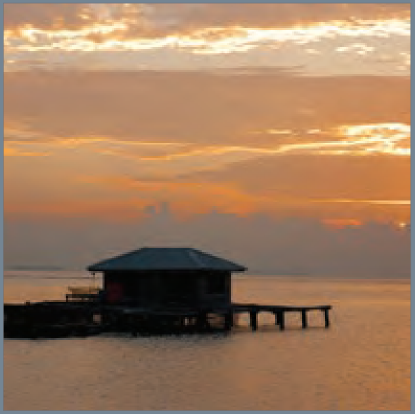
National Aeronautics and Space Administration

Sensing Our Planet




NASA Earth Science Research Features **2017**

Sensing Our Planet

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National Aeronautics and Space Administration

NASA Earth Observing System Data and Information System (EOSDIS)
Distributed Active Archive Centers

www.nasa.gov

Front cover images

Top row, left to right:

Researchers from the NASA Jet Propulsion Laboratory test Global Positioning System (GPS) receivers in California. See the related article, "Warnings from the ionosphere," on page 42. (Courtesy M. Tule/NASA JPL)

The sun rises over a fishing platform in Kepulauan Seribu (Thousand Islands) in the Java Sea. See the related article, "From Indonesia to India," on page 46. (Courtesy buitenzorger/flickr)

This close up of the *Aedes aegypti* mosquito shows a distended abdomen after feeding. See the related article, "Zika zone," on page 8. (Courtesy J. Gathany, Centers for Disease Control)

A prolonged drought across Texas desiccates plants and dries up livestock watering holes. See the related article, "Drought on the range," on page 30. (Courtesy AgriLife Today)

Bottom row, left to right:

Residents in Ecatapec, a borough of Mexico City, wait for their family's barrels to be filled. See the related article, "Closed season," on page 24. (© L. Forsyth)

Bill Baccus does a snow survey on the top of Snow Dome, Mount Olympus in early April 2016. See the related article, "Mountains of precipitation," on page 2. (Courtesy B. Baccus)

A full moon illuminates this power plant near Seal Beach in Rossmoor, California, not far from Los Angeles. See the related article, "Carbon control," on page 20. (Courtesy alkhodarev/flickr)

Back cover images

Top row, left to right:

This aerial view shows Spectacle Reef Light on the northwest side of Lake Huron, 11 miles east of Bois Blanc Island. See the related article, "To the lighthouse," on page 38. (Courtesy US Coast Guard)

Swampy forests, or taiga, are common across sub-Arctic Russia. See the related article, "A spread of green," on page 50. (Courtesy I. I. Savin)

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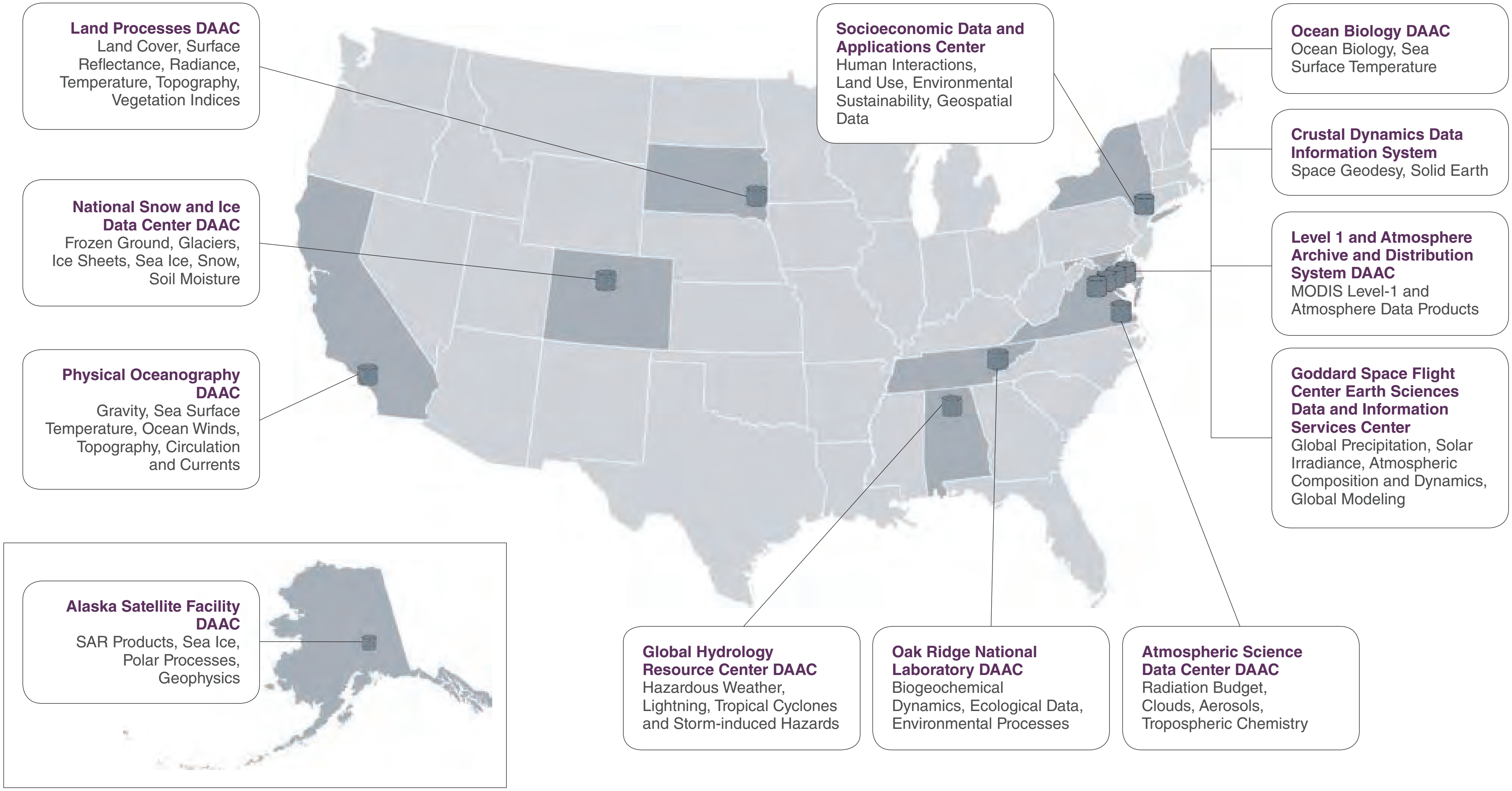
Vehicles emit many of the chemicals that cause Denver's brown cloud of air pollution. See the related article, "A rising problem," on page 12. (Courtesy J. Tarbell)

Crew onboard the *Thetys* research vessel recover Marisonde drifting buoys from the northwestern Mediterranean Sea. The buoys collected sea surface and air measurements for an oceanographic campaign in May 2013. See the related article, "Spin cycle," on page 16. (Courtesy M. Herrmann)

These images show brown fat (left) and white fat (right). Brown fat cells look darker because they contain numerous mitochondria, organelles that convert oxygen and nutrients into adenosine triphosphate (ATP). However, in brown fat, a protein called Uncoupling Protein 1 short-circuits the production of ATP and causes the mitochondria to release heat as energy instead of ATP. This enables brown fat to burn calories as well as generate heat. See the related article, "The big fat puzzle," on page 34. (Courtesy Shutterstock)



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About the EOSDIS Distributed Active Archive Centers (DAACs)

The articles in this issue arose from research that used data archived and managed by NASA Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs). The DAACs, managed by NASA's Earth Science Data and Information System Project (ESDIS), offer more than 11,140 Earth system science data products and associated services to a wide community of users. ESDIS develops and operates EOSDIS, a distributed system of discipline-specific DAACs and science investigator processing systems. EOSDIS processes, archives, and distributes data from Earth observing satellites, field campaigns, airborne sensors, and related Earth science programs. These data enable the study of Earth from space to advance scientific understanding.

For more information

"About the NASA Earth Observing System DAACs" (page 56)
NASA Earthdata website
https://earthdata.nasa.gov
NASA Earth Science website
http://science.nasa.gov/earth-science

About Sensing Our Planet

Each year, *Sensing Our Planet* features intriguing research that highlights how scientists are using Earth science data to learn about our planet. These articles are also a resource for learning about science and about the data, for discovering new and interdisciplinary uses of science data sets, and for locating data and education resources.

Articles and images from *Sensing Our Planet: NASA Earth Science Research Features 2017* are available online at the NASA Earthdata website (https://earthdata.nasa.gov/sensing-our-planet). Electronic versions of the full publication are available on the site. *Sensing Our Planet* is also available as an iBook from the Apple iBooks Store.

For additional print copies of this publication, please email nsidc@nsidc.org.

Researchers working with EOSDIS data are invited to email the editors at eosdis.editor@nsidc.org with ideas for future articles.

* * *

Water's presence or absence plays an essential role in Earth's climate and biological processes, influencing everything from weather patterns to cattle grazing. Whether as precipitation or permafrost, circulating in oceans or filling aquifers, water supports life across the globe.

Acknowledgments

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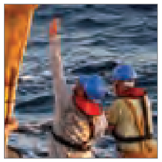
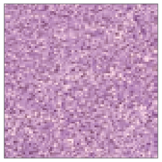
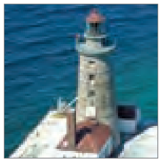






Mountains of precipitation

“But how, physically, does it happen?”

Lynn McMurdie
University of Washington

by Jane Beitler

After the fresh snow, the forest is quiet, save for the soft crunch of snowshoes. High in the rugged terrain of Olympic National Park, two hikers find the long metal snout of a scientific instrument barely poking through five feet of snow from an epic storm. It is no small job to shovel out the instrument, riding on sawhorse legs too short to keep its nose above the surface. Its camera can capture high-resolution video of falling snowflakes and raindrops—but not from beneath a snowdrift.

The instrument and its minders are part of a NASA mission to enable satellites to better

Bill Baccus does a snow survey on the top of Snow Dome, Mount Olympus in early April 2016. (Courtesy B. Baccus) measure precipitation in all types of terrain. When University of Washington professor Lynn McMurdie and colleagues designed the Olympic Mountains Experiment (OLYMPEX), they got what they wanted, and then some. They knew that the park's mountainous landscape and stormy weather would be ideal for studying precipitation in the mountains. They had given slight thought to how they would get equipment into the remote mountain sites, and maintain it all winter. What they had not considered was how wind storms, heavy rains and flooding might nearly drown instruments and make trails to them impassible. Park Service scientist Bill Baccus said, "Nearly the entire area was a designated wilderness, with no roads, no electricity and strict regulations concerning installations and helicopter use. While the area had elements ideal for the study, it was not a very practical place to do the work." The researchers were undeterred. "We need to know how much it rains, where, and when," McMurdie said.

Ready or not, here it comes

The last of many ground instrument sites for OLYMPEX had just been installed in the park when a November 2015 storm dropped up to 10 inches of precipitation, falling mostly as rain at both lower and high elevations. While nearby communities braced for flooding, McMurdie, the OLYMPEX project manager, was excited. After two years of planning, the heavy rains over the mountains were a precipitation scientist's dream.

McMurdie and her colleagues would collect data to evaluate how well the recently launched Global Precipitation Measurement (GPM) mission measures precipitation from space. The GPM Core Observatory and other GPM satellites together provide worldwide observations of rain and snow every three hours. The Core satellite was designed to sense a wide range of precipitation—such as drizzle, rain, snow and sleet—including rain and snow influenced by terrain. The meteorological phenomenon, called orographic precipitation, is McMurdie's bailiwick.


The portable Doppler on Wheels at Lake Quinault is raised in anticipation of flooding rains. Kayaks provided a break when researchers were not operating the equipment, and were eventually used to access the truck, once flood waters raised the lake level. (Courtesy J. Zagrodnik/University of Washington)

Complicated storms coming from the ocean get even more complicated when the storms encounter mountains. When moist air of a storm runs into mountains, it is forced to rise up and over the mountain slopes. As it rises, the air expands and cools, and when it cools enough to reach saturation, rain or snow can form and

National Park scientists make a rare winter trip to the upper reaches of the Wynoochee River to perform maintenance on OLYMPEX equipment. (Courtesy B. Baccus)

fall onto the ground. As the saturated air flows over the top of the mountain crest, it continues to create rain and snowfall, but as it reaches the lee side of the mountains, the air will start to sink and warm on the other side, becoming unsaturated so that rain and snow no longer forms. Because of this rising and sinking of moist air over the slopes, the windward side often gets much more rain and snowfall than the lee side. However, not all storms are the same. Sometimes instead of flowing up and over the mountains, the air can go around the mountains. Or in some storms, the lowest level air goes around the mountains, but the mid level air goes up and over the mountains. These complex air flow patterns make the distribution of rain and snow in mountainous regions quite variable.

"But how, physically, does it happen?" McMurdie said. Forecast models have to make approximations of how precipitation particles form and change. "When it comes to big flooding events, forecast models often under-predict how much rain comes out of the sky and the possibility of flooding," McMurdie said. More details about orographic precipitation would help researchers better interpret the data coming from GPM, and help them dial in the models that consume the data.

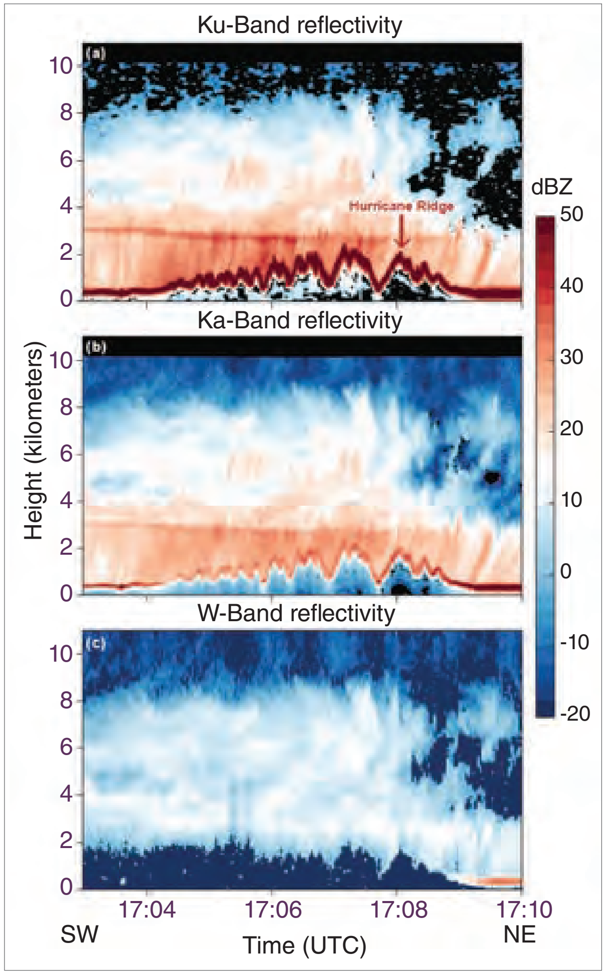
And then there is snow. "It's incredibly hard to figure out how much water is in the snow while it's falling," said OLYMPEX snow scientist and professor Jessica Lundquist. "It's a lot easier to measure when it's on the ground. Then we can measure snow depth. But what hydrologists want is snow water content: if you melt down that snow, how much water do you have?" she said. Snowfall in the Olympic Mountain Range is even harder to measure, because it may be a mix of rain and snow.

Measure, measure, measure

Storms roll in from the Pacific Ocean and abruptly meet the Olympic Mountains, rising to dump heavy precipitation on rainforests in the western valleys and ridges on their way east. A network of instruments would follow their progress. On the coast, a dual polarization S-Band Doppler radar called NPOL and a Ka- Ku-Band radar called the D3R would characterize the storms as they approached the mountains. The team needed to check these radars daily, accessing them over often muddy and rutted roads. Because the coastal Doppler could not see all the way to the valley floor, researchers installed another Doppler radar on a flatbed truck and placed it near Lake Quinault in the Quinault Valley. A fourth radar was placed on Vancouver Island to intercept the storms on the lee side of the Olympic Mountains.

In between the windward and leeward sides, where the mountains would catch the precipitation, the team strung instruments at different elevations to measure the rain and snow and observe the shape, size, and velocity of drops and flakes. As the sites became steeper, higher, and wilder, instrument placement became more challenging. Mule trains carried equipment in pieces over rough trails to higher elevations, while in the highest and remotest locations the team got creative. "Extremely hardy students carried twelve-foot snow measuring poles to eighteen remote sites," Lundquist said. "The Park Service also sent out scientists via helicopter who went

Constant rains from storm after storm breed life in the rainforests of the Pacific Northwest. (Courtesy D. Stolz)



Down-looking APR-3 radar data as the DC-8 flew southwest (left side) to the northeast (right side) over the Olympic Mountains on December 8, 2015. The flight track was from the Pacific Ocean, over the Queets Valley, over the high terrain and the Hurricane ridge area, to the lee side of the mountains. (© American Meteorological Society. Used with permission.)

and probed snow depth and weighed the snow." Sophisticated instruments like the Parsivel Disdrometer and the soon-buried Precipitation Imaging Package were deployed in some areas, and in others lower-tech instruments such as the snow measuring poles. McMurdie admitted it was challenging. "It was hard getting instruments into the wilderness and keeping things working when it's a fifteen-mile hike in," she said.

OLYMPEX found a great partner in Baccus. It was clear to him that they would need logistical help from his team, who knew the terrain and had the backcountry skills, to site dozens of precipitation instruments in the park and across the Olympic Peninsula and its river basins, and to help researchers access the backcountry safely. "The most interesting part of the program were the several trips in mid-winter to the Enchanted Valley and upper Quinault headwaters," Baccus said. "We don't normally go there in the wintertime. It was a unique opportunity to get up into some very remote sites in the winter."

At the same time, aircraft were ready to watch the storms from above. Four NASA research aircraft, including the DC-8 flying laboratory and the ER-2 aircraft, carried precipitation-sensing radars and passive microwave sensors similar to the GPM satellite instruments, so that the team could compare what the satellite would see to actual ground observations and measurements. Another aircraft flew inside the clouds equipped with instruments to measure the sizes and shapes of the snow and rain as they were created in the clouds. The Airborne Snow Observatory aircraft flew two lidar flights to measure the depth of the snowpack over the entire Olympic Mountains late in the winter season.

In early October, the storms began to roll in, over and over, continuing until the next May.

A vertical view

The design of the study, and its many instruments and platforms, began to unveil some of the unknowns in how orographic rain and snow form. Do ice crystals get thrown high aloft, then turn to rain, or does the uplift of warm air create small drops? "We're finding that it's both," McMurdie said, "and small drop production is important."

