting a new and unique multisensor data set that will be used, along with models, to guide the formulation of a future space mission targeting remote SWE measurement.

The airborne and ground-based observations made in the first year of the SnowEx project will be used to develop algorithms for measuring SWE and also to test and evaluate multiple snow modeling and data assimilation frameworks for the estimation of global snow volume.

Researchers will use SnowEx data to benchmark current model performance, provide information to improve future model design, and assess error structures of various remotely sensed snow characteristics. These efforts are all essential for designing a global system to assimilate remotely sensed snow data from multiple sensors.

In year 2, the community is focused on analysis of the voluminous data from the year 1 campaign. The knowledge gaps identified by these analyses are being used to design future SnowEx campaigns. Planning for the 2019 campaign is in full swing, and discussions about the 2020 and 2021 campaigns are under way.

A Unique Data Set

SnowEx is the most comprehensive snow remote sensing study of its kind to date. Its unique data set collected in 2017 will be mined for years to come.

All of the remote sensing and in situ data from SnowEx will be archived by and freely available through the NASA Distributed Active Archive Center at the National Snow and Ice Data Center (see https://nsidc.org/daac).

Acknowledgments

We offer a giant thank-you to the dedicated team that made SnowEx possible and for support from NASA's Terrestrial Hydrology Program.

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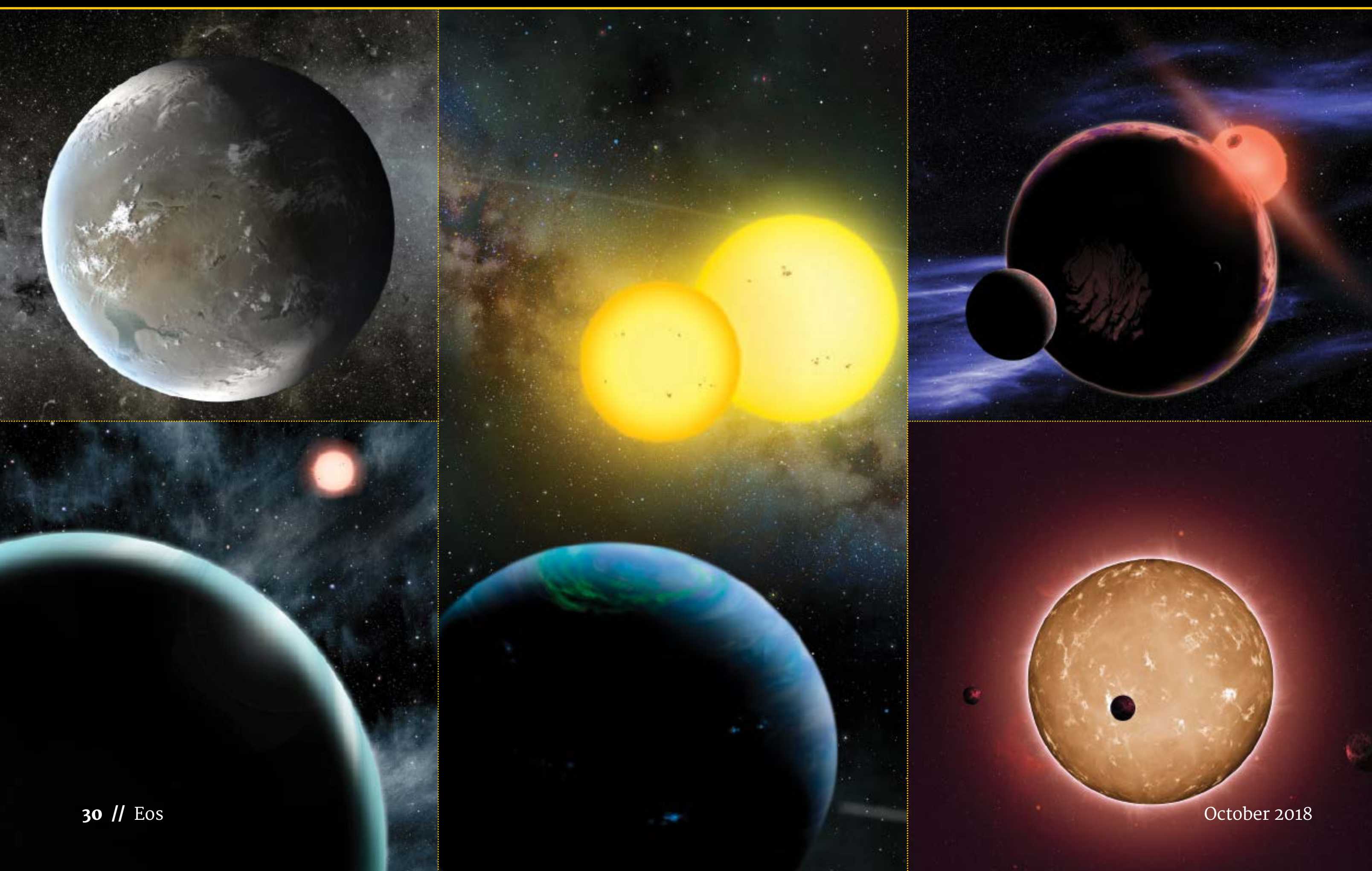
THE KEPLER REVOLUTION

By Kimberly M. S. Cartier

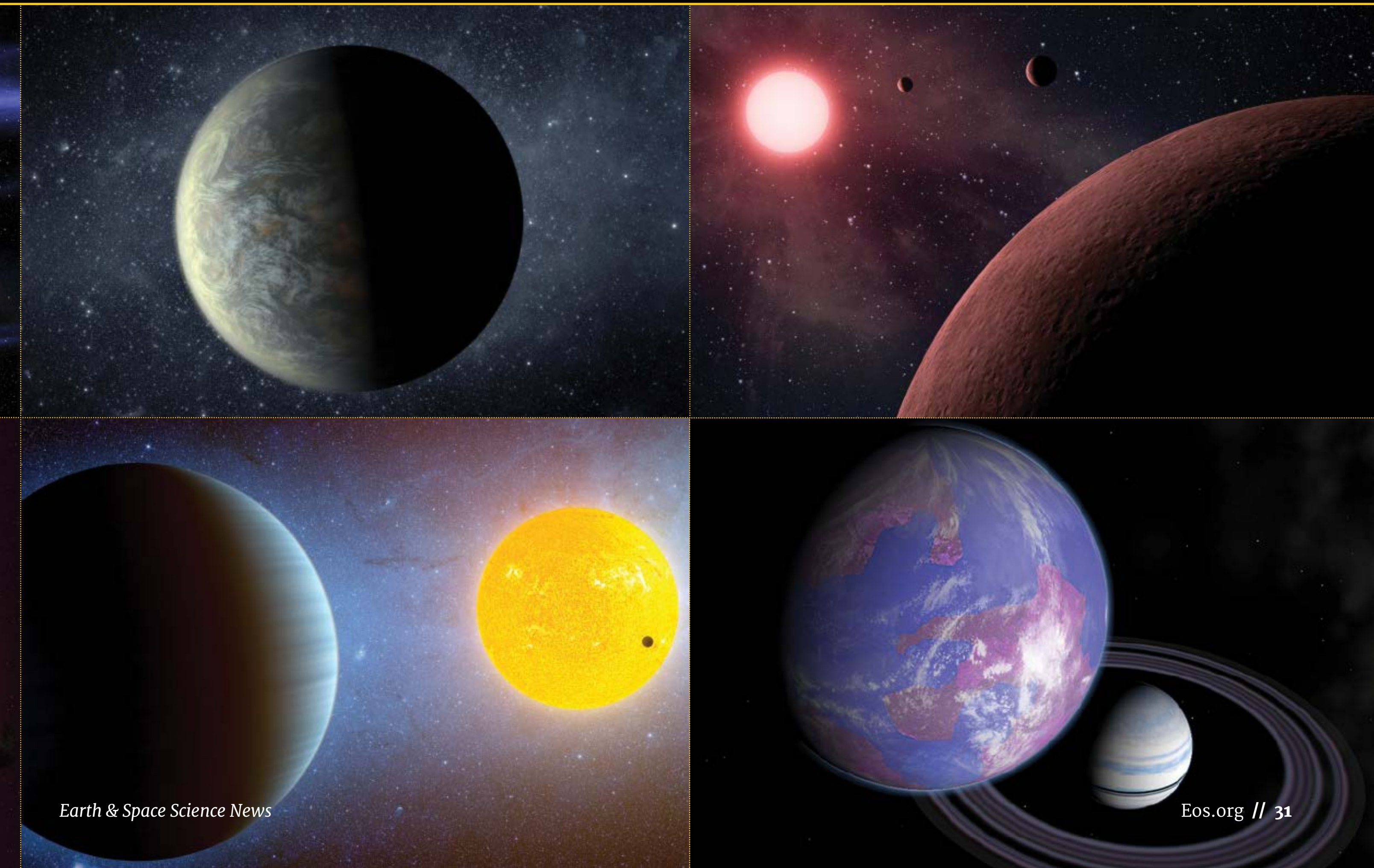


In early 2009, a rocket was launched carrying an instrument that would fundamentally change our views of our position in the universe.

That instrument is the Kepler Space Telescope, a small spacecraft that opened a large window to the many thousands of exoplanets strewn throughout the Milky Way. Thanks to Kepler, we now know that Earth is not a unique pale blue dot in the universe.

On 14 March, NASA announced that the Kepler spacecraft was exhibiting the first signs of low fuel and that the telescope likely would be functional for only a few more months. Its fuel tank hit critically low levels on 2 July, so mission sci-

Image credits: NASA



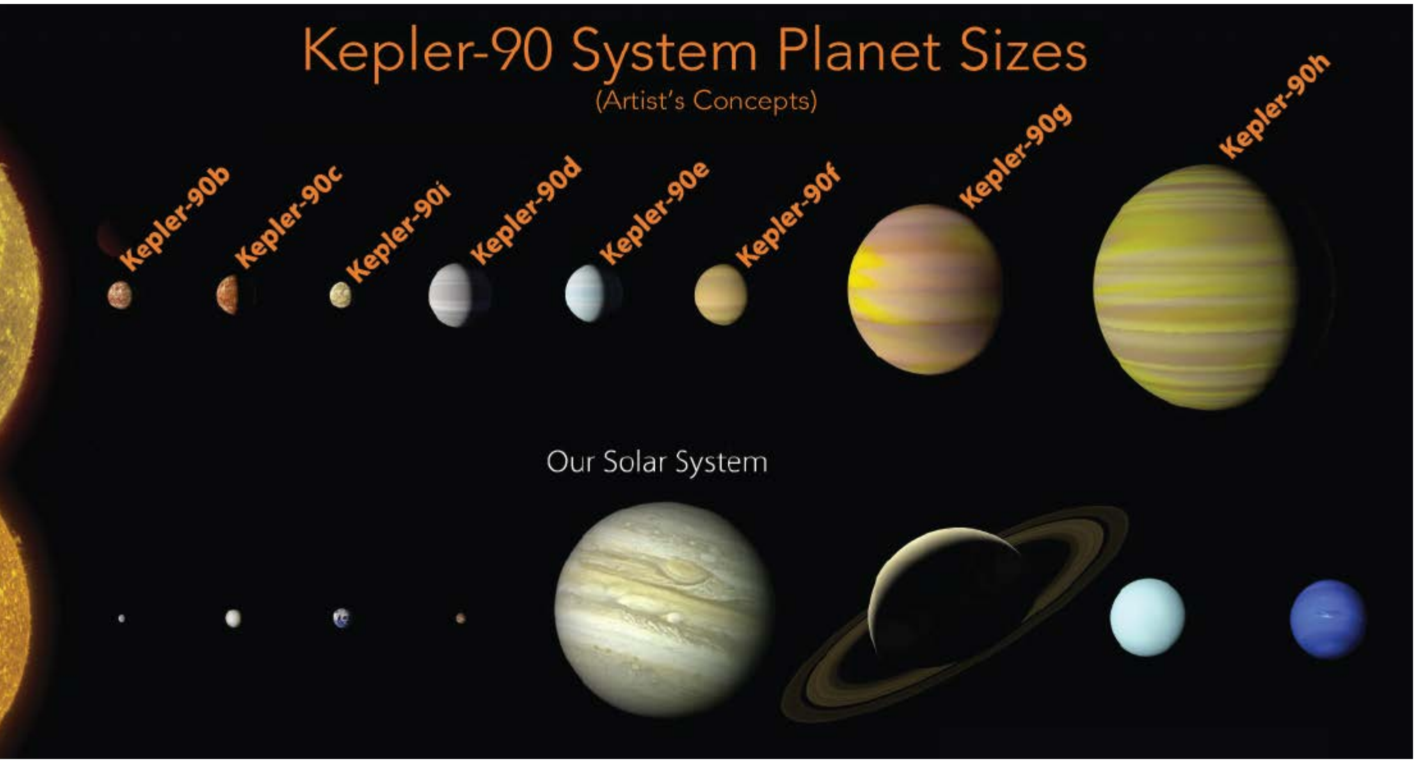


Fig. 1. Artist's conception of the eight exoplanets in the Kepler-90 system compared with those in our solar system. Kepler-90 is the only exoplanet system detected to date that has as many planets as our solar system. The planet sizes are to scale, but the distances between planets are not. Credit: NASA Ames Research Center/Wendy Stenzel

entists put Kepler into a no-fuel hibernation mode until its latest round of data was downloaded in early August. New observations are cautiously proceeding. This fuel failure was anticipated; it is likely the spacecraft will not reach its tenth birthday.

Kepler, whose eye is roughly a meter in diameter, was launched 17 years after the first planet was discovered outside of our solar system. By then, roughly 300 other exoplanets had been discovered, most of them too large, too hot, or in environments too extreme to even consider that they could harbor life. The available data left scientists scratching their heads. Did exoplanets analogous to Earth even exist? If they were out there, could we even see them?

The answer to both questions turned out to be an enthusiastic yes. "Yes, there are lots of Earth-sized planets in the habitable zones of other stars—billions," said William Borucki, principal investigator of the original Kepler mission who is now retired from NASA. "We had to have Kepler, because Kepler was designed to find them."

The data show that the telescope was a game changer. "It's probably the one mission that's changed the history of humankind more than any other," Borucki said.

Just how revolutionary has this space telescope been? Here are nine notable findings from Kepler that forever changed the field of astronomy.

1. Planets Are Everywhere, Equally

Imagine staring at the same patch of sky for more than 4 years. After Kepler was launched in March 2009, it did just that, turning its lenses to the space surrounding the constellation Cygnus.

"The mission was designed to be the most boring mission that mankind has ever produced," Borucki said. "We stared at the same part of the sky and sent pictures back over and over, hour after hour, year after year."

The telescope precisely measured the brightnesses of more than 150,000 stars simultaneously to a precision of

"It's probably the one mission that's changed the history of humankind more than any other."

about 50 parts per million. Any temporary and repetitive dips it saw in a star's light might indicate that a planet was crossing between the telescope and the star. These signatures, or planetary transits, are Kepler's way of finding exoplanets.

Through its unblinking gaze, Kepler discovered 4,571 planetary signatures, 2,327 of which have been confirmed as actual exoplanets. Astronomers are still working to confirm or refute the planetary status of the remainder of Kepler's discoveries.

Those planets, Kepler scientists found, are everywhere, equally. The distribution of exoplanets across Kepler's view of Cygnus follows the distribution of the stars. And no one area on Kepler's map hosts more exoplanets than another.

A hardware failure in 2013 left the spacecraft unable to accurately point at its original targets and ended Kepler's primary mission. Despite the setback, the telescope kept on discovering exoplanets elsewhere in the galaxy after engineers found a new way to keep the craft stable enough for observations. The second phase of Kepler's mission, called K2, began in 2014.

"K2 has enabled us to explore different portions of the galaxy that were not accessible to the original Kepler mission," said David Ciardi, a research astronomer at the NASA Exoplanet Science Institute at the California Institute of Technology in Pasadena. As exciting as the original Kepler was, "K2 was perhaps more exciting because of how we worked to never give up," he said. The K2 mission has so far discovered hundreds of new exoplanets distributed around the Milky Way.

Some stars have no planets, and some have many, but Kepler found that on average, there are more planets than stars in the sky (see https://go.nasa.gov/2nL3FnQ).

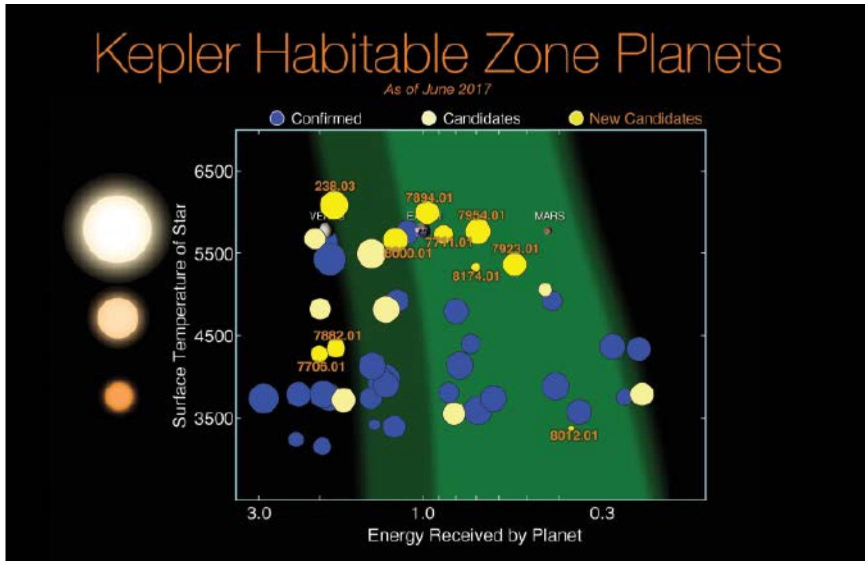
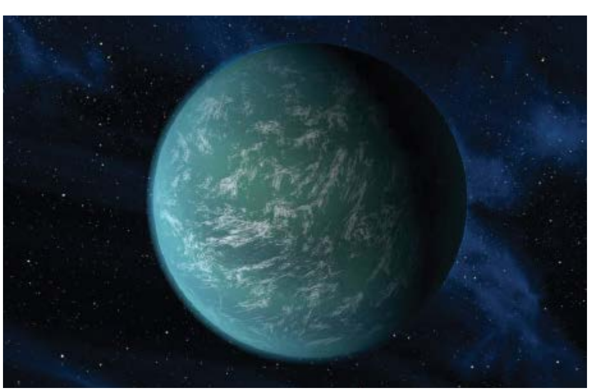


Fig. 2. The dozens of exoplanets discovered by Kepler that are less than twice the size of Earth and orbit in or near their stars' habitable zone. These planets are likely to be rocky or ocean worlds and are the most likely candidates for supporting life. Exoplanets are plotted by the star's temperature (vertical axis) and the energy received at the planet relative to Earth (horizontal axis). The size of exoplanet markers indicates their size compared with Earth, which is included along with Venus and Mars for comparison. The dark green swath represents the optimistic boundaries of the habitable zone, and light green represents the conservative boundaries. Orange labels indicate a planet's identifier in the Kepler catalog. Credit: NASA Ames Research Center/Wendy Stenzel

2. The Solar System May Not Be Unique

Kepler measures the size of exoplanets and their orbital period when they transit their host star. The bigger the dip in the star's brightness, the bigger the planet is relative to the star. The more frequent the dips are, the faster the planet orbits. If Kepler sees a star that shows dips with different strengths or timings, astronomers know that there might be more than one planet in that exosolar system.



Artist's rendering of probable ocean world Kepler-22b. Credit: NASA Ames/JPL-Caltech

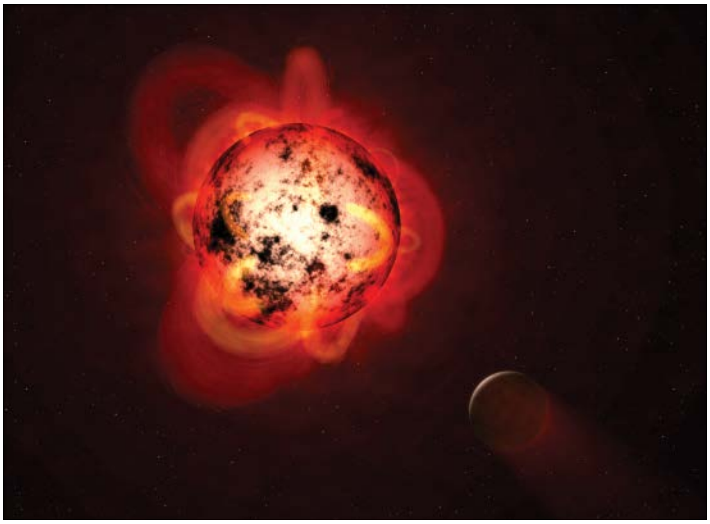
With the help of an artificial intelligence algorithm, Kepler discovered another star with the same number of planets as our solar system. The star, Kepler-90, is 2,545 light-years away and slightly hotter than the Sun. Seven of its eight planets were discovered in 2013, and the elusive eighth planet rounded out the set in December 2017. The data show that the orbits of all eight Kepler-90 exoplanets fit within Earth's orbit around the Sun (Figure 1).

Although Kepler discovered thousands of exosolar systems with one or two planets, systems with more planets than that are still relatively rare. For example, in February 2017 the TRAPPIST-1 system was discovered to have seven exoplanets, but to date, it and Kepler-90 are the only two exosolar systems on the books with more than six planets. Astronomers are not sure whether the paucity of populous planetary systems is a real phenomenon or due simply to a lack of data.

3. Earth May Not Be Unique

One of Kepler's fundamental science goals was to discover how common planets similar to Earth in size, composition, and temperature are in the galaxy. Pinpointing the number of these "Earth siblings" or "Earth cousins" is a steppingstone to calculating the probability of alien life in the universe.

Earth-sized planets are very common, Kepler found. So far, astronomers have confirmed 29 exoplanets (Figure 2) less than twice the diameter of Earth that fall in or near



Artist's rendering of a flaring red dwarf star orbited by an exoplanet. Credit: NASA/ESA/ G. Bacon (STScI)

their star's habitable zone, the region of space surrounding a star that has the right temperature to keep water in a liquid state on the surface of a planet. Seventy more possible Earth cousins remain as candidate exoplanets until astronomers can verify them.

Given the trove of Kepler data still left to sift through, astronomers are hopeful that they will eventually find Earth's "twin." In the meantime, one exoplanet that is close but not quite right is Kepler-452b, which is slightly larger and colder than Earth. Another is Kepler-296e, which is nearly identical in size and temperature but orbits in a system with two stars and four other Earth-sized exoplanets.