Since mountains block the radars' view, the DC-8 and ER-2 flew over the tops of the storms, with their radars looking down through the storm. Orographic precipitation had never been sampled in this way. "Along a line, we documented exactly how the rain patterns, the production of rain in the atmosphere, the whole vertical depth change as you go across a mountain barrier. I had never seen that before," McMurdie said. The insights from these data will change assumptions that algorithm developers have been using for their precipitation models. These results are also critical for improving the satellite measurements of rain and snow.

Lundquist said that the data are promising for snow as well. Colleagues ran a weather model and compared its output with OLYMPEX snow observations. She said, "It was able to represent snowfall surprisingly well." The model could also differentiate rain, graupel, and snow. "It's still not perfect, as mixed rain and snow events are difficult to get right. But the data from OLYMPEX are helping us improve snow modeling," she said.

When OLYMPEX ended in 2016, it left mountains of data, which researchers will analyze for years to come. "It's one of the best data sets ever collected of rain and snow in mountainous regions," McMurdie said, "because of the design of the network, the fact that Mother Nature cooperated, and we were ready. The very first day we had the biggest storm in the whole campaign, and we were ready." The NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC) is in the process of archiving the entire OLYMPEX data collected. Published data are available at https://ghrc.nsstc.nasa.gov/hydro/?q=OLYMPEX.

It took the Park Service over a year to clear and repair the trails into the high country and they still need to retrieve some equipment from the wilderness. "I'm glad the project is over and this winter we didn't have to go up there over and over again," Baccus said. As a scientist and park steward, he looks forward to the long-term results. He said, "We are really interested in the science moving forward. We may get better information from satellites about how much rain is falling, or how much water is in our snow-packs. These are the types of tools we'll need in the future."

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/mountains-of-precipitation.

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About the data

Platforms	Global Precipitation Measurement Mission NASA DC-8 aircraft NASA ER-2 aircraft UND Citation II aircraft NASA/JPL Airborne Snow Observatory Ground stations
Sensors	See list at https://ghrc.nsstc.nasa.gov/home/field-campaigns/OLYMPEX/instruments
Data set	Olympic Mountains Ground Validation Experiment (OLYMPEX)
Parameters	Precipitation and other meteorological parameters
DAAC	NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC)

About the scientists

Bill Baccus is a physical scientist at Olympic National Park in Washington state. He works with the National Park Service's long-term monitoring program where he studies key ecosystem elements for the park, including collection of climate data, surveying animal populations, and studying coastal and mountain lake ecosystems. The National Park Service supported his participation in OLYMPEX. (Photograph courtesy J. Baccus)

Jessica Lundquist is a professor of engineering and the lead of the Mountain Hydrology Research Department at the University of Washington. Her research focuses on spatial patterns of snow and weather in the mountains and how those patterns are likely to affect streamflow and water resources in a changing climate. NASA and the National Science Foundation supported her research. Read more at https://goo.gl/Zbmjmy. (Photograph courtesy University of Washington)

Lynn McMurdie is a research associate professor at the University of Washington (UW). Her research focuses on the synoptic and mesoscale structure of midlatitude oceanic storms, orographic precipitation, predictability of west coast cyclones, winter-time lightning in cold air outbreaks over the ocean, and remote sensing of water vapor and precipitation. NASA and the National Science Foundation supported her research. Read more at https://goo.gl/NqzMGB. (Photograph courtesy UW)

For more information

NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC)
https://ghrc.nsstc.nasa.gov
OLYMPEX Data at GHRC DAAC
https://ghrc.nsstc.nasa.gov/home/field-campaigns/olympex
https://ghrc.nsstc.nasa.gov/hydro/?q=OLYMPEX

Zika zone

> “Outside the research community, maps are powerful tools to communicate to the wider public.”
>
> Moritz Kraemer
> Harvard Medical School

By Agnieszka Gautier

João Lucas da Silva Araújo lies on a u-shaped nursing pillow next to his year-old, twin sister Ana Vitória. Though the same size as his sister, João acts like a newborn—suckling and clenching his fists with closed eyes. Green tape, a form of physical therapy treatment to relax muscles, circles his mouth and covers the back of each little finger like a green skeleton. His sister prods his face, alert and smiling.

João was the first baby in Brazil believed to be identified with Zika-related microcephaly, a brain defect associated with a small head and brain that causes cognitive and physical disabilities, even death. Once the medical community recognized that the rapidly spreading Zika virus was linked to microcephaly, a global health crisis emerged.

Zika appears to attack fetal brain cells key for brain development, but why one twin was spared

This close up of the *Aedes aegypti* mosquito shows a distended abdomen after feeding. (Courtesy J. Gathany, Centers for Disease Control) highlights how much is not yet understood about transmission. Undeniable, however, is the culprit in Zika's spread: the mosquito. A group of scientists at the University of Oxford had already followed this villain while pursing dengue fever. Now once more, they gathered in computer labs to offer their support. "When the outbreak was at its peak, we felt it was important to get some maps out," said Janey Messina, a researcher from the university's School of Geography and the Environment. The team wanted health officials to be one step ahead by providing them with maps of potential Zika outbreaks.

The path of least resistance

To map Zika, the researchers first looked at historical accounts, then at its progression. Zika was not new. It surfaced in 1947 from the depths of the Congo, but its mild symptoms—a rash and low fever—meant scientists largely ignored it. Zika infection was also rare. Only 14 cases had been identified until 2007 when it hit Micronesia in the Pacific. "It burned through the population very quickly because island people live so closely together," said Moritz Kraemer, then a postdoctoral researcher at Oxford and now a research associate at the Harvard Medical School. Roughly 75 percent of the population of 5,000 was infected. The world, however, paid no attention to the remote island.

In 2013 and 2014 Zika struck another island nation, French Polynesia, where only 20 percent of Zika infections were symptomatic. The next jump landed in the Americas. "Only after it was introduced into the Americas, people started to worry because of its spread," Kraemer said.

Based on infection rates a viral evolution was suspected. It wasn't until 2014 that researchers confirmed the mutation that allows for easier transmission, identifying the first Zika transmission to the fetus in French Polynesia. In the following years, the brain malformation affected more than 3,500 Brazilian pregnancies—João being one such case. The hardest hit with microcephaly was the northeastern state of Pernambuco, where rates jumped from five cases per 100,000 births to 300.

As fear of microcephaly swept the world, obstetricians advised against travel to tropical climates, but mere distance proved insufficient. Scientists soon found that Zika could be sexually transmitted, even if infected individuals did not show symptoms, and many did not. All of a sudden, clear boundaries faded, and families everywhere worried where the next case of microcephaly could pop up.

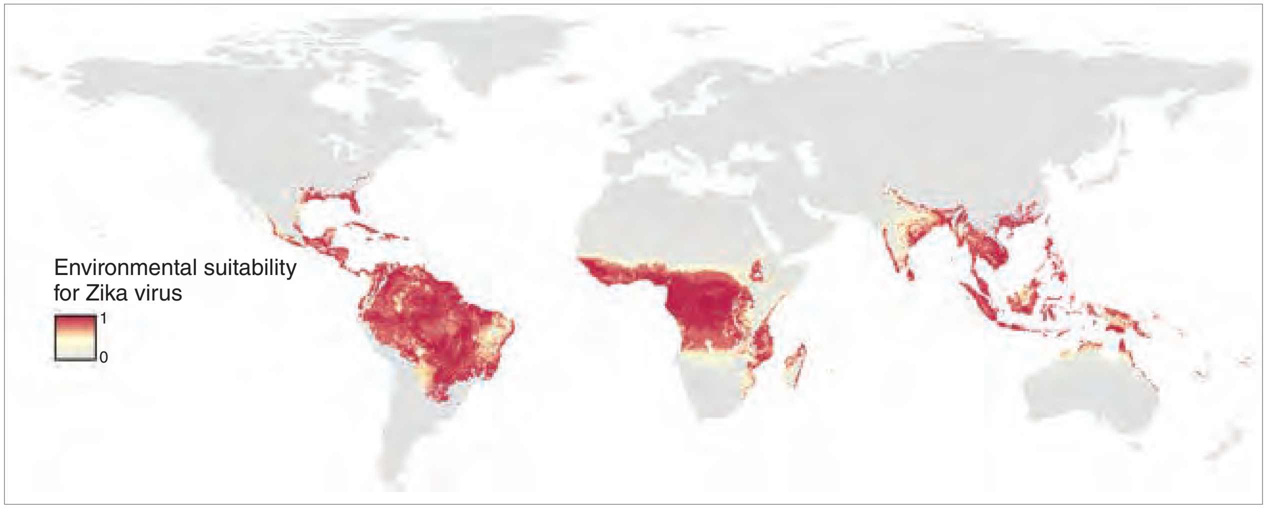
The white stripes

But sexual transmission alone does not sustain an outbreak, because the reproductive number is low, meaning not enough people get infected from one case. The most effective transmitter is the mosquito. Both *Aedes aegypti* and *Aedes albopictus* can spread the virus, but the former has adapted to urban environments better, preferring to feed on people. "What fascinates me about Zika is that we not only deal with the human-to-human interaction but have an intermediary that becomes very important in controlling the disease," Kraemer said.

For an outbreak to occur, the mosquito bites an infected person during the first week of infection when the virus swims in a person's blood. The infected mosquito lives long enough to bite again. This cycle continues multiple times to start an outbreak. Typically, *A. aegypti* live two to four weeks, but their eggs are viable for more than a year in dry state. Moisture and warmth are needed for the mosquito to re-emerge.

In Guatemala, a governmental relief worker checks this family's living quarters for potential mosquito breeding. (Courtesy ConredGautemala/flickr)

The female *A. aegypti*, with its white-striped legs and abdomen, bites during the day, digesting blood proteins to lay eggs. It lives in tropical and subtropical regions; it needs high temperatures, ample rainfall, stagnant water for laying eggs, and heavily populated urban environments. "This is what we know from other viruses like dengue," Kraemer said. Now those factors could be applied to map the potential for Zika. And because there were no Zika data, the researchers really had no other alternative. But Zika and dengue are both flaviviruses, whose genomes share quite a lot of information. "So it's likely the temperature constraints we used from dengue are quite accurate for Zika as well," Messina said.



This map shows global environmental suitability for the Zika virus, ranging from 0 (grey) to 1 (red) with dark red being the optimum environment, white as minimal, and grey as not at all. (Courtesy J. Messina)

Mapping Zika

Once the researchers knew where Zika had been, they could figure out what the environment had in common—urban versus non-urban and temperature, precipitation, and humidity levels—to find similar environments. Moisture is key in egg and larvae development, so the researchers also considered vegetation canopy cover, which reduces evaporation and is associated with higher *A. aegypti* larvae density. The researchers used an Enhanced Vegetation Index (EVI) calculated from data from the NASA Moderate Resolution Imaging Spectrometer (MODIS) to provide a proxy for the level of moisture available given the relationship between precipitation and vegetation growth.

"The main idea is pretty straightforward," Messina said. "Obviously, the models we run are complex and it's a lot of data, but at the end we are just trying to understand where this disease might spread to or where it might already be and where we should be on the lookout for a potential outbreak."

Not surprisingly, in Brazil's ongoing epidemic, the maps show that the high population areas of northern and southern coastal cities show the highest environmental suitability for Zika. Potential outbreaks stretch into the United States from Texas to Florida. "In addition, there are areas in Asia and central Africa with high suitability but only a few locations reported Zika virus," Kraemer said. "We would expect given certain travel patterns of people that the disease would arrive there in the future."

The last step was to identify the populations living in those areas. The researchers essentially built a global map of appropriate environments, and then overlaid each 5-kilometer-square pixel with gridded population data from the NASA Socioeconomic Data and Applications Center (SEDAC), allowing them to line up the environmental data with population.

They then identified certain thresholds with high transmission potential, leading to an estimate that more than two billion people are globally at risk for Zika virus transmission. "It doesn't mean that all those people will contract Zika," Messina said. It means that Zika could, however, emerge in these areas. "Outside the research community, maps are powerful tools to communicate to the wider public," Kraemer said. "Through Google Maps and other mapping products we are now more than ever before exposed to maps in our everyday life."

Fugitive pieces

The researchers hope these maps will help inform pregnant women and other travelers about possible Zika exposure and let public health officials better target higher-risk communities with an integrated control program, which may include aerial spraying, eliminating mosquito habitats, putting up structural barriers like screens and nets, and educating people about protective clothing and topical repellents like DEET.

Currently, mosquito control is the best method for disease prevention. Vaccines are in the works, with some already through human trials, but it may still take years for them to reach the general public. Efforts are also under way to suppress reproduction by releasing genetically modified male mosquitos to mate with the pest females.

And research continues into microcephaly. Twins may still be the best bet for understanding how Zika attacks the fetus and why some babies escape the disease. Their biological similarities—genetic makeup and fetal environment—allow scientists to identify relevant differences. Identical twins often share the same fate, but fraternal twins in their separate placentas can be quite different, sparing one from Zika—as in the case of João's sister.

Poverty can also exacerbate Zika. In the *favelas*, or slums, of Northeast Brazil, Zika found its paradise. Poor sanitary conditions and poor nutrition, leading to weaker immune systems, may explain why these areas were hardest hit with microcephaly.

For now, physical therapy and sensory stimulation may give these babies a fighting chance, sometimes defying developmental barriers detected in their black and white brain scans.

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/zika-zone.

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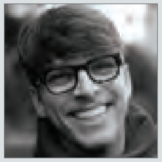
About the data

Satellites		Terra and Aqua
Sensor		Moderate Resolution Imaging Spectroradiometer (MODIS)
Data sets	Gridded Population of the World (GPW), v4	Nadir BRDF-Adjusted Reflectance 16-Day L3 Global 1km V005 (MCD43B4)
Resolution	30 arc-second (~1 kilometer grid)	1 kilometer
Temporal resolution	5-year intervals between 2000 and 2020	16-day
Parameters	Population density	Nadir reflectance
DAACs	NASA Socioeconomic Data and Applications Center (SEDAC)	NASA Land Processes Distributed Active Archive Center (LP DAAC)

About the scientists



Moritz Kraemer is a research associate at Harvard Medical School and was a postdoctoral researcher at the University of Oxford. He is interested in the global patterns of emerging infectious disease risk and the determinants of their expansion. The International Research Consortium on Dengue Risk Assessment, Management, and Surveillance (European Union) supported his research. Read more at https://goo.gl/H2Vb4N. (Photograph courtesy M. Kraemer)

Janey Messina is an associate professor at the University of Oxford, holding a joint appointment in the School of Geography and the Environment and the School of Interdisciplinary Area Studies. Her research focuses on the geography of human health. The International Research Consortium on Dengue Risk Assessment, Management, and Surveillance (European Union) supported her research. Read more at https://goo.gl/2tGcm8. (Photograph courtesy J. Palmer)

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A rising problem

"It turns out that pollutants originating near Denver do not always stay in Denver."

John T. Sullivan
NASA Goddard Space Flight Center

By Laura Naranjo

Pollution has clogged Denver's air since the 1960s. As the city's population grew, so did a hazy layer, nicknamed the brown cloud. During the 1970s and early 1980s, Denver violated air quality standards up to 200 days a year. Since then, successful environmental campaigns and improvements in engine design have brought Denver air quality within standards, except for one pollutant: ozone. Why does ozone remain so persistent?

Denver is part of Colorado's Front Range—a north-to-south string of cities nestled against the Rocky Mountains. Unique airflow patterns frequently trap air pollution, curdling it into a dense, visible layer. In addition, researchers have long known that Denver's air quality problems were traveling into the mountains and

Vehicles emit many of the chemicals that cause Denver's brown cloud of air pollution. (Courtesy J. Tarbell) nearby communities. John T. Sullivan, a NASA atmospheric physicist and postdoctoral fellow, participated in a recent campaign to better sample how air in the region circulates and how it transports pollutants. “We found evidence of a recirculating polluted air mass,” he said. “It turns out that pollutants originating near Denver do not always stay in Denver.”

Honing in on ozone

The brown cloud over Denver comes mostly from vehicles, which emit nitrogen dioxide, formaldehyde, and benzene. Some days, these noxious chemicals dissipate, whisked away by prevailing westerly winds. Other days, pollution hangs in the air. Ozone itself is not one of these emitted chemicals: it forms when emitted pollutants interact with sunlight and heat in a photochemical process that converts them into ozone.

Likewise, ozone is not what people see in the brown cloud. “A lot of the brown comes from nitrogen dioxide, and from particles created when ammonia emitted from agricultural sources to the east combines with nitric acid from the nitrogen dioxide,” said Andrew Langford, a researcher with the National Oceanic and Atmospheric Administration (NOAA). “Nitrogen dioxide is also one of the main precursors for forming ozone.” Ozone is a colorless gas, but visible haze often indicates the ingredients necessary to bake pollutants into ozone. Consequently, high ozone levels often coincide with smoggy days.

Ozone can aggravate lung conditions such as asthma and emphysema. It damages healthy lungs, can cause chronic obstructive pulmonary disease, and may be behind the increasing prevalence of asthma. The Environmental Protection Agency (EPA) began regulating ozone in 1971. By 2008, air containing more than 75 parts per billion by volume (ppbv) would exceed EPA air quality standards. In 2015, the EPA tightened the ozone standard to 70 ppbv.