"We asked the question about how many Earth-sized planets there might be, and we built a spacecraft to answer that question," Ciardi said. "No longer is the Earth the only Earth-sized planet—we know there are likely millions of such worlds in the galaxy. Now we are asking the question, 'Do any of those worlds hold life?'"

4. An Earth-Sized Planet May Not Be Earth-Like

A true Earth twin will resemble Earth not just in size but in composition and temperature too. To learn what a Kepler exoplanet might be made of, scientists need to measure its mass. For some exosolar systems with multiple planets, Kepler data can reveal exoplanet masses by measuring variations in when they transit, which are caused by the planets' tugging on each other gravitationally.

If transit timing variations are not an option, astronomers can attempt to use other telescopes to measure the Doppler shift that an exoplanet induces on its star, from which they can find the planet's mass. Once scientists have a measure of an exoplanet's mass to go along with its size from Kepler, they can calculate the planet's average density and compare it with known planet-forming materials.

However, just because a planet is the same size as Earth and has a similar density does not mean it would be a nice place to live. Worlds likely to be covered with molten lava abound in the Kepler data set. These worlds are assumed to develop when a small, rocky planet orbits close enough to its star that its surface melts.

Lava worlds are easier for Kepler to detect than exoplanets in habitable zones because the former orbit their stars more frequently. Two of the first rocky, Earth-sized exoplanets discovered by the spacecraft, Kepler-10b and its smaller sibling Kepler-78b, are lava worlds with densities similar to enstatite, a mineral common in Earth's mantle.

Fire and lava are common, but Kepler found plenty of ocean worlds too. The size and density of these exoplanets suggest that they contain a significant amount of water, perhaps enough to cover their surface entirely. Planetary temperatures, inferred from their distance from their host stars, suggest that their surface waters are liquid. Kepler-22b, discovered in 2011, was the first example of such a Kepler ocean world. With so much water on its surface, Kepler-22b almost certainly has an atmosphere, said Borucki, who called it one of his favorite Kepler planets.

"The planet may be covered in an ocean," he said. "Life may have begun in an ocean....If you wanted to pick something that probably has an atmosphere and might well have life, that the conditions might very well be just right, it's a great planet to pick."

5. "Habitable" Is Not a Straightforward Idea

In an uncomplicated universe, a planet orbiting within a star's habitable zone would, by definition, be hospitable to life. Some stars, however, pose more challenges to habitability than others.

For example, a star smaller than half the Sun's size emits more red and infrared light. An exoplanet orbiting in that star's habitable zone would quickly become tidally locked to the star, with one hemisphere too cold and the other too hot for life as we know it to thrive. These red dwarf stars can also produce extreme flares that emit harmful X-rays and particles that could scour away a planet's atmosphere, oceans, and, possibly, life.

These stars, however, are the most common type of star in the galaxy, and Kepler observed thousands of them. The telescope discovered more than 1,000 possible exoplanets around red dwarf stars during its primary mission. One of those planets, Kepler-186f, is one of Ciardi's favorites.

"Kepler-186f is fascinating because the planet is Earth-sized and it orbits in the habitable zone of its star, but the star is much cooler and smaller than the Sun," Ciardi explained. "Kepler-186f begs the question, Can life like we know it exist on a planet like the Earth but around a star that is so different from the Sun?"

Habitable moons are possible too. "If you have a giant planet in the habitable zone," explained Borucki, "but its moon is small and has an atmosphere—like Titan, which has a big, heavy atmosphere—the moon could have life."

If the exoplanet transits the star, the moon might too, making it possible that exomoons lay hidden within Kepler data. So, Borucki explained, the hunt for exomoons is on. There has been one promising Kepler candidate identified (see http://bit.ly/Kepler-exomoon), but there are no verified exomoons yet.

6. Planets Don't Always Look Like Those in the Solar System

Planets in our solar system fall into two categories: small and rocky, like the four inner planets, and large and gaseous, like the four outer planets. What's more, there is a large jump in size between our largest rocky planet, Earth, and our smallest gassy planet, Neptune. There is no in-between.

So astronomers were understandably surprised to find that things don't shape up quite that way elsewhere in the galaxy.

Kepler discovered that the majority of exoplanets are larger than Earth but smaller than Neptune, a variety unseen in our solar system. These exoplanets are called super-Earths or mini-Neptunes and can be mostly rock, mostly gas, or mostly water.

"We're finding a huge number of planets unlike any in our solar system," Borucki said. "We were finding these things by the hundreds, by the thousands."

In addition, there is a significant fraction of Kepler's exoplanets that are larger than Jupiter and orbit extremely close to their stars. Called hot Jupiters because of their size and temperature, these behemoths typically orbit a star in a matter of days. Astronomers are still puzzling out how hot Jupiters managed to move so close to their suns without falling in.

7. Planets Exist in Unlikely Places

Our solar system's planets orbit around one star. But Kepler found that exoplanets can commonly orbit two, three, or even four stars.

Kepler-16b was a particularly exciting discovery for *Star Wars* fans, as its solar system's structure mimics that of Tatooine, the home world of Luke Skywalker. Kepler-16b's path takes it around both stars in that system in a circumbinary orbit. Kepler-16b is the first exoplanet confirmed to orbit two Sun-like stars. Unlike the fictional planet, Kepler-16b is frigid, inhospitable, and approximately the size of Saturn.

Kepler-16b is one of only about 20 known circumbinary planets. Kepler revealed that planets that orbit a single star in a binary, triple, or quadruple star system are much more common.

But what if there were even more nearby stars? The Sun was born possibly in a dense grouping of stars that has since drifted apart but once contained dozens or hundreds of members. Could our solar system have formed if the Sun had remained trapped in that kind of an environment?

Kepler said yes. During its primary mission, it discovered two mini-Neptune planets, Kepler-66b and Kepler-67b, orbiting different stars in a distant and crowded star cluster. A few years later, the K2 mission observed the young Hyades star cluster and found that one of its hundreds of stars hosts three planets. That star, K2-136, is the first multiplanet system known to survive in a dense stellar environment, and it could help astronomers understand the birth our solar system.

8. Planets Follow Defined Trends and Come in Distinct Groups

Kepler didn't find just individual exoplanets. It found them by the thousands. The unprecedentedly large number of exoplanets with precisely measured sizes and temperatures enabled studies of planetary demographics for the first time.

A recent study showed that planets smaller than Neptune fall into two distinct and separate categories, like two branches of a family tree (Figure 3). The branches were already familiar to astronomers—rocky super-Earths and gaseous mini-Neptunes—but they now know that the categories represent a more fundamental planet property. Where previously the distinction was made purely by size or composition, it's apparent that the two types really outline the end states of different planet formation pathways. Scientists are still working out what guides a planet-to-be down one path or the other.

The thousands of exoplanet measurements from Kepler also let astronomers explore relationships between different properties of the planets—such as size, mass, composition, and star type—that theoretical models could not

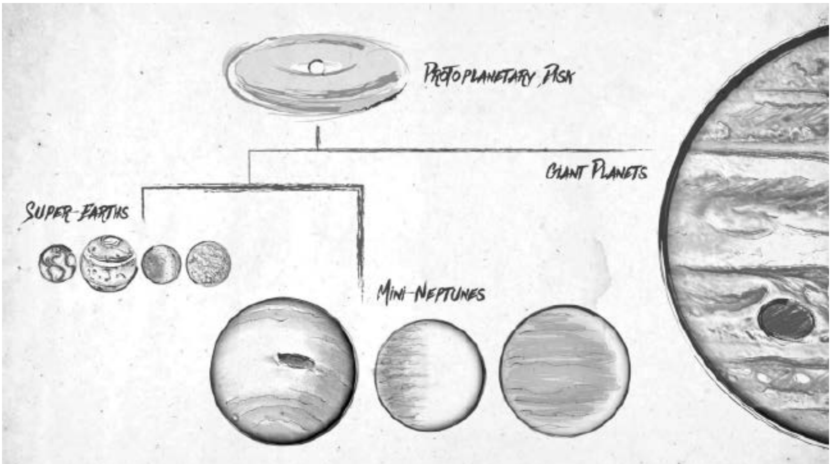


Fig. 3. Recent research discovered that small planets typically come in two distinct sizes: super-Earths and mini-Neptunes. Astronomers are still exploring the reasons a small planet becomes one or the other, with few exceptions in between. Credit: NASA Ames Research Center/JPL-Caltech/Tim Pyle

yet predict. For example, astronomers found that for a planet smaller than Neptune, measuring its radius could allow researchers to reasonably estimate the planet's mass and density on the basis of demographic trends. In addition, analysis of Kepler planets and their stars has shown that rocky planets are twice as likely and gas giants are 9 times more likely to form around stars abundant in elements heavier than helium.

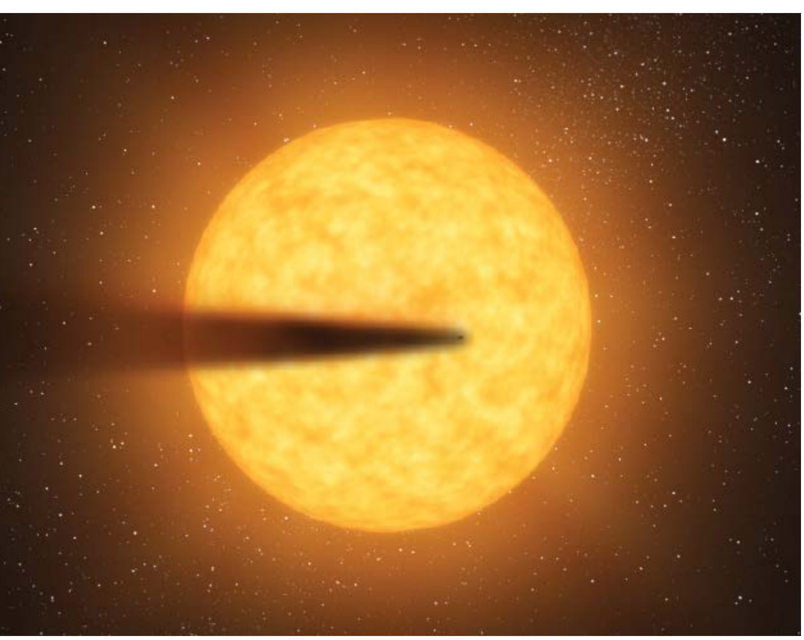
9. Planets and Stars Can Be Oddballs

Our solar system has a neat configuration: All the planets orbit in a mostly flat plane, move in the same direction that the Sun rotates, and have orbits that are only slightly skewed from circular.

Kepler saw that exoplanetary orbits are not always so tidy. Some exoplanets, like Kepler-419b, a hot Jupiter around a star hotter than the Sun, travel in highly elliptical orbits. On a scale in which 0 is a perfectly circular orbit and 1 is an oval so stretched out that it appears to be a line, Kepler-419b's orbit ranks 0.83, one of the most highly eccentric orbits discovered.

In the Kepler-56 system, a Jupiter-sized exoplanet somehow torqued the orbits of two other planets so they are misaligned by 45° from their star's rotation. Another exoplanet, Kepler-63b, orbits its star from pole to pole rather than parallel to the equator, which hints that it may have interacted with another, unseen planet sometime in its past.