Mapping the solenoid

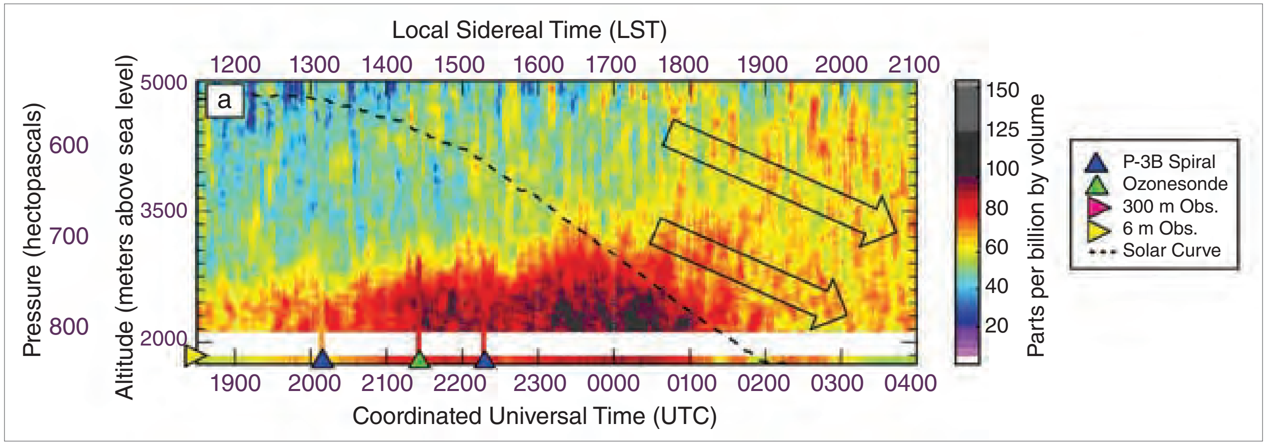
Most cities use ground stations to monitor ozone. Single-location measurements, however, cannot capture the three-dimensional air flow that is important for understanding air quality. In Denver, for instance, prevailing winds usually breeze down the mountains and across the city toward the open plains, clearing the city’s air. But on hot summer days, heat generated by buildings and roadways combines with soaring temperatures, producing a mass of air that is warmer than surrounding areas. This warm mass forms a column of rising air, or a thermal. Along the Front Range, thermals can temporarily shift prevailing winds, sweeping air and pollution westward. “Air flow actually goes reverse of what you would normally expect, and blows back up the mountains,” Sullivan said.

In the evening, if the reverse flow is strong enough, the air often recirculates back down to Denver and other cities. Sullivan compared this flow to a solenoid, a cylindrical coil, stretching along the Front Range. Air flows clockwise, funneled high up the mountains west of Denver and spiraling northeast before circling back down over cities like Fort Collins in northern Colorado. Researchers knew that air pollution was included in this solenoid circulation. For direct evidence, they needed continuous profiles of chemical pollutants and winds during the entire recirculation event.

Sullivan and Langford participated in just such a study. For 31 days, from July 16 to August 16, 2014, a NASA P-3B aircraft flew ozone sensors over ground stations dotting the Front Range from Denver to Fort Collins. At three ground stations, researchers operated lidar instruments that were part of the Tropospheric Ozone Lidar Network (TOLNet), sending pulses of light up into the air column to measure ozone concentrations. The aircraft would ascend or descend in a tight spiral over each station, gathering data vertically along the entire air column as the station instruments recorded. Ozonesondes, or balloon-borne instruments, were launched to help with lidar validation and analysis.


At 3:00 in the afternoon on July 22, 2014, Denver’s air pollution is so thick it obscures the Rocky Mountains. (Courtesy Colorado Department of Public Health and Environment)

Sullivan and his team operated the lidar instrument at the Fort Collins site as part of the NASA Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) campaign, which was conducted in conjunction with the National Science Foundation Front Range Air Pollution and Photochemistry Experiment (FRAPPÉ).



Between noon and 9:00 p.m. on July 22, 2014, ozone concentrations increased over the Fort Collins study site. Concentrations peaked late in the evening, after daytime pollution from the Denver area recirculated into the Fort Collins region. Red, orange, and black indicate concentrations that violate ozone level standards set by the Environmental Protection Agency. (Courtesy J. T. Sullivan, et al., 2016, *Journal of Geophysical Research: Atmospheres*)

Langford and his team from NOAA operated a lidar station at the Boulder Atmospheric Observatory, located between Denver and Fort Collins. A third NASA lidar operated in Golden, west of Denver. These stations required round-the-clock diligence. Langford said, "Our laser system is finicky enough that while a lot of the activities are automated, the whole system is not autonomous, and people have to be there with it all the time." This nonstop effort was critical for gaining uninterrupted data mapping flow along the entire air column. Sullivan said, "That's why ozone lidar is really valuable, because we were able to, throughout the entire day, see the time record of ozone at the surface as well as aloft."

A week into the study, the morning of July 22 started out clear and cool, with winds out of the west. Temperatures soon sizzled at 96 degrees Fahrenheit, and by early afternoon, a thermal began rising up the foothills. From afternoon into evening, the researchers caught the solenoid in action, swooping Denver's air—and its pollution—up the mountains, high into the atmosphere, and swirling back down over Fort Collins. That day, out of the 17 Front Range sites the campaign monitored, three exceeded EPA 2008 ozone standards, including Fort Collins. Six sites would have violated the stricter 2015 standards. "The ozone lidar verified a return flow much later in the day, which corresponded to increases at many of these sites," Sullivan said. "It's very obvious evidence that we're getting a return flow of this polluted air mass that impacts surface conditions."

Factoring in the fold

Denver's ozone problem also has more distant sources. A thin ozone layer sits high in Earth's atmosphere, at least 10 kilometers (6 miles) in altitude. This far from the surface, ozone forms a protective layer, shielding the planet from ultraviolet sunlight. Certain atmospheric conditions can force tongues of this naturally-occurring ozone to fold down, intruding into the atmospheric layer near Earth's surface, and depositing yet more ozone at the ground level. These descending tongues are more likely to reach high altitude regions, making the high deserts of southwestern United States and mountains of Colorado a hot spot for intrusions. Langford said, "These are regions have more frequent deep intrusions there than any other place in the world except the Tibetan Plateau."

Making matters worse, folds of intruding ozone can recirculate pollution from elsewhere. "It can bring down with it transported pollution from Asia, either from industrial sources or from wildfires in Siberia, for example," Langford said. Pollution included in these folds contributes to background ozone, levels that would exist regardless of local sources. These higher background levels affect air quality in cities like Los Angeles, Las Vegas, and Denver. "If you've got background levels of 50 to 60 ppbv, and the standard is at 70, that's not a lot of room for additional production," Langford said. "That's the challenge much of the West is facing."

Sullivan, Langford, and their colleagues continue to operate lidar instruments at campaigns across the United States and around the world to help researchers understand why some areas still struggle with air pollution. Multiple agencies coordinate the labor-intensive campaigns between flight teams and ground crews. Langford said, "We really tie together interactions between NOAA, NASA, and the EPA on this problem. The synthesis of using information from a lot of different sources, and getting the agencies working together is very powerful."

Although city officials continue to rely on surface monitoring, campaigns like this help them account for regional circulation patterns. Air quality managers can incorporate this three-dimensional airflow into models normally based on ground measurements, refining their ability to understand and predict poor air quality. This is especially true for a city like Denver that has high background levels of ozone coupled with airflow patterns that recirculate pollution. Sullivan said, “The vertical profile is really one of the key measurements needed in understanding the complexities of pollution formation and transport.”

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/a-rising-problem.

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Tropospheric Ozone Lidar Network (TOLNet) Data and Information
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About the data

Platforms	NASA P-3B	Tropospheric Ozone Lidar Network (TOLNet)
Sensors	Various	Ozone lidars
Data sets	Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ)	TOLNet O3 Surface Photometer data
Parameters	Aerosols, aerosol backscatter, trace gases/trace species, air quality	Aerosols, aerosol backscatter, trace gases/trace species, air quality
DAAC	NASA Atmospheric Science Data Center Distributed Active Archive Center (ASDC DAAC)	NASA ASDC DAAC

About the scientists

Andrew Langford is a research chemist at the National Oceanic and Atmospheric Administration (NOAA). He studies background ozone and air quality, as well as stratospheric contributions to tropospheric ozone. NOAA supported his research. Read more at https://goo.gl/3S6Du7. (Photograph courtesy W. von Dauster)

John T. Sullivan is a postdoctoral fellow at the NASA Goddard Space Flight Center (GSFC). He studies atmospheric constituents relating to air quality and human health. NASA, University of Maryland, Baltimore County, the Maryland Department of the Environment, and NOAA Cooperative Center for Earth System Sciences & Remote Sensing Technologies Foundation supported his research. Read more at https://goo.gl/zwXZ6c. (Photograph courtesy NASA GSFC)

Spin cycle

> “Understanding the sea couldn’t be more fascinating to me. It’s life.”
>
> Pierre-Amaël Auger
> Instituto Milenio de Oceanografía

By Karla LeFevre

From space, a kaleidoscope of aquamarine and green can be seen swirling around Earth’s oceans each spring. Algae glide near the water’s surface, soaking up sunlight and reflecting green-blue hues back to satellites. Their color reveals patterns of ocean currents and marks the abundant sea life that feed on them, from toothpick-size krill to whales weighing many tons.

Scientists are anticipating changes, though. Algae rely on phenomena called deep water masses to mix the ocean and dredge up nutrients from the seafloor, in effect seeding the water so they can bloom in spring. Yet warmer wind and ocean temperatures could weaken these currents. Pierre-Amaël Auger, a researcher at the Instituto Milenio de Oceanografía, said, “If there’s no wind and no mixing to bring nutrients to the top, there’s no fish.”

This image of Turkey offers a comparison of the color of the Black Sea (top of the image), which shows a phytoplankton bloom, and the Mediterranean Sea (bottom of the image). Data are from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS). (Courtesy SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE)

Researchers like Auger have eyed chlorophyll, the bright green pigment that gives algae their color, in satellite images since the late 1970s as a way to study ocean mixing. What has been missing was a longer case study on deep water masses. How they form is not completely understood. Marine Herrmann, Auger's colleague and a researcher at Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, said, "If you want to understand how they work, you need to understand how they vary." So they took a closer look at the Mediterranean Sea, an area where deep water masses regularly form and feed algae.

Circulation and phytoplankton

To study deep water masses, Herrmann and Auger have long kept tabs on algae, or phytoplankton, by monitoring chlorophyll. More green chlorophyll is a giveaway for phytoplankton blooms. No green is a sign that deep mixing has diluted chlorophyll in an area. When deep waters circulate, Herrmann said, "It's very blue, there's nothing to see in the images, no green at all."

Year after year, they have observed the same seasonal cycle: deep mixing in winter followed by spring blooms. To bloom each spring, phytoplankton need the water's surface to be well stocked with minerals and nutrients, and deep mixing in winter delivers them. When spring sunlight warms the water, places like the Mediterranean Sea and temperate North Atlantic explode with emerald color. Mixing wanes with spring warm up, allowing phytoplankton to float near the surface. The calm seas leave them to the task of turning sunlight into energy, of photosynthesis. And less wind and wave turbulence allows the water to settle until winter kicks off another season of deep mixing.

The best way to observe this happening in the Mediterranean, Herrmann reasoned, was to contact Auger in Chile. Auger specializes in ocean models and could recreate the conditions that exist when a deep water mass forms. By stitching together chlorophyll and other ocean measurements from three different models, he created a new model that spanned 38 years. That made Auger's model four times longer and twice the resolution than had been seen before.

After poring over the model results, Herrmann noticed something odd. She had been tracking a deep water mass in the Mediterranean when she spotted green appearing in winter. It appeared during unseasonably warm winters, which suggested deep mixing had stalled with added heat. She needed to dig deeper to be sure.

Deep sea diving

In the Mediterranean Sea, deep mixing is triggered each winter by frigid winds from the Alps, the Massif Central, and the Pyrenees that blow across the southern lip of France and whip up water in the Gulf of Lions. In the center of the gulf, where these winds buffet the surface, the water cools and becomes heavier than the surrounding water. As a result, a mass of dense, salty water sinks. Lighter water rises in its place, creating convection that surfaces nutrients.

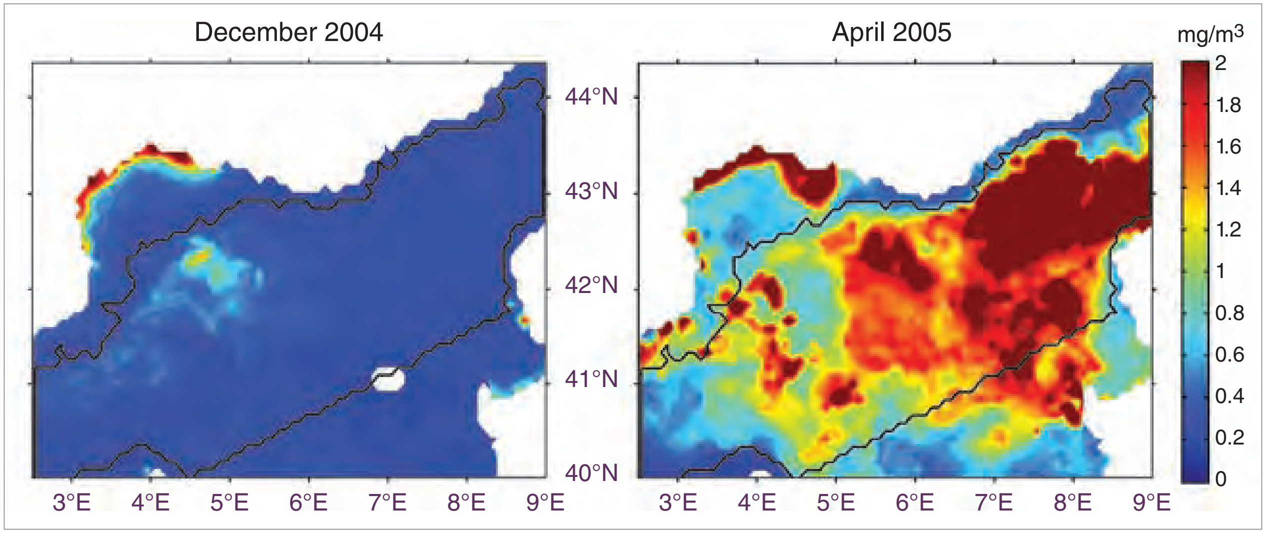
From the beginning, Herrmann and Auger knew they could compare chlorophyll, or lack thereof, with sea level to learn more about this deep water mass. "When water is more dense and sinking, it causes an overall depression in sea level," Herrmann said. Lower sea levels could help show the mass as it formed, and reveal its size. "If I know the size of the blue area and the size of the dropped sea level area," she said, "I can give you the volume of the deep convection area."

Crew onboard the *Thetys* research vessel recover Marisonde drifting buoys from the northwestern Mediterranean Sea. The buoys collected sea surface and air measurements for an oceanographic campaign in May 2013. (Courtesy M. Herrmann)

In her balmy office in Vietnam, Herrmann crunched the numbers between chlorophyll and sea level readouts from Auger's model. In a previous study, she had linked sea level and deep water circulation in the Mediterranean Sea using this formula, but sea level data available at the time spanned nine years. With the new model, her calculations again showed a clear link between the blue area and dropped sea level. She now had a good idea how big the deep water mass was over the 38-year period.

Intense in situ

The mass in the Gulf of Lions, called Western Mediterranean Deep Water, regularly plunges 2,400 meters (7,874 feet) to the seafloor and keeps the Mediterranean circulated and healthy. "It acts like a washing machine where everything gets mixed from top to bottom, bottom to top," Herrmann said.



These images show changes in chlorophyll between winter (December 2004) and early spring (April 2005) in the Mediterranean Sea in milligrams per cubic meter. The images were generated by combining observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) with those from the NASA Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), and data from other NASA and Centre National D'Etudes Spatiales (CNES) satellites. (Courtesy M. Herrmann, et al., 2017, *Journal of Geophysical Research: Oceans*)

Was this deep water mass weakening over time? The answer lay in calculating its intensity—how quickly it had been forming and sinking each year. How much water had it been mixing from year to year? Was it sluggish in some years or declining overall?

Readings from oceanographic ships and drifting sensors helped her test the accuracy of their model with those questions in mind. While the ship data covered only one year and data from drifting sensors just a smattering of years, they were indispensable. Judging by temperature and salinity measurements of the upper 2,000 meters (6,562 feet) of the ocean, and how quickly they changed, Herrmann was able to estimate both the size and intensity of the Western Mediterranean Deep Water mass. Most importantly, the in situ data helped them fine-tune the model.

Like Herrmann's earlier findings, their improved model showed a direct connection between chlorophyll and sea surface height, along with atmospheric changes, salinity, and how quickly dense water formed. It also showed how deep water masses vary from year to year, making it a more realistic case study.

Layering effect

Other modeling studies have suggested that higher temperatures may lead to significantly less frequent, less intense circulation by the end of the 21st century. Those studies make it all the more pressing to monitor deep water masses over the long term. But data have limits.

"We usually have a lot of in situ observations for just one area," Herrmann said. One buoy in the middle of the Gulf of Lions, for instance, is loaded with sensors that log conditions from the surface to the seafloor. "This buoy is precious because it provides continuous monitoring, but it only covers one point," she said.

Satellites have better coverage, although they too present challenges. "Satellites for these measurements don't measure through clouds," Auger said, "so a model can be used to fill gaps in the data."

To get around this limitation, Herrmann created a multilayered satellite data set. With chlorophyll measurements from the NASA Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS), she merged sea level data from nearly a dozen satellites, the result of a NASA and Centre National D'Etudes Spatiales (CNES) collaboration. She then applied the same formula for calculating the volume of the deep water mass. The data set confirmed her findings and covered 19 years, making it the first long time series of deep water convection in the northwestern Mediterranean Sea. Until now, there had only been short time series or evaluations for individual years, either from in situ or satellite data, Herrmann said.

As with the in situ data, the new satellite time series can be used to evaluate and correct models, benefitting all researchers who study deep convection. "We are helping to complement all the measurements," Auger said. "And thanks to the models, we know more about these processes."

Fruits de mer

Herrmann added, "Reality is much more complicated of course, so we will keep adding new elements, like information on tides." Eventually, they plan to build long case studies for more regions where deep water masses form, such as the Greenland and Labrador Seas.

Other developments are in the works, too. A joint NASA-CNES altimetry satellite called Surface Water and Ocean Topography (SWOT) will be launched in 2020. SWOT's sharper resolution and better spatial coverage could improve the accuracy of future studies.

"It is very difficult to monitor long-term deep convection, but it is very important," Herrmann said. "It affects the whole ocean ecosystem. It also redistributes heat. Without deep convection, you would have a very different climate." Teasing out the details of how these global processes work is its own process, and is ongoing. And surfacing answers inspire them to ask new questions. Auger said, "Understanding the sea couldn't be more fascinating to me. It's life."

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/spin-cycle.