Although some of Kepler's exoplanets found stable orbits after chaotic interactions, others were not so lucky. Kepler-1520b, for example, at first appears like a supersized comet with its dense core surrounded by a coma and trailed by an extended tail. Scientists assume that this is because the planet orbits so close to its star that the star must be stripping away the planet's rocky surface and any atmosphere it might have had. Had it not been for the extended tail of debris the planet leaves in its wake, Kepler would not have been able to detect this smaller-than-Mercury disintegrating world.



Hiding among the trove of Kepler data are some oddball signals, including the disintegrating exoplanet Kepler-1520b, depicted here in an artist's rendering that showcases its cometlike debris tail transiting the star. Credit: NASA/JPL-Caltech

A "Revolutionary" Telescope

When Kepler runs out of fuel, it will no longer be able to collect data or transmit them back to Earth. But that doesn't mean that its work will be done.

"Endings are never really the end, in my view," said Ciardi. "Yes, the spacecraft will be turned off, but the science of the mission will continue, and the legacy of what Kepler has brought to us will not be forgotten."

One legacy of Kepler has been educating future generations of exoplanet scientists and astronomy enthusiasts.

Kepler is "bringing this to the young people," Borucki said, "the grade school kids, the high school kids, and inspiring them to say, 'I'll make the effort to learn. I'll make the effort to become part of humankind exploring space.'"

"We live in a richer world of knowledge than we would have if Kepler had not launched," Ciardi noted. "In the future, when the world talks of scientific discovery, it will speak of astrophysics before Kepler and after Kepler. That is how revolutionary the mission has been."

Author Information

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

2018 Class of AGU Fellows Announced

Each year since 1962, AGU has elected as Fellows members whose visionary leadership and scientific excellence have fundamentally advanced research in their respective fields. This year, 62 members make up the 2018 class of Fellows.

AGU Fellows are recognized for their scientific eminence in the Earth and space sciences. Their breadth of interests and the scope of their contributions are remarkable and often groundbreaking. Only 0.1% of AGU membership receives this recognition in any given year.

On behalf of the AGU Honors and Recognition Committee, the Union Fellows Committee, the section Fellows committees, and AGU leaders and staff, we are immensely proud to present the 2018 class of AGU Fellows.

We appreciate the efforts of everyone who provided support and commitment to AGU's Honors Program. Our dedicated volunteers gave valuable time and energy as members of selection committees to elect this year's Fellows. We also thank all the nominators and supporters who made this possible through their dedicated efforts to nominate and recognize their colleagues.

Honor and Celebrate Eminence at Fall Meeting

At this year's Honors Tribute, to be held Wednesday, 12 December, at Fall Meeting 2018 in Washington, D. C., we will celebrate and honor the exceptional achievements, visionary leadership, talents, and dedication of 62 new AGU Fellows.

Please join us in congratulating our 2018 class of AGU Fellows, who are listed below in alphabetical order.

By **Eric A. Davidson,** President, AGU; and **Mary Anne Holmes** (email: unionfellows@agu.org), Chair, Honors and Recognition Committee, AGU

Jess F. Adkins, California Institute of Technology
Donald F. Argus, Jet Propulsion Laboratory, California Institute of Technology
Paul A. Baker, Duke University
Cecilia M. Bitz, University of Washington
Nina C. Buchmann, ETH Zurich
Marc W. Caffee, Purdue University
Gregory R. Carmichael, University of Iowa
Andrew Cohen, University of Arizona
Patrick M. Crill, Bolin Centre for Climate Research, Stockholm University
Thomas L. Delworth, Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration
Donna Eberhart-Phillips, GNS Science and University of California, Davis
Kerry Emanuel, Massachusetts Institute of Technology
Andrew T. Fisher, University of California, Santa Cruz
Marilyn L. Fogel, University of California, Riverside
Hayley J. Fowler, University of Newcastle
S. Peter Gary, Los Alamos National Laboratory (Ret.)
Steven J. Ghan, Pacific Northwest National Laboratory
Joris Gieskes, Scripps Institution of Oceanography, University of California, San Diego
Karl-Heinz Glassmeier, Technische Universität Braunschweig
Dorothy K. Hall, University of Maryland and Cryospheric Sciences Laboratory, NASA Goddard Space Flight Center
Charles Franklin Harvey, Massachusetts Institute of Technology
Sidney R. Hemming, Columbia University
Benjamin P. Horton, Nanyang Technological University
Bruce F. Houghton, University of Hawai'i at Mānoa
Catherine Jeandel, Centre National de la Recherche Scientifique, Université de Toulouse
Tomoo Katsura, University of Bayreuth
Kimitaka Kawamura, Chubu University
Simon L. Klemperer, Stanford University
Cin-Ty Lee, Rice University
Jos Lelieveld, Max Planck Institute for Chemistry and the Cyprus Institute
Philippe Lognonné, Institut de Physique du Globe de Paris, Université Paris Diderot
Timothy William Lyons, University of California, Riverside
Trevor McDougall, University of New South Wales
Bruno Merz, GFZ German Research Centre for Geosciences and University of Potsdam
Stephen A. Montzka, Earth System Research Laboratory, National Oceanic and Atmospheric Administration
Rumi Nakamura, Space Research Institute, Austrian Academy of Sciences
Heidi Nepf, Massachusetts Institute of Technology
Victor P. Pasko, Pennsylvania State University
Adina Paytan, University of California, Santa Cruz
Christa D. Peters-Lidard, NASA Goddard Space Flight Center
Balaji Rajagopalan, University of Colorado Boulder
Cesar R. Ranero, Catalan Institution for Research and Advanced Studies
Geoffrey D. Reeves, Los Alamos National Laboratory
Josh Roering, University of Oregon
David B. Rowley, University of Chicago
Vincent J. M. Salters, Florida State University
Gavin A. Schmidt, NASA Goddard Institute for Space Studies
Richard Seager, Lamont-Doherty Earth Observatory of Columbia University
Nikolai Shapiro, Institut de Physique du Globe de Paris and Centre National de la Recherche Scientifique
Eli A. Silver, University of California, Santa Cruz
Mark Simons, California Institute of Technology
Bradley S. Singer, University of Wisconsin–Madison
Lee Slater, Rutgers University–Newark
David G. Tarboton, Utah State University
Doerthe Tetzlaff, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Humboldt University, and University of Aberdeen
Friedhelm von Blanckenburg, GFZ German Research Centre for Geosciences
Christopher R. Webster, Jet Propulsion Laboratory, California Institute of Technology
Naohiro Yoshida, Tokyo Institute of Technology
Vladimir E. Zakharov, University of Arizona
Fuqing Zhang, Pennsylvania State University
Pei-Zhen Zhang, Sun Yat-sen University
Francis W. Zwiers, Pacific Climate Impacts Consortium, University of Victoria

AGU Announces Education Section

Educators participate in a Geophysical Information for Teachers (GIFT) workshop at a recent Fall Meeting. Credit: Karna Kurata

I am incredibly pleased to announce that AGU is launching a new section: the Education section. AGU's sections reflect the scientific breadth of the Union and are responsible for fostering scientific discussion and collaboration, identifying emerging issues, providing member input, and nominating scientists for honors and recognition. The Education section marks the second new section launched by AGU in the past year; the Geohealth section was launched in December 2017.

> The new section was established to provide a transdisciplinary home and voice for educators and education researchers.

Bringing a Diverse Community Together

After supporting an Education Special Interest Group for a number of years and seeing a significant increase in the number of education-related abstracts and sessions at Fall Meetings, AGU realized that the community's needs had evolved and grown and that it was time to create a formal Education section.

The Education section was established to provide a transdisciplinary home and voice for educators and education researchers, enhancing connectivity across all of the Earth and space sciences by providing educational expertise, scholarship, and partnership development with other organizations and the public. It will catalyze and shape Earth and space science education activities to develop a diverse Earth and space science talent pool, improve global scientific literacy, and increase access to scholarship and collaboration in Earth and space education research and practice.

The education sessions that have occurred at AGU's Fall Meetings for a number of years now will continue and will be managed by the section.

Making an Impact

Clearly, the Education section will play an important role in developing a diverse, inclusive, and dynamic Earth and space science talent pool and in AGU's strategy to support and advance that talent pool, not to mention increasing public understanding of the Earth and space sciences, all of which are vital to the long-term health of AGU.

In addition, an important and unique contribution that the Education section will make is in shaping the knowledge and skills of future generations of students, educators, and the public, grounded in the emerging field of geoscience education research. Education research is a rigorous science that addresses critical issues of learning, communication, diversity, equity, inclusion, and the research enterprise. The discipline of geoscience education research, which focuses on forming and testing geoscience education research hypotheses, as well as the development, application, and evaluation of new geoscience teaching innovations and curricula, is also emerging.

Advancing Earth and Space Science

AGU strives to lead in myriad ways, including pioneering new approaches to growing the exchange of scientific knowledge, encouraging the emergence of new and transdisciplinary fields of study, transforming our programs and operations as we anticipate the changing needs of our worldwide community, helping scientists improve their work, and strengthening the integrity of science. Specifically, by supporting people preparing for or engaged in any stage of Earth and space science and related careers, AGU strengthens the global Earth and space science community and enlarges its impact on society.

Next Steps

The AGU Leadership Development/Governance Committee is in the process of selecting founding leaders for the Education section and working on the transition to elected leadership in the next AGU election (2020). When joining AGU or renewing their membership, AGU members can now select Education as their primary or secondary section. We hope you will join the Education section and participate in this unique opportunity to provide input and help shape the future of the discipline.

By **Chris McEntee** (email: agu_execdirector@agu.org), Executive Director/CEO, AGU

Scraping Bottom: Iceberg Scours Reveal North Atlantic Currents

A snapshot of an Arctic iceberg on 20 July 2015. Credit: AWeith, CC BY-SA 4.0 (http://bit.ly/ccbysa4-0)

As part of the global oceanic circulation system, the near-surface North Atlantic Current transports heat and salinity northward into the Nordic seas. As this water cools off, it sinks to the ocean bottom and moves southward in a conveyor belt–like system that continuously redistributes heat. Because changes in the circulation of the northernmost Atlantic Ocean have the potential to affect Arctic and global climate, understanding the history of these currents can provide crucial context for interpreting modern changes occurring within this system.

To understand the currents' evolution during the Pleistocene, *Newton et al.* analyzed an extensive database of 3-D offshore seismic data collected west of central Norway's rugged coast. The data span 50,000 square kilometers of the Naust Formation, a late Pliocene–Pleistocene sedimentary shelf deposit that records multiple glacial-interglacial cycles beginning about 2.8 million years ago.

On the 33 stratigraphic surfaces found within this record, the researchers identified more than 17,000 V- and U-shaped grooves up to about 500 meters wide and extending 10–30 meters below the paleoseafloor. The team interprets these structures as scours made by icebergs that became grounded as they floated above the shallow continental shelf during the Pleistocene.

Because the grooves on all of the surfaces are oriented predominantly southwest–northeast, the authors argue that they represent the direction of the surface paleocurrent at the time each horizon was deposited. In combination with numerical modeling studies and other geologic evidence, these data indicate that surface currents in this region consistently flowed northward throughout numerous Pleistocene glacial-interglacial cycles.

This study expands our knowledge of the currents and the behavior of icebergs in the Norwegian Sea during the past 2.8 million years. It also suggests that the position and direction of surface currents in the eastern North Atlantic during the Pleistocene were similar to those observed today. The results will help place modern observations within a long-term perspective and improve the calibration of Earth system models. (*Geophysical Research Letters,* https://doi.org/10.1029/2018GL077819, 2018) **—Terri Cook, Freelance Writer**

A Better Way to Predict Indian Monsoons

The Indian monsoon arrived early in 2013, leaving thousands of residents stranded by floods and landslides. Credit: AFP photo/Indian Army, CC BY 2.0 (http://bit.ly/ccby2-0)

Roughly 1.7 billion people rely on the annual Indian summer monsoons for water to drink, to grow crops, and to raise livestock. The deluges usually fall between June and September, delivering roughly 80% of the Indian subcontinent's yearly rainfall. But sometimes the monsoons fail to deliver, resulting in drought, or they dump too much water too fast, causing devastating floods. Accurately forecasting such vagaries can be lifesaving, but predictions often fall short. A new model that includes improved representation of land processes, along with mountainous Himalayan topography promises greater accuracy.

One region where scientists have consistently failed to accurately predict monsoon behavior in the 21st century is over the sprawling 860,000-square-kilometer Ganges river basin in central India. Each year, the June–September forecasts simulated by the operational model of the India Meteorological Department seem to have a "dry bias" over the Ganges basin, predicting that less rain will fall than actually does.

To fix this bug, *Devanand et al.* decided to use their models to zoom in closer to Earth's surface. The standard models for predicting Indian monsoons don't take into account local topographical details, such as the western Himalaya. These models often miss complex interactions between the land and the atmosphere, such as how moisture evaporates from the land, then falls back down as precipitation. The researchers remedied this by combining a regional climate model called the Weather Research and Forecasting Model with two land surface models that can simulate interactions between the atmosphere and north central India's agricultural land, along with Himalayan mountainous topography. To verify their model's accuracy, they checked it against real-world weather data from 1981 to 2015.

Including this finer-grained detail largely did the trick, the authors report, correcting the dry bias of earlier models from a rainfall deficit of -4.82 millimeters per day to -1.37 millimeters per day. Global models, which smooth out local topography, allow too much cold, dry air to travel into the region, skewing predictions toward less rainfall, they concluded. The team hopes next to tackle another potentially important source of error in the models: irrigation. When used on a large scale, as it is in the Ganges basin, irrigation can lead to cooler local temperatures and more rain due to recycled precipitation. (*Geophysical Research Letters,* https://doi.org/10.1002/2018GL077218, 2018) **—Emily Underwood, Freelance Writer**

On the Origin of Infragravity Waves

Waves on the surface of the ocean with long periods (1–5 minutes) and low frequencies (0.005–0.05 hertz) are called infragravity waves. These features, which appear to originate from physical interactions between wind-driven waves near coastlines, play an important role in sediment transport, coastal erosion, and other nearshore processes. In addition, infragravity waves have significantly longer wavelengths compared with swell, which means that they can more easily penetrate beneath sea ice and are believed therefore to catalyze the breakup of ice shelves.

Although previous studies have suggested that some infragravity wave energy can cross continental shelves and radiate into the ocean basins, this process is still poorly understood. To further investigate the phenomenon, *Smit et al.* analyzed records collected in March 2012 by the Cascadia Amphibious Array, a group of pressure sensors deployed along a seafloor transect west of the Oregon coast at depths ranging from 54 meters on the continental shelf to 1909 meters west of the shelf break.

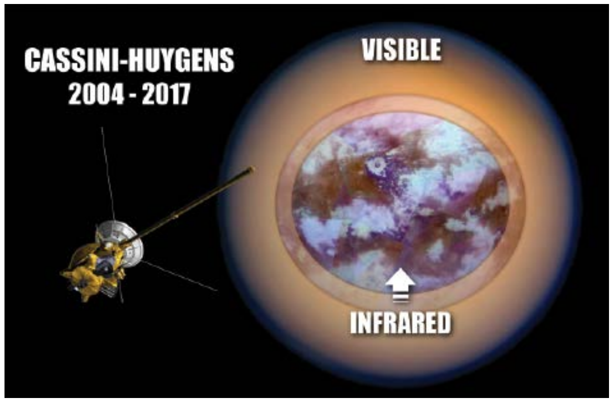
The observations confirm that infragravity waves originate near the coast and demonstrate that the waves experience a 2-order-of-magnitude reduction in energy when they cross the shelf break. The authors explain this sharp attenuation using a simple model of geometrical optics, which assumes that the shelf and the shelf break effectively trap most of the infragravity energy and allow only a small fraction to escape into the basin. Because this propagation was not strongly affected by the geometry of the Oregon continental shelf, the team concluded that the infragravity waves' energy levels can be directly estimated from coastal observations. This finding should simplify future efforts to predict the impacts of infragravity waves on ice shelves and other remote sites. (*Journal of Geophysical Research: Oceans,* https://doi.org/10.1029/2018JC013986, 2018) **—Terri Cook, Freelance Writer**

Infragravity waves originate from the world's coastlines, like this one in central California. Credit: iStock.com/MAYBAYBUTTER

Peering Through Titan's Haze to Better Understand Its Surface

Since 2004, when instruments aboard NASA's Cassini spacecraft began peering through Titan's dense nitrogen- and methane-rich atmosphere, scientists have discovered a surprisingly Earth-like world; stable liquid hydrocarbons evaporate, condense, rain down, and flow along its surface in a pattern akin to our planet's hydrologic cycle. Although observations from Cassini's Visual and Infrared Mapping Spectrometer (VIMS) have offered tantalizing clues about the moon's surface composition, which are needed to unravel potential interactions between Titan's atmosphere, surface, and interior, interpretations depend on accurately correcting for the interfering effects of the moon's murky atmosphere.

Brossier et al. have developed an advanced processing method to glean more information about Titan's equatorial belt from the VIMS data. Using their different infrared signatures, they first remapped the moon's three primary surficial units: infrared (IR) bright, IR blue, and IR brown. Next, the researchers selected five areas that display transitions between these surficial units and applied models to extract their albedo—a proxy for grain size—and composition on the basis of a range of possible mixtures of water ice and organic aerosols, the two substances believed to be the major components of the moon's surface. Finally, they correlated the results with morphological terrains identified from Cassini's radar data.



An artist's rendition showing the surface under Titan's atmosphere, now mapped through a technique that processes infrared signatures in Cassini-Huygens data. Credit: NASA/JPL/University of Arizona/LPGNantes

The results indicate that the IR-bright surficial unit consists of upland hills and plains that are covered with organic material and incised by stream networks. As these areas erode, the debris is transported downstream to IR-blue areas, which appear to be outwash plains that are enriched in large grains of water ice that may have resulted from ice bed erosion following the precipitation of hydrocarbons upstream.

Farthest from the uplands, the IR-brown surficial unit, which makes up 18.6% of Titan's surface, consists of windblown dunes composed of dust- to sand-sized hydrocarbon grains derived from the highlands.

Because the topographic and geographic distribution of these three units resembles the progression of sediment from mountains to deserts on our planet, these findings suggest that the locations of the infrared-derived surficial units observed in Titan's equatorial belt may, like their counterparts on Earth, be linked by geological processes. (*Journal of Geophysical Research: Planets,* https://doi.org/10.1029/2017JE005399, 2018) **—Terri Cook, Freelance Writer**

How Are Sediment Pulses Generated?

Rivers transport sediment along their beds when the force of the flowing water exceeds the material's cohesion and weight. The rate at which this process occurs is known to vary considerably over time even when the water's discharge is constant. Various explanations have been offered for these pulses, including the role played by grain sorting, but no clear connection has been established to date.

Dhont and Ancey consider whether sediment pulses could instead be related to the migration of bed forms—features like ripples that develop in the bed as water flows across it. They conducted an experiment in which they held the water discharge and the rate of gravel supply constant in a steeply inclined, 19-meter-long flume for 570 hours and used state-of-the-art techniques to monitor the results.

The researchers found that within a few hours, the flume's originally flat bed had developed into an alternating series of pools and gravel bars. These bars displayed what the researchers call stick-slip motion, in which the sediment remained stable for long intervals but would then suddenly shift downstream. These pulses, which occurred about every 10 hours on average, collectively transported roughly one third of the total sediment volume. The remainder was carried downstream by cycles of accumulation in the pools, which stored and then sporadically released gravel, creating sediment waves that caused many of the observed fluctuations in sediment transport rates.

As water runs out of a flume, particles of sediment strike impact plates. Researchers record these vibrations to measure sediment transport. Credit: Bob de Graffenried

The authors note that they do not yet know whether their finding that sediment travels in regular 10-hour pulses is a new observation of a previously unnoticed phenomenon or whether this stick-slip motion is specific to their experimental setting. If the former, these results may cause other researchers who study sediment transport to reconsider how they model the long-term transport of gravel. (*Geophysical Research Letters,* https://doi.org/10.1029/2018GL077792, 2018) **—Terri Cook, Freelance Writer**

Measurements of Kelvin-Helmholtz Waves in Earth's Magnetic Field

The instability that arises where there's a difference in velocity at the boundary between two fluids—like wind blowing across water—can create Kelvin-Helmholtz waves (KHWs), which look like a series of breaking waves hitting a beach. KHWs are frequently observed along the outermost boundary of Earth's magnetic field, where they presumably help transfer energy and plasma from the solar wind into our planet's magnetosphere. Yet the conditions under which these waves form and how they evolve over time are still poorly understood.

To better characterize KHWs, *Ling et al.* used the Advanced Relay and Technology Mission Satellite (ARTEMIS) and Geotail satellites to make simultaneous observations of the waves from opposite sides of Earth's magnetic tail during an instability event that occurred between 13 and 14 March 2014. They then compared their point measurements with computer simulations of the magnetosphere's response to the solar wind conditions observed during the same period of time.

The results offer evidence that KHWs develop in Earth's magnetic tail and that their wavelengths increase as they move tailward along the boundary layer, a finding that agrees with previously published simulations. The observations also suggest that vortices created by the instability develop at roughly the same time on the tail's dawn and dusk sides, although slight differences between the two sets of satellite observations prevented the researchers from completely ruling out dusk-dawn asymmetry.

In addition to providing new observational evidence for the growth of KHWs in Earth's magnetic tail, these findings provide insight into how this crucial means of interspace energy transfer evolves through both time and space. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2018JA025183, 2018) **—Terri Cook, Freelance Writer**

This artist's rendering shows how Kelvin-Helmholtz instability waves in Earth's magnetic tail might propagate through time and space. Credit: Quanqi Shi

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* 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

Assistant/Associate Professor in Regional Climate Modeling at Indiana University

The Department of Earth and Atmospheric Sciences at Indiana University Bloomington invites applications for a tenure-track position in climate modeling to begin in Fall 2019. Applicants with strengths in a general area of earth system modeling, climate dynamics, or land-atmospheric coupled models are encouraged to apply. Experience with regional climate downscaling and high-performance computing will be considered strong assets. The successful candidate will establish an internationally recognized, externally funded academic research program, and have a strong interest in graduate and undergraduate instruction including mentoring of M.S. and Ph.D. student research. Service to the department, college, and university is expected.