About the remote sensing data

Satellites	Terra and Aqua	GeoEye SeaStar
Sensors	Moderate Resolution Imaging Spectroradiometer (MODIS)	Sea-Viewing Wide Field-of-View Sensor (SeaWiFS)
Data sets	Level 3 Mapped Chlorophyll (MODISA_L3m_CHL)	SeaWiFS Global Daily Mapped 9km Chlorophyll a
Resolution	9 kilometer	9 kilometer
Parameter	Near-surface chlorophyll-a concentrations	
DAAC	NASA Ocean Biology Distributed Active Archive Center (OB.DAAC)	NASA OB.DAAC

About the scientists

Pierre-Amaël Auger is a postdoctoral fellow at the Instituto Milenio de Oceanografía. His research interests include conducting model simulations to study the marine food web and the processes that influence how carbon is exported to the deep ocean. The Iniciativa Cientifica Milenio supported his research. Read more at https://goo.gl/ihgMkA. (Photograph courtesy P.-A. Auger)

Marine Herrmann is a researcher at the Laboratoire d'Etudes en Géophysique et Océanographie Spatiales. Her research interests include deep water masses and regional ocean circulation, and how they affect nutrients and plankton in the open ocean. The Institut de Recherche pour le Developpement supported her research. Read more at https://goo.gl/n5SzRe. (Photograph courtesy M. Herrmann)

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https://modis.gsfc.nasa.gov
Sea-Viewing Wide Field-of-View Sensor (SeaWiFS)
https://oceancolor.gsfc.nasa.gov/SeaWiFS

Carbon control

> “The uncertainty reduction tells you it works.”
>
> Nick Parazoo
> NASA Jet Propulsion Laboratory

By Agnieszka Gautier

On a hilly peninsula overlooking the Pacific Ocean and San Francisco Bay, 5,000 miles of pipeline zigzag over Richmond, California. The Chevron Richmond Refinery, established in 1902, is one of five refineries in the East Bay region, coined “refinery corridor,” where industrial grids dominate and stacks disrupt the horizon. Air quality has been an issue here for over a century, but recently the invisible ingredients—the health-damaging pollutants and warming greenhouse gases—are of major concern in the backdrop of climate change.

California’s 2016 bill is intended to give lawmakers more oversight of the state’s Air Resources Board with a goal of reducing 40 percent of greenhouse gas emissions by 2030 and 80 percent by 2050. As Nick Parazoo, a researcher at the NASA Jet Propulsion Laboratory put it, “There is no easy way of verifying whether that

A full moon illuminates this power plant near Seal Beach in Rossmoor, California, not far from Los Angeles. (Courtesy alkhodarev/flickr) is going to happen or not." To help lawmakers know if targets have been met, a group of scientists led by Heather Graven at Imperial College in London created a simulation, or a theoretical case study, to see how best to increase confidence in greenhouse gas emission measurements.

The measure of life and death

Typical measurements of fossil fuel emissions look at fuel consumption, and the potential carbon dioxide (CO_2) within that fuel. On a global scale, accuracy can be within 5 percent, but testing fossil fuel emission on a regional scale requires isolating factors that easily cross arbitrary borders, such as wind blowing across California state lines.

By modeling the motion of air over California in fine detail, the researchers could observe where air came from, how it moved, and how it interacted with the environment. "We're basically looking at the difference between what's in California and what's flowing into California as a way of judging what California must have added or subtracted," said Marc Fischer, an atmospheric scientist at Lawrence Berkeley National Laboratory.

Only four hundredths of a percent of air is composed of CO_2, a heat-trapping greenhouse gas. Methane (CH_4) warrants equal attention as an emission source from cows, landfills, and gas leaks, but limitations in satellite instrumentation, which have yet to detect methane, led the researchers to focus solely on CO_2 emissions.

All life respires, releasing CO_2 into the atmosphere, but plants do more. "Plants are supremely beautiful living organisms because they are both breathing in CO_2 during the day and breathing it out at night," Fischer said. During photosynthesis, plants absorb CO_2 and sunlight to create fuel—glucose and other sugars—to build plant structures. This accumulation of CO_2 as biomass in plants removes CO_2 from the atmosphere.

Measuring CO_2 in the biosphere, where exchanges occur between living organisms, gets complicated because life is dynamic. Seasons shift, droughts happen, and plant metabolism decreases. To differentiate between fossil fuel emissions, which also spew CO_2 into the atmosphere, the team traced the origins of the carbon molecules. All life, living and long dead as with fossil fuels, is composed of carbon. Carbon holds six protons, but can have a different number of neutrons in its nuclei, thus changing its mass to become an isotope. Carbon has two stable isotopes, ^{12}C and ^{13}C, and the unstable, radioactive ^{14}C, also called radiocarbon, with a half-life of 5,700 years.

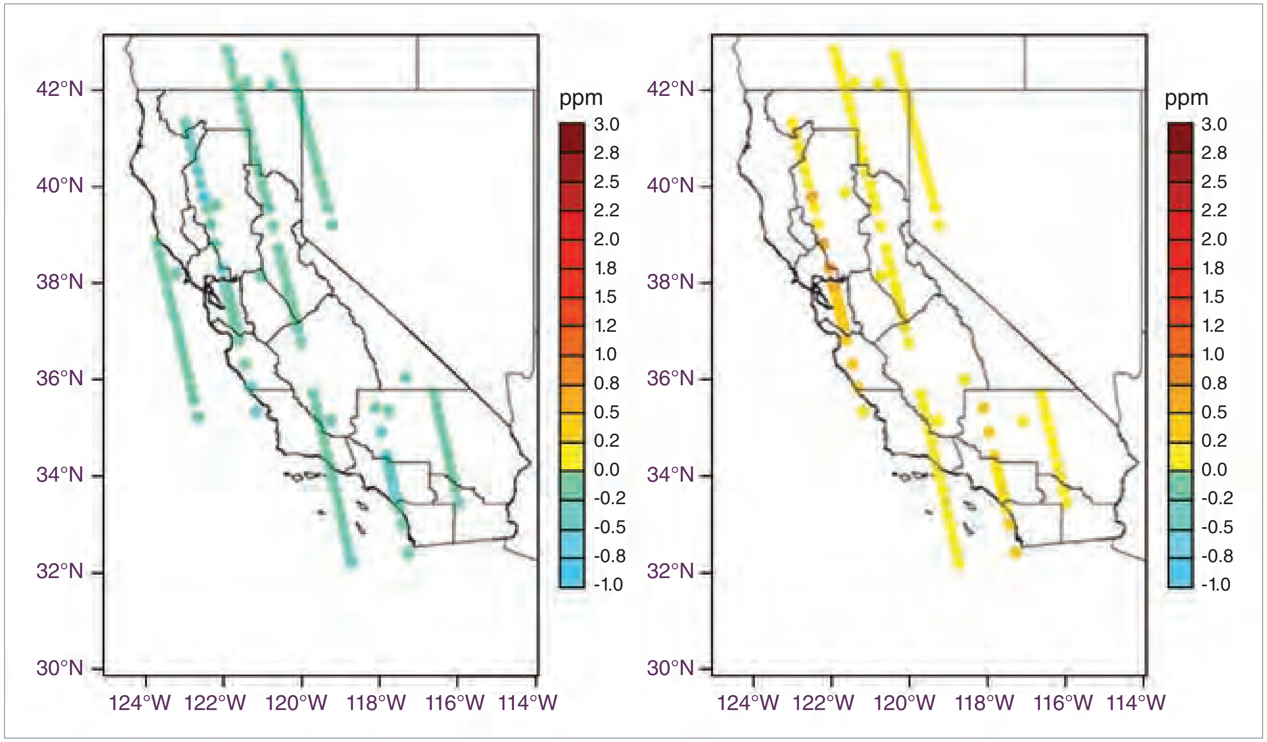
When solar particles smack into the upper atmosphere, they form a tiny, continuous amount of ^{14}C, which plants incorporate through photosynthesis and animals by eating plants. When an animal dies, carbon is no longer exchanged with its environment, and radiocarbon begins to decay. The older a sample, the less radiocarbon it carries. Fossil fuels, or decayed organic matter that has been underground for millions of years, contain no radiocarbon. So a big drop of radiocarbon in the atmosphere indicates a rise in fossil fuel emissions.

A tower for all seasons

Oil tanks dot the hilly peninsula next to residents of Richmond and Albany, California. (Courtesy Decaseconds/flickr)

Measuring radiocarbon accurately can be tricky because the atmosphere contains little radiocarbon. For every ^{14}C atom there are a trillion ^{12}C atoms. Faint CO_2 clouds swirl in the atmosphere, and the most accurate method to measure them requires capturing air in a flask, and then taking it to a lab. "It's the most precise measurement you can get, but it's also expensive," Parazoo said. Hence, the study also considered data from a tower network and data that simulates the NASA Orbiting Carbon Observatory-2 (OCO-2) satellite. Since OCO-2 launched in July 2014 and the first observations were under scientific analysis, no actual data were used for this simulation. Instead, synthetic results were generated using the OCO simulator at Colorado State University.

In addition to being the sites of flask sampling, the 10 towers could continuously measure the carbon exchange, providing total CO_2 calculations, which offered an in-depth look at the biosphere exchange through the seasons. "What we're doing is not completely new," Fischer said, "but it will be the first time researchers have used OCO-2 data in combination with radiocarbon data to tell the bigger story of fossil fuels and the biosphere." For this study, however, only the flask samples were used, though the researchers note that the addition of continuous CO_2 data



This pair of images shows carbon dioxide levels from the biosphere column, in parts per million, from simulated Orbiting Carbon Observatory-2 (OCO-2) satellite overpasses for May 2011 (left) and November 2010 (right). (Courtesy M. Fischer, et al., 2017, *Journal of Geophysical Research: Atmospheres*)

could improve estimates of CO_2 exchange in future studies.

The towers measured close to the surface, about two meters high. Ninety-five percent of air particles hover at that level, but gases in the atmosphere mix at different heights depending on the weather. Things shift up on hot, dry days and down on cooler days. “The thing about OCO-2 is it looks through the entire column, from space to surface, and estimates the average concentration for the entire column,” Fischer said. That has an advantage over the tower measurement.

Large-scale patterns of CO_2 on a global scale are expected: Earth’s Northern Hemisphere greens in the summer, breathing in CO_2, and browns in winter while breathing out CO_2. OCO-2 detects those oscillations, but Parazoo was skeptical the satellite would detect useful information from thousands of miles away. The challenge is that a CO_2 particle is hard to track because OCO-2 has a long observation cycle. Once emitted, CO_2 moves through life close to the surface, but once it gets carried away from the surfaces and mixes with the background atmosphere, it gets smoothed out. By the time OCO-2 returns 16 days later, the CO_2 particle is long gone.

In addition, a column can have a value of 400 parts per million (ppm), but to understand something about climate change the precision must be crazy sensitive to detect changes, which occur at about 2 ppm.

The biosphere element is key to determine yearly emission levels because years of drought remove less CO_2 than non-stressed years. “With climate change, and warming and drying, you are affecting the ability of plants to grow in response to increasing carbon,” Parazoo said. To isolate fossil fuel combustion, the team had to estimate the total carbon exchange, a mixture of biosphere and fossil fuel emission. Then, the fossil fuel portion could be subtracted, leaving only the biosphere contribution on a daily, seasonal, inter-seasonal, and year-to-year scale.

Simulation sandwich

The results are part of a hypothetical scenario, using CO_2 exchange data for May 2011 and November 2010, dates that were simply a matter of convenience. In May, the biosphere is wide awake, increasing the sink of CO_2. In November, the biosphere sleeps and the dominating carbon signal comes from fossil fuel emissions.

The simulation creates an alternate reality where researchers can predict CO_2 concentrations based on a fossil fuel emission scenario. Then they become architects, designing a system that reflects a given quantity. “The simulation is more of a thought experiment to see if it’s possible to get the desired result of an emission measurement,” Parazoo said. Specifically, this simulated world took different estimates of fossil fuel emissions, averaged them, and then created synthetic observations to detect simulated changes in the fossil fuel emissions. “What you want is to verify that your experimental setup works so you can apply it to real observations, and understand the results,” Parazoo said. “The uncertainty reduction tells you it works.”

The simulation is a competition between initial emission sources and the addition of observed sources. More observation can identify flaws in prior knowledge and reduce uncertainty. “In a perfect world, you would have an unlimited amount of observations over California. Then your uncertainty theoretically would go down to zero,” Parazoo said.

The combination of flask measurements and satellite observation dropped uncertainty to 5 to 10 percent over California. “I am surprised about how much work it is to get this problem of emissions,” Fisher said. “It is not easy.” Right now, California is on track to meet its 2020 deadline: cutting greenhouse gas emission by 15 percent. The next step is to run the model with actual, instead of simulated satellite measurements to help officials target California’s biggest polluters and to help communities breathe easier.

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/carbon-control.

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Satellite	Orbiting Carbon Observatory (OCO-2)	
Project		Carbon Monitoring System (CMS)
Data sets	OCO-2 Level 2 Geolocated XCO2 Retrieval Results and Algorithm Diagnostic Information V7	CMS: CO2 Signals Estimated for Fossil Fuel Emissions and Biosphere Flux, California
Temporal resolution	16 days	November 1, 2010 to May 31, 2011
Resolution	2.25 x 1.29 kilometer	
Parameter	Carbon dioxide	
DAACs	NASA Goddard Space Flight Center Earth Sciences Data and Information Services Center (GES DISC)	NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC)

This study used simulated data generated with the OCO simulator at Colorado State University.

About the scientists

Marc Fischer is a scientist at the Lawrence Berkeley National Laboratory, and an associate researcher at the University of California, Davis. Fischer’s work focuses on quantifying and mitigating Earth radiative forcing caused by greenhouse gases and human habitation. NASA supported his research. Read more at https://goo.gl/vwVHav. (Photograph courtesy K. Garbesi)

Nick Parazoo is a research scientist at the NASA Jet Propulsion Laboratory. His research focuses on understanding feedbacks between climate and terrestrial ecosystem carbon storage, and how these will impact future climate. He uses atmospheric and remote sensing observations to develop an understanding of these processes, and ultimately improve Earth System Models. NASA supported his research. Read more at https://goo.gl/p9H2M6. (Photograph courtesy N. Parazoo)

For more information

NASA Goddard Space Flight Center Earth Sciences Data and Information Services Center (GES DISC)
https://disc.gsfc.nasa.gov

NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC)
https://daac.ornl.gov

NASA Orbiting Carbon Observatory-2 (OCO-2)
https://oco.jpl.nasa.gov

Closed season

> “Trying to explain something with satellite data has to make sense with what we see in the field.”
>
> Pascal Castellazzi
> Institut National de la Recherche Scientifique

By Natasha Vizcarra

When Pascal Castellazzi moved to Toluca in 2012, it was not for the world famous red and green chorizos. Nor was it for the cool climate or the Spanish colonial architecture. The French researcher came to the bustling capital city in search of odd things. He walked around, noting fissures in the ground. Along buckling *avenidas*, he spied tilting churches and monuments. “Once I saw people enter their sunken house almost by the second floor,” he said. Once, he stood by the banks of the funky-smelling Rio Lerma noting something else that was odd. “The river doesn’t flow much,” he said. “It doesn’t flow at all some parts of the year.”

Castellazzi is a hydrogeologist. To him all these odd notes about Toluca were evidence of a population taking more water from the

Residents in Ecatapec, a borough of Mexico City, wait for their family’s barrels to be filled. (© L. Forsyth) ground than nature can replenish. And it was not just happening in Toluca. "In a lot of places in Mexico, groundwater depletion leads to land subsidence," he said. "When you pump too much water out of the ground, pressure decreases in the aquifer below."

He was referring to the vast layers of water-bearing rock, gravel, or silt underneath Mexico's landscape, from which groundwater is extracted. Like underground sponges, aquifers compact when too much water is siphoned from them. At the surface, the ground sinks. Whatever is built above an over-exploited and compacted aquifer then tilts, buckles, or fractures.

Castellazzi was keen on studying Mexico's groundwater supply—more specifically how to measure it. Were the Mexican government's measurements reliable? If they were, why is the country still in a water shortage so severe that it puts many of its citizens' lives on hold?

Pascal Castellazzi and colleague Jaime Garfias stand in front of an abandoned house in Toluca Valley, Mexico. The house is located along a fracture showing differential movement of up to 5 centimeters (2 inches) per year. (Courtesy P. Castellazzi)

Endangered aquifers

The way they describe aquifers in Mexico, you would think they were hunted animals. Many are declared by the government as *vedados*, which roughly translates to "closed season." A *vedado* label means the aquifer is overexploited and must be protected. That does not stop water tankers, or *pipas*, from pulling up to pumping stations and poaching the water.

Illegal water extraction is probably more the norm than the exception. "Out of Mexico's 653 aquifers, about 18 percent are *vedados*," said Alfonso Rivera, who grew up in Northern Mexico and is now chief hydrologist with the Geological Survey of Canada. It is a troubling statistic, considering these aquifers are supposed to provide 70 percent of the water needs of rapidly expanding industries and the country's growing population of 120 million.

And Mexico's residents are feeling it. Sometimes the water flows. More often, it is rationed—days or weeks can go by before residents have access to water. Not all homes in Mexico have multiple faucets. Most people have supply lines coming into their homes, while others have a spigot in their yard, or share a neighborhood spigot. Sometimes the government sends *pipas* to deliver water from the aquifers. Often, families are forced to purchase water from private *pipas* and their delivery schedules are seldom reliable. That is why households will either have plastic water tanks called *tinacos*, or big, blue plastic drums, or smaller jars to store water until the next delivery. In areas too remote for the *pipas* to reach, residents pay for donkeys to deliver water to their homes. These tedious chores occur weekly, or even daily for the poor. The pursuit of water is nationally viewed as a colossal time suck.

Although Castellazzi saw the day-to-day reality of the water crisis in Toluca and in nearby Mexico City, he was keen on looking at the larger geography for data on aquifer depletion. What if he looked at a major watershed near the cities?

Algae clogs a lagoon in Toluca Valley, Mexico. Factories and homes that deplete the valley's aquifers dump their wastewater here. (Courtesy P. Castellazzi)

The Lerma-Santiago-Pacifico (LSP) seemed ideal. It supplies groundwater to Central Mexico's busiest cities and industrial areas, namely Mexico City, Guadalajara, Léon, Zapopan, Aguascalientes, Queretaro, Morelia, and Toluca. Data from the NASA Socioeconomic Data and Applications Center (SEDAC) showed these were also among Mexico's most populated cities. Because the climate in the region is arid to semi-arid, these cities are dependent on groundwater instead of surface water.

Castellazzi checked with Mexico's National Water Commission, Conagua, and found that the LSP has a deficit of about 2,000 million cubic meters of water per year. That was not surprising. Castellazzi was mostly interested in how they arrived at this number.

Pushing the limit

"Conagua uses the water budget method to determine if an aquifer is depleted or not," Castellazzi said. To calculate changes in groundwater supply, Conagua adds the discharge rate to the net extraction rate, and then subtracts the sum from the recharge rate. If the result is a negative value, that means the water budget is in deficit.