Applicants must have a Ph.D. in Atmospheric Sciences or a related field prior to employment. To ensure full consideration, applications should be submitted by Oct 15, 2018 but they will continue to be considered until the position is filled. Interested candidates should review the job description and submit application materials online at http://indiana.peopleadmin.com/postings/6515. Questions about the position should be directed to: Dr. Chanh Kieu, Search Committee Chair (ckieu@indiana.edu). Details about the Department, IU Environmental Resilience Institute, and Bloomington can be found at http://geology.indiana.edu/department/index.html. Indiana University is an equal employment and affirmative action employer and a provider of ADA services. All qualified applicants will receive consideration for employment without regard to age, ethnicity, color, race, religion, sex, sexual orientation, gender identity or expression, genetic information, marital status, national origin, disability status or protected veteran status. Enhancing diversity within our faculty and students is an important aspect of department and college strategic planning.

COLORADO STATE UNIVERSITY

ATMOSPHERIC SCIENCE TENURE TRACK FACULTY POSITION

The Department of Atmospheric Science at Colorado State University invites applications for a tenure-track faculty position in the dynamics and physics of the climate system. We solicit candidates with expertise in geophysical fluid dynamics, coupling between clouds and radiation, climate dynamics, and/or planetary atmospheres across a range of spatial and temporal scales. Candidates will be considered at the assistant or associate professor level.

The new faculty member will be expected to build and maintain a strong, internationally recognized research program supported through external funding, complement and expand upon current research and teaching activities, and provide service to the University and broader community. She/he will contribute to teaching and intellectual leadership in our atmospheric science curriculum at the M.S. and Ph.D. levels by teaching courses in the Department's core graduate curriculum, advising graduate students, and developing advanced courses in his or her areas of expertise. Further information about the Department can be found at http://www.atmos.colostate.edu.

A Ph.D. in atmospheric science or a related field is required by the position start date. Candidates should have an outstanding research record in the areas of interest commensurate with experience and should demonstrate potential for continued extraordinary scholarship. Candidates must exhibit ability and enthusiasm to teach courses in their respective areas of interest in the Department's graduate curriculum. Reflecting departmental and institutional values, candidates are expected to have the ability to advance the Department's commitment to diversity and inclusion.

Applications and nominations will be accepted until the positions are filled; however, applications should be received by October 15, 2018 to ensure full consideration. The search will remain open until the position is filled. Application materials of candidates, including letters of recommendation, will only be made available for review by the broader faculty of the Department of Atmospheric Science if the applicant reaches the semifinalist stage. Applicants should submit a cover letter, one to two page statements on research and teaching interests, a diversity statement, a curriculum vitae, and the names of four references (who will not be contacted without prior notification of the candidate) at the following link: http://jobs.colostate.edu/postings/58106

Please address inquiries about the position to:

Professor David Thompson, Search Chair

Department of Atmospheric Science
Colorado State University
Fort Collins, CO
80523-1371
david.thompson@colostate.edu

Colorado State University (CSU) strives to provide a safe study, work, and living environment for its faculty, staff, volunteers and students. To support this environment and comply with applicable laws and regulations, CSU conducts background checks. The type of background check conducted varies by position and can include, but is not limited to, criminal (felony and misdemeanor) history, sex offender registry, motor vehicle history, financial history, and/or education verification. Background checks will be conducted when required by law or contract and when, in the discretion of the university, it is reasonable and prudent to do so.

Colorado State University is committed to providing an environment that is free from discrimination and harassment based on race, age, creed, color, religion, national origin or ancestry, sex, gender, disability, veteran status, genetic information, sexual orientation, gender identity or expression, or pregnancy. Colorado State University is an equal opportunity/equal access/affirmative action employer fully committed to achieving a diverse workforce and complies with all Federal and Colorado State laws, regulations, and executive orders regarding non-discrimination and affirmative action. The Office of Equal Opportunity is located in 101 Student Services.

Senior Research Scientist-Atmospheric Science

FM Global is a leading property insurer of the world's largest businesses, providing more than one-third of FORTUNE 1000-size companies with engineering-based risk management and property insurance solutions. FM Global helps clients maintain continuity in their business operations by drawing upon state-of-the-art loss-prevention engineering and research; risk management skills and support services; tailored risk transfer capabilities; and superior financial strength. To do so, we rely on a dynamic, culturally diverse group of employees, working in more than 100 countries, in a variety of challenging roles.

The person in this position will be responsible for planning and conducting research in atmospheric hazard modeling to evaluate, develop, and implement new techniques and models for tropical/extra tropical/severe convective storms, hail, tornadoes, and extreme precipitation that can lead to property losses.

Work will include preparing reports and presentations describing the results of studies completed or in progress, the relevance of the results for loss prevention and risk management, and the development and implementation of loss prevention and mitigation techniques; and developing plans for strategic research that will lead to measurable, significant improvements in the ability to estimate future property losses.

The position requires a PhD degree and a solid research record in atmospheric science or related field demonstrating a broad physical understanding of atmospheric processes and experience using and combining large atmospheric data sets in various formats; strong programming

UNIVERSITY OF MIAMI — CIMAS

POSITIONS IN OCEAN MODELING AND DATA ASSIMILATION FOR IMPROVING OCEAN OBSERVATION STRATEGIES

The University of Miami invites applications for **two positions** in ocean modeling and forecasting systems, dedicated to improving ocean observation strategies.

The first position is for a **Postdoctoral Associate**, who will contribute to the development of an observing system evaluation capability to improve ocean prediction for a broad range of applications. We seek candidates with a PhD in oceanography, meteorology, or a related field.

The second position is for a **Senior Research Associate**, who will provide computer programming support for the implementation of numerical simulations and will take part in the analysis of the results. We seek candidates with a M.S. in computer science, oceanography, meteorology, mathematics, statistics, or a related field.

For more details and to make application, please visit www.miami.edu/careers (positions P100039284 and P100039249). If you have any question, please contact Matthieu Le Hénaff (m.lehenaff@miami.edu).

and numerical analysis skills. Applicants must have demonstrated project management abilities and excellent written and verbal communication skills.

Previous experience with modeling wind and precipitation from tropical cyclones, analysis of related data, and generation of synthetic event sets is a plus. Desired to have a sound background in statistics and previous experience with high-performance computing.

The job title depends on qualifications and experience.

Apply at https://jobs.fmglobalcareers.com/job/norwood/senior-research-scientist-atmospheric-science/474/6907908

Two tenured/tenure-track faculty positions at Texas A&M University

The Department of Atmospheric Sciences at Texas A&M University is searching for candidates in the areas of atmospheric chemistry, aerosol science, physical meteorology, remote sensing and instrumentation, 'big data' science, high-performance computing, extreme event attribution, boundary layer meteorology, or microphysics. Candidates working in other areas of atmospheric sciences that complement the current strengths of the department are also invited to apply. We anticipate filling two tenured or tenure-track positions — one of the positions at the associate or full professor level, while the other could be filled at any rank.

The successful candidates will be expected to establish and maintain an independent and externally funded research program and contribute to transformative teaching at the undergraduate and graduate levels. Applicants must have a Ph.D. in atmospheric sciences or a related field at the time of appointment. Postdoctoral experience is desirable but is not required. Applicants seeking appointment at the associate or full professor rank must be recognized leaders in the field with a record of scholarship and teaching commensurate with their rank.

Information about the Department of Atmospheric Sciences can be found at: https://atmo.tamu.edu/. The Department of Atmospheric Sciences is part of the College of Geosciences, which also houses the Departments of Geology and Geophysics, Geography, and Oceanography, and the interdisciplinary Environmental Programs and Water Management and Hydrologic Sciences degree programs. The College of Geosciences also includes the International Ocean Discovery Program and Texas Sea Grant, among numerous other interdisciplinary centers. Texas A&M University is a land-,sea-, and space-grant university, with a dynamic and international community of over 250,000 people. The Texas A&M System is an Equal Opportunity/Affirmative Action/Veterans/Disability Employer committed to diversity. Texas A&M University and the College of Geosciences are highly responsive to the needs of dual-career partners.

To apply, please submit your CV, statement of research, and teaching interests, and names and contact information for at least three references to: https://apply.interfolio.com/51962

Informal inquiries or requests for more information may be sent via email directly to the Search Committee Chair:

Prof. Andrew E. Dessler
Chair, Faculty Search Committee
Department of Atmospheric Sciences
Texas A&M University
College Station, TX 77843-3150
Email: adessler@tamu.edu

The position will remain open until suitable candidates are found. Initial review of application will begin on September 1, 2018

Tenure Track Professorship (W1/W2) in Energy Meteorology

The Faculty of Mathematics and Natural Sciences of the University of Cologne invites applications for a Tenure Track Professorship (W1/W2) in Energy Meteorology

This call is part of the Federal Tenure Track Programme. It addresses researchers at an early career stage. We seek a candidate with experience in basic research related to the potential of solar and wind energy, with focus on climate diagnostics characterizing the variability of solar radiation and wind. Collaboration with the Faculty of Economics regarding the development of new methods for using meteorological variables for advanced energy models, e.g. networks, energy markets, is desired.

The candidate will be involved in the bachelor programme "Geophysik und Meteorologie" (in German) and the master program "Physics of the Earth and Atmosphere" (in English). In addition to teaching basic meteorological modules, teaching connected to the research fields energy meteorology and climate diagnostics is expected.

More details on the qualification requirements and the evaluation process are available in the full announcement on the Academic Job Portal of the University of Cologne (https://berufungen.uni-koeln.de).

The University of Cologne is an equal opportunity employer. Applications of women and individuals with disabilities are strongly encouraged. Applications should include a letter of motivation with teaching and research statements accompanied by supporting documents. Applications should be submitted via the Academic Job Portal of the University of Cologne (https://

RICE | EEPS
Earth, Environmental and Planetary Sciences

Wiess and Pan Post-Doctoral Research Fellowships
Department of Earth, Environmental and Planetary Sciences, Rice University

The Department of Earth, Environmental and Planetary Sciences at Rice University is inviting applications for the Wiess and the Pan Postdoctoral Research Fellowships. We are seeking candidates with independent research interests that intersect with one or more faculty within our department. Both domestic and international applicants are welcome, but applicants must have a Ph.D. awarded within three years of the time of appointment.

The research fellowships will be supported for two years, pending satisfactory progress during the first year, and covers an annual stipend of $60,000 with a benefits package and an additional annual discretionary research allowance of $3,500.

Applicants are requested to develop a proposal of research to be undertaken during the fellowship period. The principal selection criteria are scientific excellence, a clearly expressed research plan to address questions at the forefront of their field of study, and research synergies with at least one faculty. The proposed research should, however, encompass independent research ideas and explore new directions beyond the applicant's Ph.D. Preference will be given to applicants whose proposals demonstrate independence and originality, and also the potential for collaboration with one or more faculty in the Department of Earth, Environmental and Planetary Sciences.

The application for both fellowships is due on 1 November, 2018. Applicants are required to submit one application only at http://jobs.rice.edu/postings/15058. The application should include the following documents:

(1) A cover letter.
(2) A research proposal of no more than 3 pages (not counting references) of single-spaced text and figures.
(3) A current CV, including a list of publications.

As part of the online application, the applicant will also have to provide the names and contact information of three or more people who will be asked to submit reference letters by the same deadline.

The highest ranked applicants will be invited to visit Rice in early 2019. Following acceptance, the appointment may begin anytime before 1 January, 2020. For further information or questions contact the chair of the search committee at esci-postdoc@rice.edu.

Rice University is located in Houston, Texas, and is a private, coeducational, nonsectarian university that aspires to path-breaking research, unsurpassed teaching, and contributions to the betterment of our world. Rice fulfills this mission by cultivating a diverse community of learning and discovery that produces leaders across the spectrum of human endeavor.