But Rivera, a co-author on Castellazzi's study, said that approach had many drawbacks. "They estimate parameters," Rivera said. "They don't measure them."

For example, the net extraction rate is only estimated. "They don't go out and measure how much water is actually being pumped out of the aquifer," Rivera said. In addition, the government may not have enough data from ground instruments to make their estimates reliable.

Castellazzi thought it was a perfect opportunity to test how data from satellites orbiting Earth could measure water in aquifers. The Gravity Recovery and Climate Experiment (GRACE) satellites synchronously orbit Earth more than a hundred miles apart. They sense variations in Earth's gravity field caused by changes in ice sheets, global sea level, and groundwater storage.

It was a great tool for Castellazzi's project, but it also had a limitation. GRACE is ideal for measuring large expanses, like continents, whole oceans, and large countries—ideally anything bigger than 200,000 square kilometers (77,220 square miles). "The LSP watershed is 133,000 square kilometers [51,000 square miles]," he said. "So we were definitely pushing it."

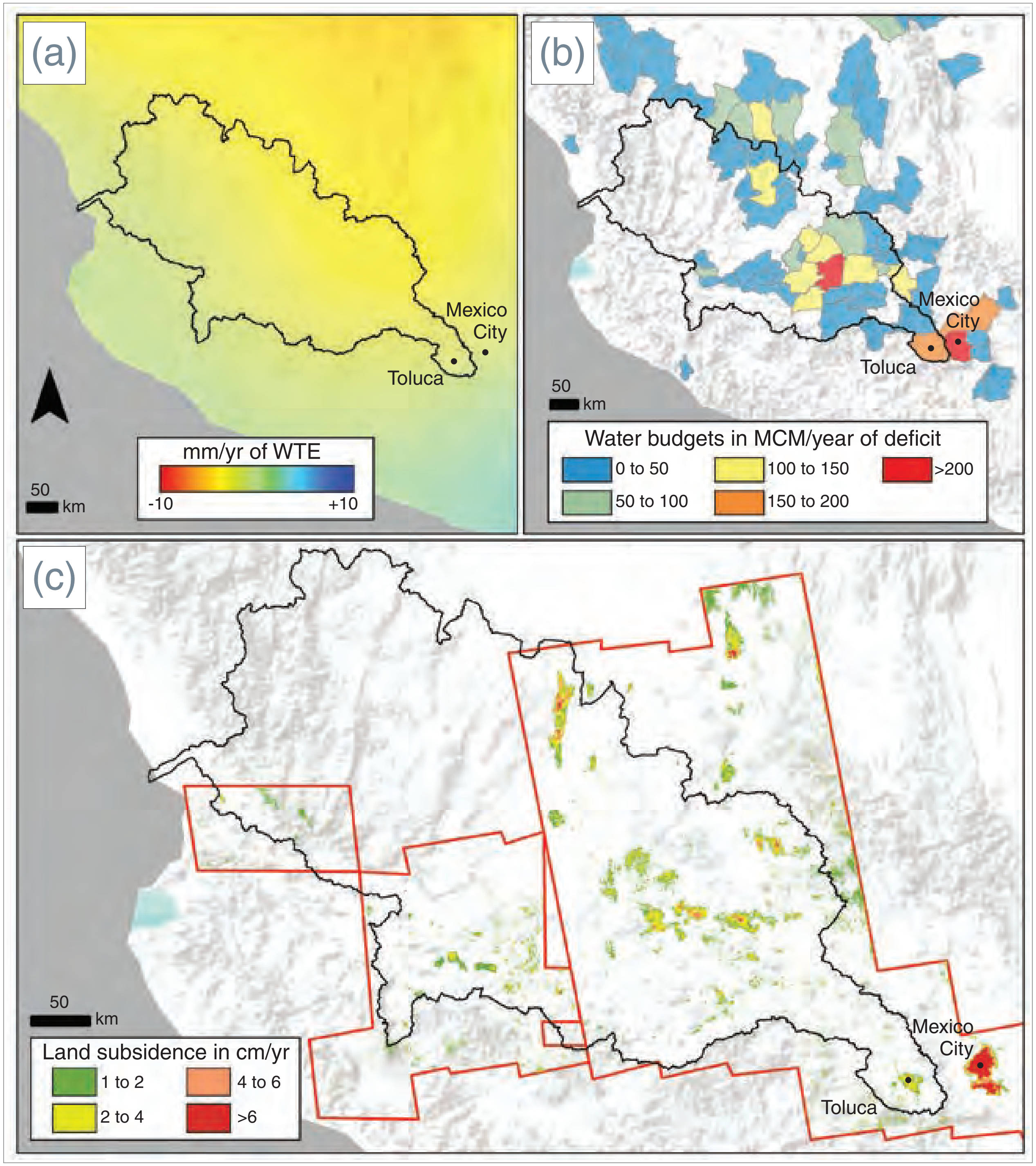
When Castellazzi extracted the LSP's water volume from GRACE data, he only found a deficit of about 158 to 210 million cubic meters of water a year, not 2,000 million. Rivera said, "That was a big difference."

Castellazzi added, "After playing with many versions of GRACE data, I could not find the deficit that we were expecting. We started to wonder why, and that's how I thought back to all the field work we had done."

Remembering all the signs of subsidence in Toluca, Castellazzi thought of another satellite sensor. The Phased Array type L-Band Synthetic Aperture Radar (PALSAR) that flies on the Advanced Land Observing Satellite (ALOS) measures ground deformation. Castellazzi used an ALOS PALSAR subsidence map to assess the error related to GRACE's low resolution, and found it could only dampen the signal by a factor of 2.7, which is still insufficient to explain the difference with data from Conagua.

That still left a 1,200 million cubic meter difference between the Conagua estimates and the satellite measurements. Where was this missing water? Were the Conagua estimates way off? Or was it the satellite measurements?

Stumped, Castellazzi once again reviewed his field notes. "I find that it is really important to link geodetic observations to field observations," he said. "Trying to explain something with satellite data has to make sense with what we see in the field." The missing water reminded him of his walks along the Rio Lerma.



Map (a) shows Gravity Recovery and Climate Experiment (GRACE)-derived groundwater storage trends, in millimeters per year of water thickness equivalent (WTE). Warmer colors indicate groundwater deficit, while cooler colors indicate groundwater surplus. The black outline marks the Lerma-Santiago-Pacifico watershed. Map (b) shows depleted aquifers as observed by the Mexican government's groundwater budget method, in million cubic meters per year. Map (c) shows areas subsiding because of groundwater overexploitation, in centimeters per year. Land subsidence data are derived from Advanced Land Observing Satellite Phased Array type L-Band Synthetic Aperture Radar (ALOS PALSAR) data, using InSAR techniques. (Courtesy P. Castellazzi, et al., 2016, *Water Resources Research*)

Castellazzi knew that many farms and industries upstream use a lot of groundwater daily, and that some of it was discharged into the Rio Lerma as wastewater or into farmland as irrigation water. Theoretically, some of that water should eventually find its way to the Rio Lerma, and yet why was the riverbed often dry downstream in Toluca? “All this extracted water, where does it go?” he said.

Unrecoverable

Castellazzi analyzed the ALOS PALSAR subsidence map again, this time comparing it with a land use map. He used both data sets to estimate how much water deficit each land use class tended to inflict on the aquifers each year. “Our results suggest that at least a third of the groundwater depletion is caused by groundwater pumping for industries and municipalities,” Castellazzi said. However, water from municipal pipes drip back into aquifers through leaky conduits. Factories discharge wastewater into canals and streams, and farms return some extracted water back into the ground through irrigation. According to Castellazzi, this “returned water” could be the missing water that GRACE could not detect.

“We trust the GRACE signal is relatively a good signal and that it is telling us what is happening,” Rivera said. “However, everything is integrated into that signal. GRACE can see a groundwater source and it sees a trend, but it doesn’t see why the trend is changing.”

Castellazzi’s findings also suggest that the water budget method that Conagua uses underestimates the amount that returns to the aquifers as wastewater and irrigation water. This supports the idea that the 2,000 million cubic meters of groundwater deficit in the LSP region should probably be lower. Castellazzi said it also suggests problems with groundwater quality in the future.

While there is still more work to be done, Castellazzi thinks combining GRACE and ALOS PALSAR observations holds promise for mapping groundwater depletion in Mexico’s endangered aquifers. Laurent Longuevergne, a researcher who specializes in developing geodetic tools in the study of hydrogeology, agrees. “The most valuable point of Castellazzi’s study is the potential to use GRACE in complex, small aquifer systems by joint interpretation with remotely-sensed interferometric synthetic aperture radar or InSAR,” he said.

“Water is a very political thing here,” Castellazzi said. “Our study offers the ability to assess the evolution of groundwater and water stocks in an apolitical way and to base governance on that.”

Recently, researchers and academics in Mexico proposed changes in the country’s water law. “They want the government to make decisions on the *vedados* based on science, and not on speculations or calculations that are not useful,” Rivera said. “When I read about this, I was very happy, because some of the work that we have done goes that direction. I truly believe that this methodology that uses remote sensing like GRACE and InSAR can be very useful in supporting this new law.”

Castellazzi feels there is no time to waste when it comes to *la veda*. “A large part of the compaction from over-depleted aquifers is unrecoverable,” he said. “Even if groundwater levels come back, an aquifer’s ability to store water could be decreased forever. And that, unfortunately, is something we are leaving our future generations to deal with.”

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/closed-season.

About the scientists

Pascal Castellazzi is a Ph.D candidate at the Institut National de la Recherche Scientifique in Quebec, Canada. His research interests focus on revealing the changes within natural and built environments through the interpretation of remotely-sensed data. The Ministère des Relations internationales et de la Francophonie du Québec and the Consejo Nacional de Ciencia y Tecnología supported his research. Read more at https://goo.gl/soFXqW. (Photograph courtesy P. Castellazzi)

Laurent Longuevergne is a research scientist at the Geosciences Rennes laboratory at the University of Rennes in France. His research focuses on water transfer in complex heterogeneous media by developing gravity and hydro-mechanical approaches. The French National Research Center, L’Agence Nationale de la Recherche, and regional funds support his research. Read more at https://goo.gl/Pi9zyv. (Photograph courtesy L. Longuevergne)

Alfonso Rivera is chief hydrogeologist at the Geological Survey of Canada in Quebec, Canada. His research focuses on the nature, dynamics, and extent of aquifer systems in Canada to inventory its groundwater resources. Natural Resources Canada supports his research. Read more at https://goo.gl/uk2PZg. (Photograph courtesy A. Rivera)

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NASA Physical Oceanography DAAC (PO.DAAC)
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Japan Aerospace Exploration Agency Advanced Land Observing Satellite (ALOS-1)
http://global.jaxa.jp/projects/sat/alos

NASA Gravity Recovery and Climate Experiment (GRACE)
https://www.nasa.gov/mission_pages/Grace

Phased Array type L-Band Synthetic Aperture Radar (PALSAR)
https://www.asf.alaska.edu/sar-data/palsar/about-palsar

About the remote sensing data

Satellites	Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS)	Gravity Recovery and Climate Experiment (GRACE)
Sensors	Phased Array type L-Band Synthetic Aperture Radar (PALSAR)	K-Band Ranging System
Data sets	ALOS PALSAR L1.1	GRACE Static Field Geopotential Degree 96 Coefficients CSR Release 5.0
Resolution	10 meter azimuth	1 x 1 or 0.25 x 0.25-degree sampling grids – actual sensor resolution is around 400 x 400 kilometer
Parameters	Terrain	Gravity
DAACs	NASA Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC)	NASA Physical Oceanography DAAC (PO.DAAC)

About the data

Data sets	Global Land Data Assimilation Systems-1 (GLDAS-1): CLM10, MOS10, NOAH10, NOAH025, and VIC10	Gridded Population of the World (GPW), v3
Resolution	Various	2.5 arc-minute 1/4 degree, 1/2 degree, 1 degree
Parameters	Land surface models	Population density
DAACs	NASA Goddard Space Flight Center Earth Sciences Data and Information Services Center (GES DISC)	NASA Socioeconomic Data and Applications Center (SEDAC)

Drought on the range

> "Soil moisture determines the biomass, or how much grass we're going to get."
>
> Gabriel Senay
> US Geological Survey

By Laura Naranjo

The grassy, high plains and rolling rangelands of Texas are perfect for grazing cattle. But the specter of drought is rarely far from ranchers' minds. Drought desiccated Texas from 2011 to 2012 so severely that many ranchers had to purchase feed and water, and truck it out to their cattle. Others chose to sell off parts of their herds well before animals reached their peak weight—and peak prices.

Although rangelands are hardy biomes that thrive in relatively dry climates, a persistent lack of water can tip them into drought, withering grasses and reducing prairies to dust. Because ranchers rely heavily on grass, they ultimately depend on water. Rain and snow are important sources, but much of that water evaporates back into the atmosphere. The remaining water either runs off into lakes or streams, or percolates down into the soil to nourish plants where their roots are, within 5 to 100 centimeters (2 to 39 inches) of the surface.

This soil moisture—or lack of it—forges a ranch's future. "Soil moisture determines the biomass, or how much grass we're going to get," said Gabriel Senay, a scientist at the US Geological Survey who studies agriculture and hydrology.

A prolonged drought across Texas desiccates plants and dries up livestock watering holes. (Courtesy AgriLife Today)

"And of course, the healthiness of the grass will determine how many cattle can be supported." But soil moisture measurements that are accurate and available over broad regions have long been missing from the drought equation.

Sensing the missing piece

When monitoring drought, researchers like Senay use data from ground stations that record rain and snowfall rates, temperature, humidity, and evaporation. Many stations also include soil moisture sensors, slender probes plunged into the soil. These stations offer single points of data, but soil moisture can vary widely over short spaces. A shady drainage may be damper than the surrounding prairie, even if they both get the same precipitation.

Soil moisture plays a large role in a landscape's resiliency or vulnerability. High soil moisture means more water is immediately available for growing plants, and also makes rain more likely to run off the saturated surface to fill streams and lakes, benefitting ecosystems nearby or downstream. Low soil moisture could mean the soil soaks up available precipitation, leaving nearby or downstream areas drier and vegetation more stressed.

Meteorologists and researchers feed soil moisture data into computer models to help create monitoring products and seasonal predictions. However, point measurements leave large spatial gaps in the data record. Satellite data fills in the gaps for precipitation, temperature, and other variables, but until recently, soil moisture has been difficult to detect from space.

"Soil moisture has been a dream in hydrology since the 1980s, and even earlier," Senay said. "I remember my advisor from 20 years ago saying soil moisture is like the holy grail." So when the NASA Soil Moisture Active Passive (SMAP) mission launched in 2015, Senay and other hydrologists were excited. SMAP works by detecting microwave radiation, which all surfaces on Earth emit in small amounts. The radiometer instrument on the SMAP satellite focuses specifically on radiation frequencies that signal minute differences in moisture on and near land surfaces. For instance, very wet surfaces, like lakes, emit low amounts of these frequencies, while a dry surface like sand will emit higher amounts.

However, can a satellite monitor soil moisture accurately enough to complement existing station data on a broad scale, and be truly useful for drought monitoring?

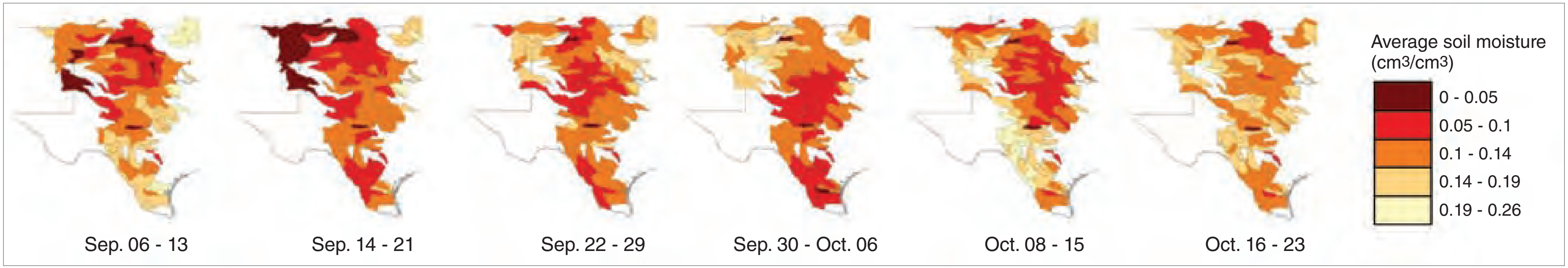
Soil moisture by satellite

To put SMAP to the test, Senay and his colleagues compared it to soil moisture data collected from ground stations between April and December 2015. They looked for the most applicable stations by reviewing land cover data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instrument. After identifying areas that contained more than 70 percent rangeland, they selected eight stations scattered across the southern Great Plains rangelands, seven in Texas, and one in the Oklahoma panhandle.

"One of the reasons we focused on Texas and Oklahoma was the availability of ground stations, which had in situ soil moisture data readily available on the Web," Senay said. Although rangelands span much of the western United States, these stations are more common in portions of the Great Plains and in agricultural areas. For a full picture of the hydrologic cycle, Senay and his team then incorporated rainfall and surface temperature data for each site over the course of their study.

Sheep graze on public rangelands at Beartrap Meadows in Wyoming. (Courtesy M. Wells, Wyoming Stock Growers Land Trust, US Department of Agriculture)

SMAP matched the ground data and models, echoing the overall variability in soil moisture over time. Likewise, the satellite data demonstrated a dry trend early in the study period that progressed into exceptional drought conditions by October. In addition, the researchers found a surprisingly useful parallel in the SMAP data. "We are getting strong correlations to deeper layers, down to 20 centimeters (8 inches), reliably, and even to 100 centimeters (39 inches) in some instances," Senay said. SMAP is designed to measure moisture in the topmost layers of soil,



This series of maps shows soil moisture in Texas in fall 2015, during extreme drought conditions. Red indicates less soil moisture; yellow indicates higher soil moisture. Data are from the NASA Soil Moisture Active Passive (SMAP) mission. (Courtesy N. M. Velpuri, et al., 2016, *Rangelands*)

about 5 centimeters (2 inches) deep. This depth captures the land-atmosphere interactions that form a large part of the hydrologic cycle. Yet the root zone of many plants extends deeper, and this is where the moisture is needed for plants to survive drought.

SMAP introduces a new and reliable source of soil moisture data, which will instill more confidence in drought monitoring and forecasting. "Drought modeling requires a convergence of evidence," Senay said. For example, looking at soil moisture or rainfall or streamflow alone will present a lopsided and incomplete view of the hydrologic cycle. "So when at least two or three of these data sets converge, we will have more confidence in the final product," he said.

From soil moisture to sirloin

Confidence is one of the keys to making drought data useful for rangeland managers, ranchers, and other stakeholders. Derek Scasta is a rangeland extension specialist at the University of Wyoming, where he searches for ways to link practical science to the people it impacts. "The variability of drought, both in space and time, is really what makes it difficult to manage," Scasta said. "And of course predicting it is the million-dollar question. If we could predict it, we could manage it a lot better." Drought is a culmination of many factors such as rainfall, soil moisture, and temperature that are highly variable not only over time, but over space. "Sometimes drought is very localized. A rancher might have seen their neighbors get rain, while they didn't get any," Scasta said.

Ranchers must analyze drought forecasts to make hard decisions. The more confident they are in the data, the more confidently they can choose how to respond when a drought looms. "One of the common tools that's used is a trigger date," Scasta said. For instance, a rancher might choose May 15 as a trigger date. "Oftentimes that spring rain or that early summer rain can be a good predictor of forage production for the year," Scasta said. "So if we've been dry, below normal that spring, we might need to make some decisions, as far as drought mitigation. If we've been pretty wet up until that point, we might have a pretty good production year." Other ranchers remain perpetually prepared. "They might build in regular rest into their rotation of grazing through pastures," Scasta said. "Some producers just build in practices to mitigate drought no matter what."

The recent drought hit Texas farmers and ranchers especially hard, causing more than $7 billion in losses. Many still struggle to recover. Some ranchers culled their herds; others quit the ranching business altogether. And after 26 years of occupying the top spot for cattle income, in 2013 Texas fell to second place behind Nebraska, largely a result of the drought.

While the drought in Texas has ended for now, it will return, and SMAP will help improve future forecasts. One of the primary tools rangeland managers use is the US Drought Monitor run by the University of Nebraska, which is working on incorporating SMAP data. Including soil moisture data across broad expanses will more accurately reveal an ecosystem's overall hydrology, and help indicate whether a drought may be looming. While that may come too late for those affected by the recent Texas drought, better forecasts will ultimately help ranchers prepare for drought more proactively.

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/drought-on-the-range.

About the remote sensing data

Satellites	Soil Moisture Active Passive (SMAP)	Terra and Aqua	Terra
Sensors	SMAP L-Band Radiometer	Moderate Resolution Imaging Spectroradiometer (MODIS)	MODIS
Data sets	L3 Radiometer Global Daily 36 km EASE-Grid Soil Moisture, Version 3	Land Cover Type Yearly L3 Global 500 m SIN Grid V005 (MCD12Q1)*	Land Surface Temperature/Emissivity 8-Day L3 Global 1km SIN Grid V005 (MOD11A2)
Resolution	36 x 36 kilometer	0.5 kilometer	1 kilometer
Parameters	Soil moisture	Land cover	Land surface temperature, land surface emissivity
DAACs	NASA National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC)	NASA Land Processes DAAC (LP DAAC)	NASA LP DAAC

*The researchers used the 0.5 kilometer MODIS-based Global Land Cover Climatology product available from the US Geological Survey Land Cover Institute (https://landcover.usgs.gov/global_climatology.php).

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About the scientists

Derek Scasta is a rangeland extension specialist and assistant professor at the University of Wyoming. He studies rangeland management and disturbances on rangelands, such as fire and drought, and strives to link people with sound research and science. The University of Wyoming supported his research. Read more at https://goo.gl/FTRC9T. (Photograph courtesy D. Scasta)

Gabriel Senay is a research physical scientist at the US Geological Survey Earth Resources Observation and Science (USGS EROS) Center, and is co-located at the North Central Climate Science Center, Fort Collins, Colorado. He conducts applied research on water use and availability assessment along with drought monitoring using satellite-derived data and hydrologic modeling. The USGS supported his research. Read more at https://goo.gl/rGJbkr. (Photograph courtesy G. Senay)

For more information

NASA Land Processes Distributed Active Archive Center (LP DAAC)
https://lpdaac.usgs.gov

NASA National Snow and Ice Data Center DAAC (NSIDC DAAC)
https://nsidc.org/daac

NASA Moderate Resolution Imaging Spectroradiometer (MODIS)
https://modis.gsfc.nasa.gov

NASA Soil Moisture Active Passive (SMAP)
https://smap.jpl.nasa.gov

The big fat puzzle

“The further north you go where it’s colder, there should be less obesity.”

John R. Speakman
Chinese Academy of Sciences

By Natasha Vizcarra

Newborn babies have it. Gray squirrels and naked mole rats have it. It is called brown adipose tissue, or brown fat. Unlike white fat, which simply stores calories, brown fat burns energy and produces heat. It helps newborns—who cannot shiver—warm their bodies when they are cold. It also helps small animals avoid hypothermia and survive frigid winters.

Scientists used to think that adult humans do not have brown fat. “As you get bigger your surface-to-volume ratio changes,” said biologist John R. Speakman, a professor at the Chinese Academy of Sciences in China and the University of Aberdeen in Scotland. “So, your need for heat decreases the bigger you become.”

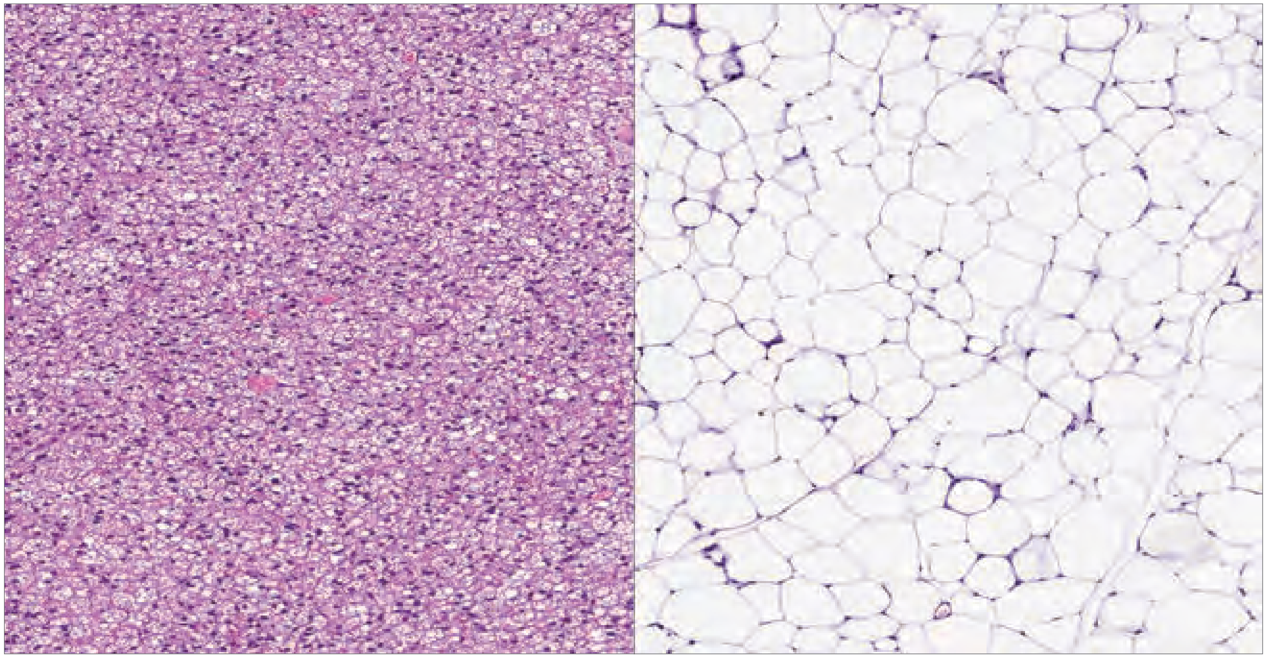
But in 2009, researchers discovered that adult humans have some of it too. Soon after, another

Skiers practice cross-country skiing drills on Bagely Hill in Duluth, Minnesota. (Courtesy University of Minnesota Duluth) study found more brown fat in lean adults than in those who are obese.

The idea that adult humans have fat cells that can burn energy when exposed to cold temperatures fascinated scientists, particularly those in obesity research. Could humans someday just pop a pill to activate this brown fat and lose weight?

"That's kind of the dream," said Speakman, who has been studying obesity for 20 years. It could be a dream for the United States, where more than one third of the population is obese and where one in eleven people have obesity-related type 2 diabetes.

"The United States is only ninth in the world for obesity," Speakman said. "But it's the biggest country that's high on the list. Other countries that rank higher are mostly small countries. America is the first country that's got millions and millions of obese people and therefore it's a massive health issue."



These images show brown fat (left) and white fat (right). Brown fat cells look darker because they contain numerous mitochondria, organelles that convert oxygen and nutrients into adenosine triphosphate (ATP). However, in brown fat, a protein called Uncoupling Protein 1 short-circuits the production of ATP and causes the mitochondria to release heat as energy instead of ATP. This enables brown fat to burn calories as well as generate heat. (Courtesy Shutterstock)

Little furnaces

The US Centers for Disease Control and Prevention (CDC) describes an obese person as one whose body mass index (BMI) is above 30. A normal BMI ranges from 18.5 to 24.9. The condition increases a person's risk for heart disease, stroke, cancer, and type 2 diabetes.

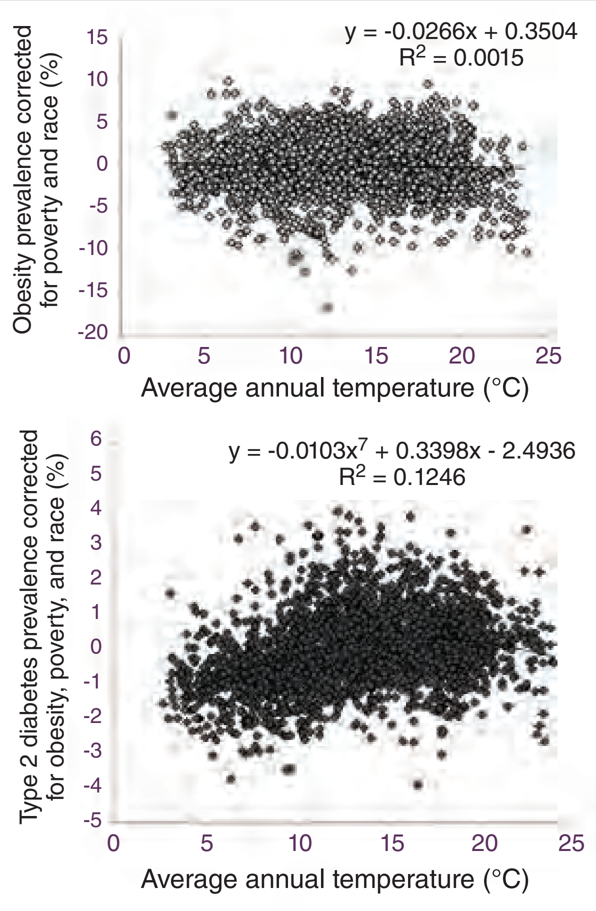
Obesity and type 2 diabetes are closely linked, as the risk of type 2 diabetes rises with increasing body weight for people of all ages. Long-term and untreated type 2 diabetes can lead to disabling and life-threatening complications affecting the heart, blood vessels, nerves, eyes, and kidneys. As of 2008, the annual medical care costs of obesity were estimated at $147 billion and as of 2012, the costs for diabetes were $245 billion.

The standard treatment for obesity is to tell people to eat less and exercise more. Physicians have been telling obese patents this for as long as there has been obesity—and it has never worked. In addition, while there have been several obesity medications, they have generally had to be withdrawn because of side effects.

However, Speakman and other obesity researchers wonder if it can be treated by exposing patients to low temperatures. The theory is that cold can activate a person's brown fat cells and that these burn calories while they are turned on. "One interesting observation is that brown fat seems to be more abundant in the winter than in the summer," Speakman said. "It looks like it's switched on seasonally."

Speakman describes brown fat cells as "little furnaces." In human babies, it has been found between the shoulder blades, around the collar bones, near the heart, kidneys, pancreas, and windpipe. In most small mammals, the cells are also in a patch of tissue between the shoulder blades. "Like a little radiator in the back," Speakman said.

"It gets more complicated," he said. "It turns out that there is a third type of fat cell known as the beige cell, because it's somewhere between white and brown." A beige fat cell can switch what it does according to what the body needs. So, if the body needs to store calories it turns into a white cell and if the body needs to produce heat it can turn into a brown cell.



These plots show the county level data (for 2,651 US counties) for obesity (top) and type 2 diabetes (bottom) corrected for levels of obesity, poverty, and race against average annual temperature in degrees Celsius. (Courtesy J. R. Speakman and S. Heidari-Bakavoli, 2016, *Scientific Reports*)

"It means there must be sort of a molecular switch that you can use to convert these beige cells from a white form into the brown form, and we think that switch can be turned on by exposure to cold temperatures," Speakman said. He wanted to test if that idea really holds water. He said, "If that's true, the further north you go where it's colder, there should be less obesity."

Data digging

To explore this, Speakman probed the distribution of obesity across the United States. He acquired county-level obesity and type 2 diabetes data from a CDC study that has been running since 1984 and includes more than 400,000 people. He also found county-level air temperature data from the NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). The data set includes data on historical climate across all counties in the United States, as well as other environmental characteristics, such as soils, air and water quality, industrial activity, and other factors that may be linked to human health.

"We looked at the data and actually that's true," Speakman said. "If you just look at the crude analysis there's a small effect of temperature. So, the colder it gets the less obesity there is."

What stunned Speakman was the type 2 diabetes prevalence. "If you live in an area where the average temperature is 5 degrees Celsius [41 degrees Fahrenheit], you have about an 8 percent risk of diabetes," he said. "Whereas if you live in an area where the average temperature is 22 degrees Celsius [72 degrees Fahrenheit], then it's about a 12 percent chance."

However, Speakman needed to eliminate other factors in the warm areas that may be causing obesity and diabetes—factors that have nothing to do with temperature. "The classic factors that are associated with obesity and diabetes are poverty and race," he said. "We wanted to statistically remove those effects and see if temperature still had an effect."

After running the numbers, the relationship between temperature and obesity completely disappeared. "This whole idea that you might be able to pop a pill and it'll switch on all your beige fat cells and they'll burn off all your fat is probably not going to work," he said. "It's kind of disappointing because that was initially the motivation, but what was amazing was that the diabetes effect was still there." What started out for Speakman as an intent to find a treatment for obesity resulted in a possible route to treating type 2 diabetes.

Speakman thinks this might be because brown fat cells use a lot of glucose to produce heat. In type 2 diabetes, the body does not use insulin properly, causing insulin resistance. The pancreas makes up for this by making extra insulin to manage high blood glucose levels. Over time, the pancreas will not be able to keep up and make enough insulin to maintain blood glucose at normal levels. So, brown fat cells may protect patients from diabetes. "When you eat something sweet, the brown fat act as a sort of buffer that can soak up all this glucose," Speakman said. "So, you don't put as much pressure on your insulin production."

Cold treatment

Other researchers have also homed in on the connection between brown fat and type 2 diabetes. Around the same period that Speakman was conducting his study, researchers in the Netherlands' Maastricht University exposed eight patients with type 2 diabetes to a cold environment of 14 to 15 degrees Celsius (57 to 59 degrees Fahrenheit) for ten days. The patients' insulin sensitivity had improved by up to 43 percent—a distinct improvement. Strangely, however, the researchers observed only a small increase in the patients' brown fat activation after the cold treatment.

While both Speakman's study and the Netherlands study point to a possible treatment for type 2 diabetes, Speakman said, "The bottom line seems to be a whole lot more complex than this simple idea that cold switches on your brown adipose tissue and cures your diabetes."

"It could be something else," Speakman said. "It could be that cold exposure increases your ability to dispose of glucose in your muscles." It could also be because people who live further north get more sunlight and Vitamin D because of long summer days. "That could possibly influence the diabetes," Speakman said. People with type 2 diabetes generally have poor vitamin D levels compared to people who do not have the disease.

And while the Netherlands study is encouraging, Speakman acknowledges that it is not practical to treat people with diabetes by sticking them into cold rooms. In that study, the subjects had to sit in a cold room for up to six hours a day. "There could be other complexities with that because diabetics have poor peripheral circulation," Speakman said. "You could improve the diabetes, but you could cause some other problems with circulation in the legs. We need to think it through a bit more carefully."

Speakman's next step is to consider what his findings might mean for the United States in terms of health policy and governance. Ideally, warmer states should allocate more money to handle diseases that can be triggered by high temperatures. "That might have implications in terms of global warming," Speakman said. "If we are predicting that states are going to experience increases in temperature, and if this is a causal relationship, then that's likely to lead to an increase in spending on type 2 diabetes."

About the data

Data set	Geoecology: County-Level Environmental Data for the United States, 1941 to 1981
Resolution	County-level
Parameter	Monthly average temperatures
DAAC	NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC)

About the scientist

John R. Speakman is a professor at the Chinese Academy of Sciences in Beijing and the University of Aberdeen in Scotland. Speakman studies energy balance and the consequences of obesity, and other physiological parameters such as oxidative stress and aging. The Strategic Priority Research Program of the Chinese Academy of Sciences, the National Science Foundation of China, and China's 1000 talents program supported his research. (Photograph courtesy J. R. Speakman)

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/the-big-fat-puzzle.

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To the lighthouse

“This is one of those oh-my-gosh-how-can-that-be stories.”

Peter Blanken
University of Colorado Boulder

By Agnieszka Gautier

Shortly after the boat set out onto Lake Huron, dense fog swelled. Unable to see beyond the bow, radar guided the researchers to Spectacle Reef Light, a lighthouse, 11 miles offshore. “We literally almost hit our heads on it,” said Peter Blanken, a researcher from the University of Colorado Boulder. The team was checking on the instruments on top of the lighthouse, which was being used as a key research site.

The Great Lakes contain 20 percent of the world’s surface fresh water and provide 35 million people with drinking water. “Surprisingly we know very little about them,” Blanken said. “They’re very poorly studied.” Their immense size has led many to perceive them as unresponsive to climate change. From 1998 to 2014, water levels dropped in the Great Lakes to the longest low-level period in over 100 years. Then in 2016, water levels recovered in Lake Huron, jumping more than three feet after 12 days of rain.