Rice University is an Equal Opportunity Employer with commitment to diversity at all levels, and considers for employment qualified applicants without regard to race, color, religion, age, sex, sexual orientation, gender identity, national or ethnic origin, genetic information, disability or protected veteran status.

https:/earthscience.rice.edu/open-positions/

berufungen.uni-koeln.de) no later than 15 October 2018.

Geochemistry

Assistant Professor of Geochemistry-Earth/Planetary Processes

The Department of Earth, Environmental & Planetary Sciences at Brown University (http://www.brown.edu/academics/earth-environmental-planetary-sciences/) invites applications for a tenure-track faculty appointment in geochemistry. Any analytical, experimental and theoretical/computational approach to understanding the origin and chemical evolution of the Earth and planets will be considered. Some examples include, but are not limited to, cosmochemistry, planetary petrology, non-traditional stable isotope geochemistry, early Earth evolution, volcanology, and interactions of planetary materials with hydrospheres and atmospheres. Preference will be given to candidates whose strengths complement departmental research expertise in Geochemistry and Petrology, Planetary Geoscience, Geophysics, and Climate and Environment. We seek scientists whose research integrates field observations, geochemical analyses, experimental studies, and geochemical theory and/or modeling. We are interested in scientists whose research transcends traditional boundaries in geochemistry, such as between high-temperature and low-temperature geochemistry, geochemistry and geophysics, and terrestrial and planetary. The successful candidate will maintain an active, externally-funded research program and enjoy a commitment to teaching at both undergraduate and graduate levels. Appointment will be at the Assistant Professor level.

Apply at: http://apply.interfolio.com/51680

Geochemistry of Near Surface Environments

The Department of Earth Sciences at the University of Minnesota-Twin Cities invites applications for a tenure-track faculty position in Isotope Geochemistry and/or Analytical Geochemistry of Near Surface Environments at the assistant professor level. Exceptional candidates at the associate professor level will also be considered. We seek a colleague who creatively uses isotopic and/or analytical approaches to understand processes and changes in near surface environments in modern and ancient systems, including the atmosphere, hydrosphere, cryosphere, biosphere, and/or the upper crust. Successful applicants will be expected to contribute to a diverse research and teaching community in the Department of Earth Sciences through the development of a vigorous, internationally recognized and externally funded research program, through teaching courses at the undergraduate and graduate levels, and through service in the department, college, and university. The Department of Earth Sciences is part of the College of Science and Engineering and houses research programs as well as state-of-the-art analytical facilities spanning a broad spectrum of Earth Science disciplines (further information is available at: http://www.esci.umn.edu).

Applicants must have a Ph.D. in the geosciences or a related field at the time of appointment. Applicants should submit a cover letter, curriculum vitae, research statement, teaching statement, names and contact information of three references, and, if applicable, a list of any planned presentations at conferences in fall of 2018. These materials must be submitted online: http://www1.umn.edu/ohr/employment/ search for Requisition Number 325790

Appointment may begin as early as August 2019. Review of applications will begin on Oct. 15, 2018, and continue until the position is filled. For further information or questions, please contact R. Lawrence Edwards, Chair of the Search Committee at edwar001@umn.edu.

The University of Minnesota values a diverse faculty, which fosters a richness of perspectives and an inclusive environment, and whose members serve as role models for a diverse student body. The University provides equal access to and opportunity in its programs, facilities, and employment without regard to race, color, creed, religion, national origin, gender, age, marital status, disability, public assistance status, veteran status, sexual orientation, gender identity, or gender expression. The University supports the work-life balance of its faculty.

Tenure-Track Faculty Position

Geochemistry of Near-Surface Processes, Boston College

The Department of Earth and Environmental Sciences at Boston College invites applications for a tenure-track faculty position at the rank of Assistant Professor. We seek candidates with expertise in low-temperature geochemistry with application to Earth's near-surface environment in the context of global change. The successful candidate will be expected to develop a vigorous externally funded research program integrated with excellence in teaching at both the undergraduate and graduate levels. The candidate should have research interests compatible with those of the current faculty in the Department of Earth and Environmental Sciences, including, but not limited to: understanding modern processes related to the exchange of water, carbon, and pollutants between the atmosphere, the oceans, the terrestrial hydrosphere, land surface, and urban systems, or reconstructing/understanding ancient environments and climates. We particularly encourage applicants whose research uses stable isotopes, integrates field-based research, and/or crosses traditional disciplinary boundaries in the sciences, thereby having the potential to also conduct innovative research within the forthcoming Schiller Institute for Integrated Science and Society at Boston College.

Applicants must hold a Ph.D. in the geosciences or a related field at the time of appointment. Complete applications should be submitted online at: https://apply.interfolio.com/53801. Review of applications will begin on November 1, 2018. Inquiries may be directed to Prof. Jeremy Shakun, Search Committee Chair (jeremy.shakun@bc.edu), or Ethan Baxter, Department Chair (ethan.baxter@bc.edu).

Boston College is an Affirmative Action/Equal Opportunity Employer and does not discriminate on the basis of any legally protected category including disability and protected veteran status.

Global Environmental Change

Tenure-Track Assistant, Associate, or Full Professor in Climate Change

The Institute at Brown for Environment and Society (IBES) — jointly with the Departments of Anthropology; Earth, Environmental and Planetary Sciences (DEEPS); Ecology and Evolutionary Biology; Epidemiology; and Sociology — invites applications from rising leaders in the natural, socio-economic, public health, and environmental justice aspects of climate change.

This open rank search will seek to fill between 2 and 4 endowed university chairs with a tenure home in any of the participating departments. The endowed chairs are named faculty positions that include a small fund in perpetuity (in addition to start up funds) to assist chair holders in achieving their research and teaching goals. We are particularly interested in scholars who demonstrate research excellence, an interest in working to promote diversity and inclusion in environmental disciplines, and a dedication to teaching and research mentoring. The successful applicant will have an outstanding record of research and teaching that complements the strengths of both DEEPS and IBES, while demonstrating the potential to work across both units. The ideal candidate is likely to be a senior assistant or associate professor (or equivalent rank).

DEEPS seeks to build on current strengths in climate change and related sciences. Examples of research areas of interest include: modeling and observation of past, present and future climate; coastal environments and geomorphology; sea level change-including oceanography, glaciology, geophysics, and paleo-records; carbon cycling and biogeochemistry; water cycling, sustainability, and hydrogeochemistry; planetary climates; and

Massachusetts Institute of Technology

Department of Earth, Atmospheric, and Planetary Sciences

Faculty Position in Geophysics and Geochemistry

The Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology (MIT), Cambridge, MA 02139, invites qualified candidates to apply for a tenure-track faculty position. The search is in the broad area of geophysics and geochemistry encompassing the Earth and other planetary bodies in the solar system. We seek candidates who use theory, observation, and/or experimentation and particularly encourage applicants whose work crosses traditional disciplinary boundaries. Candidates should have the potential for innovation and leadership in research and a commitment to teaching at the undergraduate and graduate levels.

Applicants must hold a Ph.D. in geoscience or related field by the start of employment. Our intent is to hire at the assistant professor level, but more senior appointments may also be considered. A complete application must include a cover letter, curriculum vitae, one- to two-page descriptions each of research and teaching plans, and three letters of recommendation. We request that in their cover letter, applicants explicitly commit to our department's code of conduct: https://eapsweb.mit.edu/about/code-conduct

Applications are being accepted at Academic Jobs Online: https://academicjobsonline.org/ajo/jobs/11380

To receive full consideration, complete applications must be received by November 1, 2018.

Search Contact: Ms. Karen Fosher, HR Administrator, EAPS, 54-924, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, email: kfosher@mit.edu

MIT is an equal employment opportunity employer. All qualified applicants will receive consideration for employment and will not be discriminated against on the basis of race, color, sex, sexual orientation, gender identity, religion, disability, age, genetic information, veteran status, ancestry, or national or ethnic origin.

http://web.mit.edu

remote sensing. Candidates whose work involves natural sciences of climate change in conjunction with societal aspects—such as hazards, resources, sustainability, and equity—are of particular interest.

Applicants must have a PhD at the time of starting work. Candidates should submit a teaching statement; a research statement; a diversity and inclusion statement; a CV; two writing samples (e.g., journal article, book prospectus, or book chapter); and a cover letter describing their interest in the position. Candidates currently holding tenured faculty positions should provide the names of three referees; these referees will not be contacted without prior authorization from the candidate. Candidates that do not currently hold a tenured faculty position should have three letters of reference submitted before the application deadline. Interested candidates should feel free to contact Prof. Greg Hirth (Greg_Hirth@brown.edu) for further information.

Full consideration will be given to applications received by October 1st, 2018, but we will continue to accept applications until the position is filled. Brown is an equal opportunity/affirmative action employer, and women and minorities are strongly encouraged to apply. Send materials to: http://apply.interfolio.com/50691

Brown University is committed to fostering a diverse and inclusive academic global community; as an EEO/AA employer, Brown considers applicants for employment without regard to, and does not discriminate on the basis of, gender, race, protected veteran status, disability, or any other legally protected status.

Hydrology

Research Scientist – Hydrology

FM Global is a leading property insurer of the world's largest businesses, providing more than one-third of FORTUNE 1000-size companies with engineering-based risk management and property insurance solutions. FM Global helps clients maintain continuity in their business operations by drawing upon state-of-the-art loss-prevention engineering and research; risk management skills and support services; tailored risk transfer capabilities; and superior financial strength. To do so, we rely on a dynamic, culturally diverse group of employees, working in more than 100 countries, in a variety of challenging roles.

FM Global Research is the driving force behind our property loss-prevention engineering and understanding of the hazards our clients face. FM Global has been the leader in property loss-prevention research for more than 175 years.

As part of our research department, you'll work alongside other researchers and independently to understand emerging property loss-prevention hazards, quantify real-world scenarios, and develop new ways to protect against today's property-loss threats. You'll also work on implementation, evaluation, and development of techniques—including computer models and experiments—and present your findings to make strategic and beneficial advancements in risk mitigation.

As part of our research division, you'll work alongside a unique group of scientists across engineering, earth, hydrological, and atmospheric sciences to protect the value of FM Global's clients' businesses by developing methods to identify hazards, assess risk, and produce loss prevention solutions that are efficient and cost-effective.

Interested in a career with our Structures and Natural Hazards group? We have an opening for planning and conducting research on flood, and subsequent property losses.

Position requires a PhD degree, and a research record in hydrology or related field. Candidates are expected to have:

- knowledge of catchment-based, lumped, semi-distributed, and distributed hydrologic models; understanding of modeling principles, and model setup, calibration and validation; experience with collecting, processing, and analyzing data, and in developing and implementing new techniques;
- solid background in probability and statistics; proven technical programming experience; and GIS skills.

Applicants must have demonstrated project management abilities and excellent written and verbal communication skills. The job title depends on qualifications and experience.

Apply at https://jobs.fmglobalcareers.com/job/norwood/research-scientist-hydrology/474/5203203

Interdisciplinary

NASA Postdoctoral Program–Application Deadline November 1, 2018

The NASA Postdoctoral Program (NPP) supports NASA's goal to expand scientific understanding of Earth and the universe in which we live.

This announcement reflects recent increases to the NPP annual base stipend and the annual travel allowance provided to fellows.

To learn more about specific opportunities and to apply, please visit: https://npp.usra.edu/opportunities/

The NASA Postdoctoral Program offers US and international scientists the opportunity to advance their research while contributing to NASA's scientific goals. The NPP supports fundamental science; explores the undiscovered; promotes intellectual growth; and encourages scientific connections.

Engage in NASA research in Earth science, planetary science, heliophysics, astrophysics, aeronautics and engineering, human exploration and operations, space bioscience, and astrobiology.

Details:

- UPDATED! Annual stipends start at $60,000, with supplements for high cost-of-living areas and certain degree fields
- UPDATED! Annual travel budget of $10,000
- Relocation allowance
- Financial supplement for health insurance purchased through the program
- Appointments renewable for up to three years
- Approximately 90 Fellowships awarded annually

Available Fields of Study:

- Aeronautics, Aeronautical or Other Engineering
- Astrobiology
- Astrophysics
- Biological Sciences
- Cosmochemistry
- Earth Science
- Heliophysics Science
- Interdisciplinary/Other
- Planetary Science
- Technology Development

Available NASA Centers:

- Ames Research Center
- Armstrong Flight Research Center
- Glenn Research Center
- Goddard Institute for Space Studies
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Kennedy Space Center
- Langley Research Center
- Marshall Space Flight Center
- NASA Astrobiology Program
- NASA HQ
- Solar System Exploration Research Virtual Institute
- Stennis Space Center
- Wallops Flight Facility

NOTE: Not all centers participate in every application round... please refer to the website for current opportunity locations

Eligibility:

US citizens, Lawful Permanent Residents and foreign nationals eligible for a J-1 visa as a Research Scholar

Recent and Senior-Level PhD recipients

Application Deadlines

Three each year–March 1, July 1, and November 1

To learn more about specific opportunities and to apply, please visit: https://npp.usra.edu/opportunities/

Postdoctoral fellows and non-tenured research professor

Several postdoctoral fellows and non-tenured research professor positions, supported by Science Research Center program (SRC) of Korean National Research Foundation are now available at a newly-opened 'Irreversible Climate Change Research Center' (IRCC center) at Yonsei University, Seoul, Korea. Postdoctoral fellow and research professor have ample opportunities for research collaboration with professors in IRCC center. Areas of research interests for the positions are climate dynamics or related fields, including global ocean climate change, paleoclimate dynamics, cryosphere dynamics, bio-climate interaction, carbon cycle, especially focusing on abrupt climate change and tipping point problem. A CGCM expert would be preferential. The positions are available immediately and will remain open until filled. Initial appointment will be for a year, with an excellent possibility of renewal for one or more years until the ending of the SRC program (7-year project). The salary will be competitive, commensurate with experience, and will comply with Yonsei University's Postdoctoral fellow and research professor guidelines. To apply to the position, please email a single file containing a letter of interest and CV to Prof. Soon-Il An (sian@yonsei.ac.kr; Chief of SRC center), and later may ask for contact information for three references. For the question, also email to sian@yonsei.ac.kr.

Rutgers University–New Brunswick seeks an accomplished scientist to serve as the first Henry Rutgers Professor of Earth, Ocean, and Atmospheric Sciences.

The successful candidate will engender cross-cutting research, teaching, and service amongst Earth, oceans, and atmospheric sciences, advancing Rutgers' leadership in critical scientific problems. S/he will engage as a key member of Rutgers' Institute of Earth, Ocean, and Atmospheric Sciences (EOAS), a broad interdisciplinary community fostering research, education, and engagement about Earth's interior, continents, oceans, atmosphere, and biosphere, their interactions and co-evolution through our planet's history, and humanity's dependence and impacts upon these systems.

Candidates should be internationally recognized for their research, have a commitment to cross-disciplinary collaboration in the natural and social sciences, and possess a commensurate record of publications, grants, teaching and service. S/he will have a tenure home in a disciplinary department, with the potential for joint appointment in multiple departments including, but not limited to: Earth and Planetary Sciences; Ecology, Evolution and Natural Resources; Environmental Sciences; Geography; and Marine and Coastal Sciences.

A member of the BTAA and AAU, Rutgers–New Brunswick is America's eighth oldest institution of higher learning, and NJ's land-grant and premier public research university. This professorship reflects Rutgers' strong tradition of cross-disciplinary research and collaborative institutions, including EOAS, Rutgers Climate Institute, Rutgers Energy Institute, and Coastal Climate Risk & Resilience initiative.

Applicants should apply electronically at http://jobs.rutgers.edu/postings/67459 with: (1) an application letter describing suitability for the position and summarizing relevant prior experience; (2) CV; and (3) list of three references. References will not be contacted without informing the candidate. Application review will start September 10, 2018. All correspondence will be held in strictest confidence. Submit nominations/questions to:

Professor Robert Sherrell, Chair
Henry Rutgers Professorship (EOAS) Committee
eoas.search@rutgers.edu
http://nbchancellor.rutgers.edu/executive-searches

An equal opportunity employer, Rutgers is committed to building a diverse community and encourages applications from women and minority candidates

Senior Research Scientist

WindLogics is seeking a Senior Research Scientist as part of our energy system R&D team. As a division of NextEra Energy, we own and operate the U.S.-largest fleet of wind, solar, and storage. Energy systems are undergoing a rapid transition in generation, delivery, and control systems, both in terms of technology and customer relationships. We are at the leading edge in developing and dispatching a new breed of integrated resource solutions to utilities, cities and municipalities, and commercial and industrial entities; optimized to deliver benefits (savings, reliability, and reduced greenhouse gas emissions) tailored to the customer's needs. We look at the inherent complexity of the energy system as an opportunity for those with the ability to envision new business models, backed up by the scientific and mathematical capabilities needed to execute on the vision.

- The position is with the Science team in support of energy systems innovation. The person will participate in and lead small teams engaged in applied research; working on challenging, complex problems in a business setting.
- The person will design and prototype algorithmic solutions to energy related scientific and engineering problems
- The position will advise the Chief Scientist as well as WindLogics and NextEra management on research topics, analytical results, and scientific and energy industry advances. Excellent verbal and written communication skills are required.

UNIVERSITY
OF MIAMI

ROSENSTIEL SCHOOL OF MARINE & ATMOSPHERIC SCIENCE

ASSISTANT/ASSOCIATE PROFESSOR IN GEODYNAMICS AND GEODESY

The Department of Marine Geosciences (MGS) at the Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami (UM), seeks outstanding candidates for a tenure track position at either the **assistant** or **associate professor level** in the fields of geodynamics, geodesy, or cryosphere dynamics. We are interested in candidates accomplished in (1) applying geodynamic modeling or geodetic techniques to the wide range of active geological processes and hazards, or (2) measuring or modeling of sea level changes, a field of direct relevance to Miami. We encourage applications from candidates who will utilize NASA's current and forthcoming Earth Observation missions as well as data from other satellites.

A Ph.D. in geology, geophysics, or related field is required.

Applications will only be accepted electronically, through the career website at **www.miami.edu/careers (Faculty Positions #R100025583).** That link describes the position responsibilities and expectations more completely.

Qualifications:
- Masters in Physics or related physical science-Required.
- PhD in Physics or related physical science – Preferred.

- Background in detailed analysis of complex systems involving large datasets, guided by physically-based conceptual models
- Use of appropriate programming and scripting languages (R, Python, Julia, Fortran, etc.)
- Innate curiosity about nearly everything
- Ability to abstract a problem in such a way as to enable 'cross-pollination' utilizing concepts and techniques from other fields

Email applications to Alison.Huston@nexteraenergy.com

Ocean Science

Postdoctoral Research Associate

The Atmospheric and Oceanic Sciences Program at Princeton University in cooperation with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) seeks a postdoctoral researcher or more senior position to conduct studies on the predictability of seasonal hydroclimate extremes. This position is a part of the Forecasting a Continuum of Environmental Threats (FACETs) project, which is a proposed next-generation hazardous weather paradigm that utilizes probabilistic information as its foundation. FACETs will leverage physical and social science research to support a system that is modern, flexible, and designed to communicate clear and simple hazardous weather, water, and climate information to serve society. FACETs supports NOAA's Weather-Ready Nation initiative to build community resilience in the face of increasing vulnerability to extreme weather, water, and climate events.

Under the supervision of Dr. Nat Johnson, the selected candidate is expected to leverage available observational and dynamical forecast model data to study the causes and predictability of hydroclimate extremes, including droughts, pluvials, and tropical cyclone impacts, over North America on seasonal timescales. The research will entail the analysis of retrospective seasonal forecasts from the North American Multi-Model Ensemble (NMME), with a focus on determining the viability of developing probabilistic hazard outlooks for seasonal hydroclimate extremes.

The selected candidate will have a Ph.D. in atmospheric science, oceanography, hydrology, or a related field. Candidates with strong backgrounds in weather or climate prediction and the analysis of large datasets are preferred. Initial appointment is for one year with the possibility of renewal subject to satisfactory performance and available funding. This position is subject to the University's background check policy.

Complete applications, including cover letter, a curriculum vitae a publication list, and contact information for three references, should be submitted online to https://www.princeton.edu/acad-positions/position/8341.

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.

Planetary Sciences

Job Title: Research Scientist: Ocean Worlds

Location: Pasadena, CA

The Jet Propulsion Laboratory, California Institute of Technology invites applications for a staff Scientist position in areas relevant to understanding Ocean Worlds.

The position is to conduct Ocean Worlds-related scientific research within the fields of Geochemistry and Astrobiology. It is expected that the successful candidate will develop an independently funded research program and will pursue new mission and/or instrument opportunities focusing on Ocean World exploration.

The candidate is also expected to be a member of the JPL Solar System Exploration Directorate Ocean Worlds team. This may involve participating in engineering-led planning teams, interaction with personnel involved in similar efforts at other NASA locations, including NASA Headquarters, and helping to play a coordination role with the interested external community.

The position requires a Ph.D. 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 Ocean Worlds exploration. The successful candidate will have a demonstrated professional reputation as a productive researcher with a track record of publications in peer-reviewed journals.

Additional desirable attributes include:

- 2-3 years of related postdoctoral experience
- A history of writing successful research funding proposals
- Experience with mission formulation and proposal preparation
- Experience working with and/or interacting with NASA Headquarters

Please visit https://www.jpl.nasa.gov/opportunities/experienced/ (Job ID 2018-9596) for a full description. Applications received by September 30, 2018, will receive full consideration.

Postcards from the Field

Dear Everyone:

We are on a field trip with University of Granada's master's students in the water science program at the Lagunas de Ruidera (Roaring Lakes) in La Mancha in central Spain. Here 15 interconnected aquifer-fed karstic lakes form a unique cascading landscape separated by travertine calcium carbonate dams of biological origin. More than 400 years ago, Miguel de Cervantes wrote his iconic novel, *Don Quixote de La Mancha,* with the adventures and misadventures therein taking place in and around this enchanting region along today's Ruta de Don Quijote. Under threat from multiple anthropogenic (e.g., groundwater extraction, summer tourism) and climate change (e.g., warming, droughts) stressors, these roaring lakes with their series of waterfalls now are falling silent. More information on these lakes is available at the Lakes of Ruidera Natural Park website (http://bit.ly/ruidera-lakes).

—**Juan Manuel Medina-Sánchez, Manuel Villar-Argaiz, Guillermo Herrera,** and **Presentación Carrillo,** Departamento de Ecología and Instituto del Agua, Universidad de Granada, Granada, Spain; and **Bopaiah Biddanda,** Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich.

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