Precipitation is one driver of year-to-year fluctuations, but Blanken suspected another cause. After observing evaporation in the Great Slave Lake, an extensive lake in northern Canada, Blanken had a hunch evaporation may also play a major role in the Great Lakes’ water cycle. Understanding how evaporation works and what it contributes to lake-level changes would

This aerial view shows Spectacle Reef Light on the northwest side of Lake Huron, 11 miles east of Bois Blanc Island. (Courtesy US Coast Guard) provide insight on where lake levels are headed in the long term.

The lake dimension

On still days, Lake Huron turns into a sheet of glass, where the horizon and water surface blur into one another. In the eerie dead calm, sound carries through biting cold and a jumping fish startles with a bang. “The lakes are so big you think you’re on the ocean,” Blanken said. Sailing out there is not easy. On stormy days, 40-foot waves have been known to rip vessels in two.

Winters also take their toll. After 2009, when Blanken equipped the top of Spectacle Reef Light, he returned yearly for upkeep. Though just a point on the lake, the lighthouse offered direct measurements that could validate satellite readings to then calculate lake-wide evaporation. Spectacle Reef Light is one of only a few lighthouses built on concrete platforms surrounded by water. These tall, stable structures make prefect weather towers. Without interference from land surfaces, the instruments record clean field measurements, and Spectacle Reef Light is the only station on Lake Huron measuring offshore, year-round weather.

The results challenged the researchers’ preconceived notions. The three key components of evaporation include heat, wind, and atmospheric vapor pressure. The sun drives evaporation, warming the lake surface and breaking molecular bonds that increase humidity in the atmosphere. And just like wet clothes on a clothesline dry faster in the wind, faster winds sweep more water molecules off the lake surface, increasing evaporation. The lower the atmospheric vapor pressure, the greater the lake-air difference in vapor pressure, the more easily water molecules lift off the surface, increasing humidity. Evaporation rates depend on the difference between the humidity at the lake surface and in the atmosphere. A dry atmosphere drives more evaporation. That seems straightforward, though these lakes defied expectations. “This is one of those oh-my-gosh-how-can-that-be stories,” Blanken said. The most surprising finding was that evaporation was not a summer phenomenon.

Cold sweat

“When you’re standing on the shore in July and you tell someone there is no evaporation from the lakes, they can’t believe it,” Blanken said. In the summer, the lakes are colder than the atmosphere so all the solar energy goes to warming the waters, not evaporation. When winter arrives six months later, these giant lakes are warmer and humid compared to the cold, dry atmosphere, boosting heavy evaporation loss.

The other misconception is that winter ice suppresses evaporation. People assume a year with a lot of ice cover will have little evaporation, but the opposite is true. Evaporation rates in the fall and early winter help determine the extent of winter ice cover. A large amount of heat loss from the lakes is required to cool the water enough to ice over. Cold, dry air pulls more water molecules off the lake surface. During a cold fall and early winter, high evaporation rates help cool the water surface, promoting broad ice cover in the winter.

In a very cold year, evaporation rates surge. “The lake’s evaporating like crazy,” Blanken said. Then ice builds. Complete ice cover would stop evaporation, though that seldom happens. During a warm fall, on the other hand, the temperature and vapor pressure differences between the lake surface and atmosphere are not large enough to promote major evaporation, so the lake does not cool enough to build its winter ice.

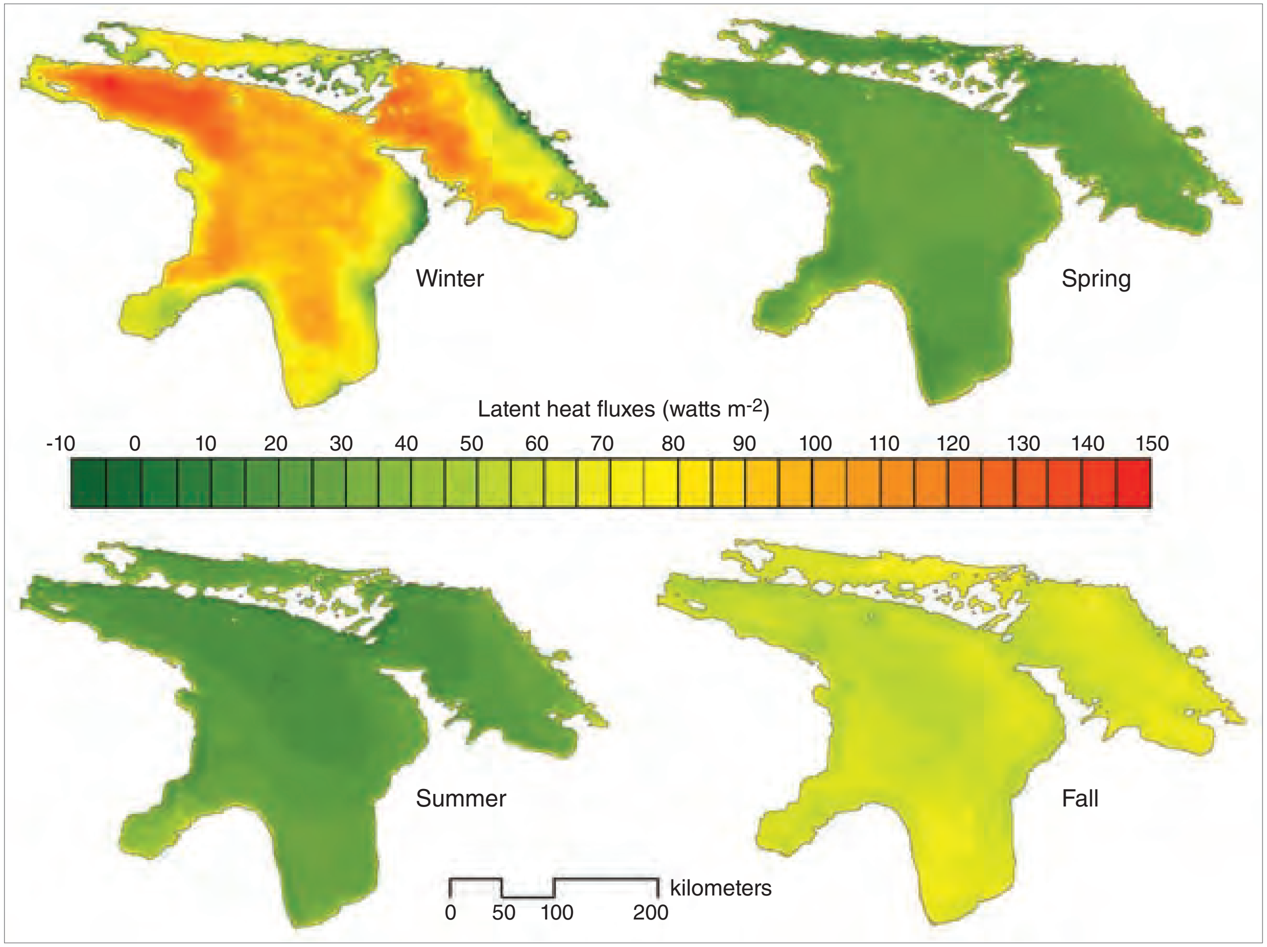
The researchers used the data from the instruments on the lighthouse to calibrate and verify satellite remote sensing for a lake-wide estimate of evaporation. “Quantifying evaporation is the hardest part of this study,” said Pakorn Petchprayoon, a researcher from Geo-informatics and Space Technology Development Agency in Thailand. On top of the lighthouse, gadgets spin and record the energy exchanges of the water molecules—their rise and fall, speed and direction, and density. With additional parameters like water and air temperature and vapor pressure, the team used an equation to calculate evaporation at the lighthouse. “One in situ point is not enough to represent the lake as a whole,” Petchprayoon said. Remote sensing then was critical.

Up in the air

“We believe the laws of physics don’t change from here to there,” Blanken said. “So we used remote sensing to move us around spatially.” To estimate evaporation for the entire lake, the team plugged in satellite data values from the rest of the lake. The key variable was surface temperature from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instrument. Comparing satellite data with the field measurements showed the two agreed. After calculating evaporation at the lighthouse, they next calibrated satellite products to extrapolate, pixel by pixel, for a lake-wide estimate.

The water loss is huge. Depending on the year, Lake Huron loses roughly a meter of water level a year. It is not alone. The researchers had previously seen similar losses in Lake Superior.

Remote sensing also allowed the team to go back in time. Measurements from the lighthouse



These images of Lake Huron show average seasonal changes in latent heat, in watts per square meter. Latent heat is the heat required for evaporation to occur without temperature changes. Data derived from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra satellite, with red showing up to 150 watts per square meter and dark green showing as low as -10 watts per square meter. (Courtesy P. Petchprayoon)

began in 2009, and remote sensing data stretches back to 2002. The study calculated evaporation from 2002 to 2012, and even in that time evaporation increased, driven by higher surface water temperatures. “Climate change is definitely increasing evaporation,” Petchprayoon said. This does not surprise him. What does is the erratic pattern of evaporation in one year. For instance, November dips after an increase in evaporation in October, only to start back up again in December.

Overall, evaporation on the lakes is becoming more dynamic. Using remotely sensed ice-cover data from the US National Ice Center and the Canadian Ice Service, the team saw that prior to 1998 ice cover behaved consistently, but after 1998 it has been highly variable. Years with high ice cover have been followed by years of record-low ice cover. And since what happens in the winter affects the following summer, and summer affects winter, the variability increases evaporation because the system is trying to balance out. That is why scientists are beginning to see abrupt oscillations in lake water levels.

Flashback

Water levels in the Great Lakes will continue to fluctuate, as they have over the past century, corresponding to changes in the water balance. The question now: Have we reached a tipping point or is climate change a more gradual effect?

The lighthouses possess historical data that may give insight into the extent of lake response to climate change. The keepers, who often lived offshore in isolation, kept the lights moving from 1874 until 1970 when lights became automated. They kept daily observations of weather—air temperature, barometric pressure, and wind speed and direction. Blanken visited the National Archives in Washington, DC where the logbooks are stored. “Sometimes the keepers would write ‘blustery winds out of the north,’ ‘lake making steam today,’ ‘ice surrounding the lighthouse today,’ or ‘waves breaking over top,’” Blanken added. “There’s a wealth of data there.” These data have yet to be analyzed.

In the meantime, climate change predictions anticipate further sudden water level changes. As this study shows, these beasts of fresh water are more fragile than suspected. “When I’m out there doing fieldwork, I think, ‘How can such a large volume of water be so dynamic?’” Blanken said. He thought the lakes would be irresponsive to short-term atmospheric conditions, but they are not. “They respond quickly, which still surprises me.”

About the remote sensing data

Satellite	Terra	Terra	Terra	Terra
Sensor	Moderate Resolution Imaging Spectroradiometer (MODIS)	MODIS	MODIS	MODIS
Data sets	Geolocation Fields 5-Min L1A Swath 1km	Cloud Product (MOD06)	Atmosphere Profiles (MOD07)	Land Surface Temperature and Emissivity (MOD11_L2)
Resolution	1 kilometer	5 kilometer	5 kilometer	1 kilometer
Parameters	Geolocation data	Cloud optical properties	Air and dew point temperatures	Land surface temperature
DAACs	NASA Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (LAADS DAAC)	LAADS DAAC	LAADS DAAC	NASA Land Processes DAAC (LP DAAC)

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/to-the-lighthouse.

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About the scientists

Peter D. Blanken is a professor at the University of Colorado Boulder. His research includes carbon and water flux measurements above alpine tundra and subalpine forests in Colorado, and evaporation measurements from the Great Lakes using offshore lighthouses and ships. The International Joint Commission and the Great Lakes Observing System supported his research. Read more at https://goo.gl/WD3yJP. (Photograph courtesy P. D. Blanken)

Pakorn Petchprayoon is a researcher at Geo-informatics and Space Technology Development Agency in Bangkok, Thailand. His research interests include integrating remotely sensed data with direct field measurements and modeling to understand the physical energy exchange processes between the land and water surface and the atmosphere. The International Joint Commission supported his research. (Photograph courtesy N. Kongkla)

For more information

NASA Land Processes Distributed Active Archive Center (LP DAAC)
https://lpdaac.usgs.gov

NASA Level 1 and Atmosphere Archive and Distribution System DAAC (LAADS DAAC)
https://ladsweb.modaps.eosdis.nasa.gov

NASA Moderate Resolution Imaging Spectroradiometer (MODIS)
https://modis.gsfc.nasa.gov

Warnings from the ionosphere

> "When the ground shakes, it causes tiny atmospheric waves that can propagate right up to the ionosphere."
>
> Attila Komjathy
> NASA Jet Propulsion Laboratory

By Natasha Vizcarra

On March 11, 2011, a powerful earthquake shook Japan. Pressure had built along a deep ocean trench off the northeast coast, and then the fault ruptured. The quake began below the seafloor, 43 miles east of the Tohoku Region, jolting part of the seafloor upwards by 30 feet. The force of the temblor thrust Honshu—Japan's biggest island—about 10 feet to the east.

Seismographs registered the quake's magnitude at 9.1, the most powerful recorded in the country. In less than a minute after the quake began, early warning systems fed quake data into computer simulations. Computer models

This photograph shows an aerial view of Oshima-Mura, Japan, 11 days after a magnitude 9.1 earthquake and subsequent tsunami. (Courtesy US Navy/Specialist 3rd Class D. McCord) processed tide gauge and deep ocean gauge observations throughout the Pacific Ocean. These systems churned out forecasts of when destructive tidal waves, or tsunamis, might arrive at coastlines in Asia and the Americas, and how big they might be.

High above Japan, something else detected signals from the quake. Global Positioning System (GPS) satellites sent their usual radio signals to Earth. As the pulses beamed down to the country's 1,200 ground-based GPS receivers, they intercepted and recorded atmospheric disturbances caused by the quake. When they arrived at the ground receivers, the radio signals carried vital information about the quake that could improve tsunami early warning systems and get people out of hazard zones faster.

A confluence of events

It is hard to separate the quake damage from the tsunami devastation in the Tohoku region and other parts of Japan. The quake lasted about six minutes and it generated tsunamis of up to 133 feet along the northeastern coast, with the worst damages in the cities of Miyako and Sendai, and in the province of Fukushima.

Here are the grim statistics for both the quake and the aftermath. More than 15,000 people died, most of them drowned. About 2,500 people were never found. The tsunami caused a power outage at the Fukushima Daiichi nuclear power plant, disabling the cooling of three reactors. All three cores melted within days, triggering mass evacuations and increased levels of radiation in local water and food supplies.

"I call it a perfect storm and sadly so because it claimed many lives and caused about $300 billion in damages," said Attila Komjathy, a scientist at the NASA Jet Propulsion Laboratory (JPL) of the California Institute of Technology. "It was a big earthquake and a big tsunami, but it so happened that about 1,200 GPS receivers were operating simultaneously and collecting data when these unfortunate events were happening." The receivers picked up effects that the quake and the tsunami had caused high in Earth's atmosphere.

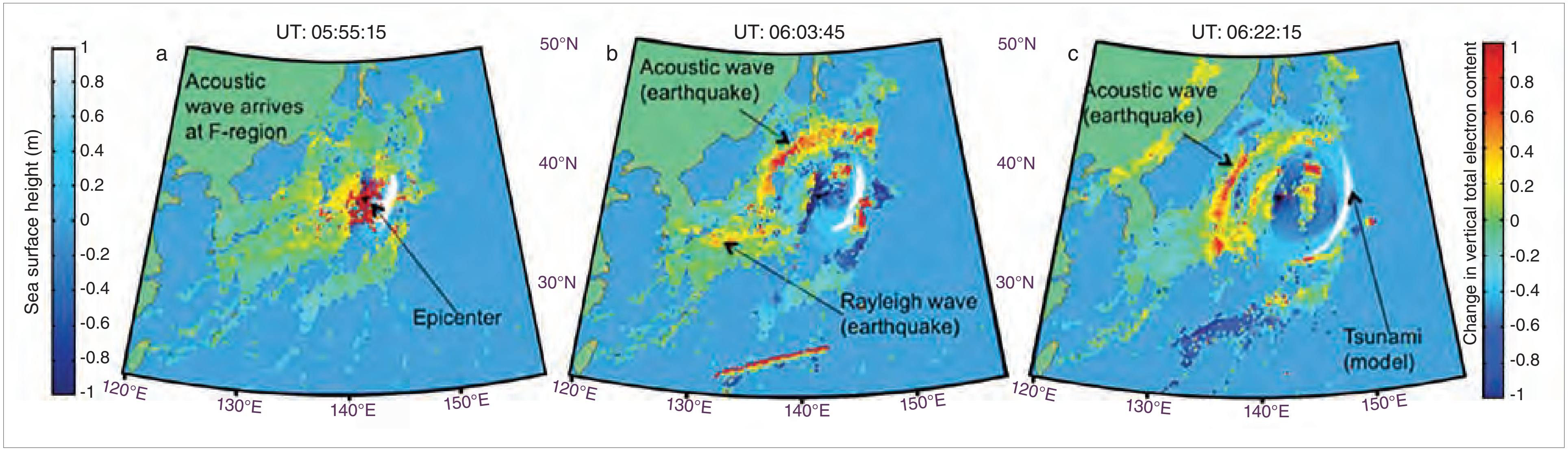
Researchers from the NASA Jet Propulsion Laboratory test Global Positioning System (GPS) receivers in California. (Courtesy M. Tule/NASA JPL)

"We are taking advantage of the fact that earthquakes generate surface waves, or what are known technically as Rayleigh waves," Komjathy said. A Rayleigh wave is one of the many seismic waves produced by an earthquake. It is an undulating wave that travels on Earth's solid surface.

When the Tohoku earthquake began under the seafloor, it caused Rayleigh waves that reached northeastern Japan's coastal regions; the Rayleigh waves also triggered waves undetectable to the naked eye.

Detection in the ionosphere

"When the ground shakes, it causes tiny atmospheric waves that can propagate right up to the ionosphere," Komjathy said. The ionosphere



Data from Global Positioning System (GPS) satellites are a powerful tool for imaging earthquakes and tsunamis. Ground-based GPS ionospheric data show earthquake-generated (b) Rayleigh, (a and b) acoustic, and (c) gravity waves in the ionosphere. (Courtesy D. A. Galvan, et al., 2011, *Radio Science*)

is the layer of Earth's atmosphere ionized by solar and cosmic radiation and is located roughly between 50 and 600 miles (80 and 1,000 kilometers) above Earth's surface.

When the atmospheric waves reach the ionosphere, they cause detectable changes to the density of electrons in that atmospheric layer. These changes can be recorded and measured when signals from global navigation satellite systems (GNSS), such as those of GPS, travel through the ionosphere.

The same satellites can also detect disturbances in the ionosphere caused by tsunamis. When a tsunami forms and moves across the ocean, the crests and troughs of its waves compress and extend the air above them, creating motions in the atmosphere known as gravity waves. These undulations of gravity waves are amplified as they travel upward into an atmosphere that becomes thinner with altitude. When they reach the ionosphere, the gravity waves also can be detected using the constellations of GNSS satellites circling Earth.

Real-time warnings

Komjathy and his colleagues have taken the GPS data from the Tohoku earthquake and tsunami, as well as from other earthquake and tsunami events, and developed a new approach to assist in the ongoing development of timely tsunami detection systems. "The goal is to detect tsunamis and warn the coastal communities in real time," Komjathy said. Komjathy's group relies on GPS data archived by the NASA Crustal Dynamics Data Information System, among other sources, for their project.

The new approach, called Variometric Approach for Real-time Ionosphere Observation, or VARION, was designed under the leadership of Mattia Crespi of Sapienza University in Rome, Italy. The main author of the algorithm is Giorgio Savastano, a doctoral student in geodesy and geomatics at Sapienza and an affiliate researcher at JPL, which conducted further development and validation of the algorithm.

VARION can be incorporated with tsunami detection systems that use data from a variety of sources, including seismometers, buoys, GNSS receivers, and ocean bottom pressure sensors. Once an earthquake is detected in a location, the system could begin processing real-time measurements of the distribution of electrons in the ionosphere from multiple ground stations near the quake's epicenter, searching for changes that may be correlated with the expected formation of a tsunami.

The researchers are incorporating the algorithm into JPL's Global Differential GPS System, which will provide real-time access to data from about 230 GNSS stations around the world that collect data from multiple GNSS constellations. Since large tsunamis like the Tohoku event of 2011 are infrequent, testing VARION using a variety of real-time data will help validate the algorithm.

However, Komjathy said they need access to more real-time GPS data streams, specifically from countries located in the Pacific Ring of Fire, a string of volcanoes and hot spots of seismic activity around the edges of the Pacific Ocean. “Some countries in this area are not always very keen on sharing data,” Komjathy said. “We need real-time access to data. Otherwise we cannot really process a global network of GPS stations.”

The researchers are currently working with the United Nations Development Program and its Environment Program to facilitate cooperation with countries in the Ring of Fire region. “It’s going to be an incremental improvement to the data coverage and we know this is not going to happen overnight,” Komjathy said. “We just need to convince the affected nations that this is for humanity’s benefit, and we are moving in that direction.”

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/warnings-from-the-ionosphere.

About the remote sensing data

Satellite	Global Navigation Satellite Systems (GNSS)
Sensor	Global Positioning System (GPS)
Data set	GNSS Daily 30-second data
Temporal resolution	1 second to <1 minute
Parameter	Geospatial positioning
DAAC	NASA Crustal Dynamics Data Information System (CDDIS)

About the scientist

Attila Komjathy is group leader and principal investigator of the Ionospheric and Atmospheric Remote Sensing Group at the NASA Jet Propulsion Laboratory. His research interests focus on various sensors to study the temporal and spatial variations of terrestrial and planetary ionospheres including the coupling between solid surface, thermosphere and ionosphere. NASA supported his research. Read more at https://goo.gl/W7k2CG. (Photograph courtesy A. Komjathy)

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For more information

NASA Crustal Dynamics Data Information System (CDDIS)
https://cddis.nasa.gov

CDDIS Global Navigation Satellite Systems Data and Product Archives
https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/GNSS_data_and_product_archive.html

From Indonesia to India

“It’s a way that the Pacific Ocean can communicate with the Indian Ocean.”

Jim Potemra
University of Hawaii

By Jane Beitler

In Indonesia, it is monsoon season. Water parachutes down from tropical clouds to start its journey toward the sea. Rain pours from the sky in slabs of water that slap the sandy ground of the Indonesian Archipelago. Water rolls off the palm fronds and rocks and saturated soil of the islands of Sumatra, Java, and Borneo, flowing into streams and bays and then out into the Java Sea. The fresh water will ultimately mingle into the crowd of salt water, but during the monsoon, enough of it sweetens a plume that spreads out on the Indian Ocean surface. And in turn, rain-freshened waters flow into the straits in Indonesia from the Pacific Ocean to the Indian Ocean.

Rain and fresh water are ingredients in the ocean’s everyday water cycle, but the oceans are a pot that is never completely stirred. Waters are constantly moving and mixing. Like the patterns of pressure and temperature in the atmosphere

The sun rises over a fishing platform in Kepulauan Seribu (Thousand Islands) in the Java Sea. (Courtesy buitenzorger/flickr) that create weather conditions, oceans are busy exchanging heat and fresh water to create a water climate. Fresh water floats near the surface, lighter than the cold, salty water that sinks, especially near the North and South Poles, causing both vertical circulation and a conveyor belt-like circulation of salty and cold water around the globe. The ocean trades its heat with the atmosphere too, helping stabilize the climate patterns that shape our world.

For researchers such as Jim Potemra, who study how oceans circulate and mix near the surface, a new global sea surface salinity-sensing satellite promised a broader, yet closer look at these processes. Still, scientists did not know exactly what the new satellite data might pick up. "When we started gridding the data, we said, let's have a look at regions where we don't have a good idea of the surface fluxes. The signal that was coming out of the Indonesian Seas was a little surprising," Potemra said. It was evidence of a feature that they had mostly imagined.

Fresher water meets saltier water

Potemra and his colleagues had some data that told them about a low-salinity plume coming out of Indonesia's Sunda Strait, which lies between the Indonesian islands of Java and Sumatra and connects the Java Sea to the Indian Ocean. It is as narrow as 15 miles, punctuated at its wider southwest end by a group of small islands, most famously home to Krakatoa Volcano, which exploded in 1883 with the force of 13,000 nuclear bombs.

The researchers had speculated that the fresh water comes not only from the adjoining islands, but also from northern areas. Until now, they had no data to verify its origins. But there in the new data from NASA Aquarius, a space-based instrument to study sea surface salinity, were the northern beginnings of the fresher plume.

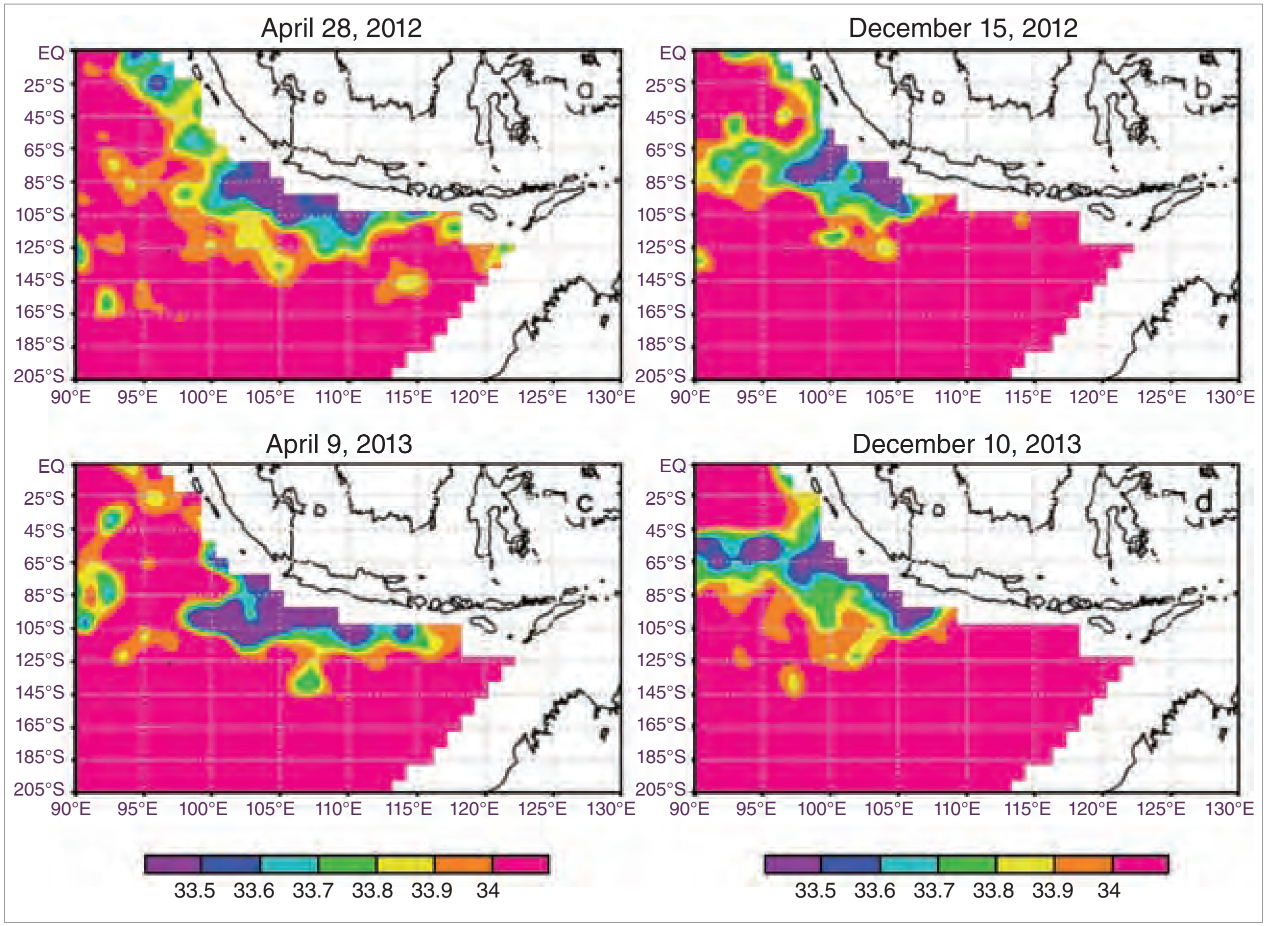
Adding rain and runoff is not like turning on a blender. In the tropics, the less dense fresh water may linger on top of the saltier surface a while. Winds and currents transport this fresher layer out to sea, where it eventually disperses and mixes. Before it disappears, this burst of freshness may leave its fingerprints on local conditions. "It could be a part of local exchanges, such as air-sea flux, or controlling local rainfall patterns," Potemra said. Could it also be part of a larger weather or climate pattern, such as El Niño phases?

In the Java Sea, fresh water from rain runoff slips through several straits, carried along a pathway between the Indian and Pacific Oceans known as the Indonesian Throughflow. It is here in the equatorial Indian and Pacific that the weather pattern called El Niño Southern Oscillation (ENSO) is born, as either the warm phase nicknamed El Niño, characterized by warmer surface waters, or its cooler sister La Niña. These ENSO phases bring wetter or drier years to Indonesia and Australia, and more or fewer cyclones and rain to the tropical Pacific, and extend wet or dry conditions across North and South America and beyond.

But what kicks off an ENSO phase? Models have some skill in forecasting ENSO based on surface temperatures and other variables, but sometimes a phase can fizzle instead of forming. Recently, researchers have noted salinity changes accompanying El Niño and La Niña, leading them to dig further into the relationship between sea surface salinity and ENSO. Could salinity help trigger these changes by influencing vertical exchange of cold and warm waters, or could changes in salinity mark the turn? What they saw suggested that it could be either or both. This was one of several compelling questions that prompted NASA to launch Aquarius.


Looking past volcanic rocks, Sebesi Island is seen from Umang-umang Island, across the Sunda Strait. Umang-umang is an uninhabited island located in the Sunda Strait, near Krakatoa. Umang-umang means hermit crab in Indonesian. (Courtesy buitenzorger/flickr)

Before satellite data became available, researchers had to build computer models to simulate and study these forces on a global scale, and buoys scattered about key locations as well as autonomous floats broadly distributed over the open ocean provided local measurements to feed the models. Potemra's colleague at the University of Hawaii, Peter Hacker said, "Jim had been doing



This image of the Indian Ocean, near the Sunda Strait, shows snapshots of sea surface salinity, in practical salinity units (psu), from the NASA Aquarius instrument. Purples, blues, and greens indicate lower surface salinity. (Courtesy J. Potemra, et al., 2016, *Journal of Geophysical Research: Oceans*)

numerical modeling on the South China Sea and Indonesia. That's how our study got started." But the buoys and floats are sparse and nearsighted, while the models are farsighted and cannot see many details.

A global look at the ocean surface

Aquarius promised to help them see in between. "Aquarius was going to provide salinity coverage on a scale we've never had, every 10 kilometers [6 miles], with 100 kilometers [62 miles] of spatial averaging for each measurement. It is a bit like having three very fast ships driving parallel to each other across the whole globe, day after day after day," Hacker said. Aquarius carried three radiometers that measured the subtle differences in levels of microwave emissions due to the salts in the waters. Aquarius team members Oleg Melnichenko and Nikolai Maximenko, together with Hacker and Potemra's colleagues at the University of Hawaii, turned these emission readings into high-resolution sea surface salinity maps.

Digging through imagery, their eyes were drawn to bursts of fresh water passing through the Sunda Strait, between the islands of Sumatra and Java, and into the Indian Ocean. "It's the only low latitude connection between ocean basins. It's a way that the Pacific Ocean can communicate with the Indian Ocean, and it's important because the dynamics of salinity are different at the equator than at the poles," Potemra said. Rather than causing deep vertical ocean circulation, as in polar oceans, contrasts in salinity in the tropics may have quicker and more local effects, helping identify highly productive fishing spots, for example.

Patches of fresh water had been identified in that area of the Indian Ocean, but many researchers thought heavy rains caused them. With the Aquarius data, the freshwater injections through the strait began to emerge in detail. Once out to sea, the bursts of fresh water could be seen to travel west, or south, or stay close to the strait, depending on the season and currents. Wind patterns around the islands create changes in sea level that help force the fresh waters through the strait, particularly during the Southeast Monsoon.

The data showed that the Sunda Strait was fresher during the 2011 El Niño, adding evidence of a link between ENSO and salinity. While this plume of fresh water would not have been the main trigger for the 2011 El Niño, it highlights the need to understand smaller scale processes better. Adding this knowledge to the complex models that help forecast ENSO patterns could increase forecast reliability. Better models could eventually trickle down to help people facing wet and dry years due to ENSO around the world make better preparations.

Near the shore

The Aquarius mission collected data from 2011 to 2015, when its satellite platform stopped operating. A European satellite, the Soil Moisture and Ocean Salinity (SMOS) mission, continues the job of sensing salinity, while other Earth observing satellites have joined the effort. The NASA Soil Moisture Active Passive (SMAP) mission, though designed to measure soil moisture, carries an instrument that also may be used to measure sea surface salinity.

While the new abundance of salinity data is promising, this study revealed the utility of remotely sensing salinity in small features like the Sunda Strait that are typically under-sampled by traditional methods. “It’s an important issue in studying the Indonesian Throughflow, where there are a lot of islands causing a problem for the satellite,” Hacker said. “Often these freshwater plumes are close to shore.” The satellite data are masked out near the shore to ensure that the land does not contaminate the signal. “How do we get to the area that’s masked out?” Potemra said. “Looking at the raw data, we could see there were some issues.” The NASA SMAP satellite is providing an advantage over Aquarius by enabling satellite salinity measurements closer to the coast.

For Hacker, Potemra, and others, finding their way in a new data set is a fun problem to have. “Doing any kind of science that has new observations is really exciting,” Hacker said. “It’s like walking through a forest you’ve never been through before. That’s what’s so interesting about Aquarius.”

About the remote sensing data

Satellite	Satélite de Aplicaciones Científicas (SAC-D)
Sensor	Aquarius
Data set	Aquarius Official Release Level 2 Sea Surface Salinity Version 4
Resolution	96 kilometer (Along) x 390 kilometer (Across)
Parameter	Salinity
DAAC	NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)

About the scientists

Peter Hacker is a retired scientist who worked at the Hawaii Institute of Geophysics and Planetology, at the University of Hawaii. His research interests include physical oceanography, upper ocean processes, air-sea interaction, and ocean circulation and mixing. NASA and the National Oceanic and Atmospheric Administration supported his research. Read more at https://goo.gl/dfyWRp. (Photograph courtesy University of Hawaii)

James Potemra is manager of the Asia-Pacific Data-Research Center at the University of Hawaii. His research interests include general ocean circulation and its relationship to climate, and processes in the western equatorial Pacific and eastern Indian Ocean. NASA and the National Oceanic and Atmospheric Administration supported his research. Read more at https://goo.gl/WeMtQt. (Photograph courtesy University of Hawaii)

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NASA Aquarius
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NASA Soil Moisture Active Passive (SMAP)
https://smap.jpl.nasa.gov

A spread of green

> “As climate change progresses, it will play a bigger role.”
>
> Nikolay Shiklomanov
> George Washington University

by Laura Naranjo

The snowy reaches of Siberia sprawl across northern Russia, spanning three-quarters of the country. Dense forests of coniferous trees rise from the cold and swampy terrain of sub-Arctic taiga. Further north, the towering woodlands give way to Arctic tundra: frigid open country encrusted with moss and lichen. Dominated by these two biomes, Siberia remained sparsely populated for centuries. By the 20th century, however, rich reserves of oil and minerals were discovered, and Russians eagerly streamed north to fill jobs. The flood of people and industry changed Siberia’s fate, turning quiet settlements first into boomtowns, then into bustling cities.

When oil was discovered in northern West Siberia, Russia wasted no time developing the new oil fields. The small fishing settlement of

These buildings in Anadyr, Russia, are built on foundation piles to prevent heat from thawing the frozen ground below. (Courtesy US Consulate Vladivostok)

Surgut was one of the remote outposts dotting the region. Located on the banks of the Ob River, Surgut's population surged, and it was granted town status in 1965. By 2015 Surgut had become the unofficial oil capital of the country, home to 340,000 people. Modern Surgut now offers theaters and shopping malls, tree-lined streets and parks. And like Russia's other booming cities, Surgut leaves a growing footprint on its environment.

Igor Esau and Victoria Miles, researchers at the Nansen Environmental and Remote Sensing Center in Norway, saw the oil and gas boom as an opportunity to study these footprints. They and their colleagues looked at 28 cities and towns across northern West Siberia as well as at the surrounding natural landscapes. How did urban development affect Arctic vegetation over time? And how might accelerated Arctic warming amplify these changes?

Biomes of green and brown

The key to understanding how cities impact taiga and tundra landscapes is permafrost, permanently frozen ground. In the northernmost stretches of Siberian tundra, permafrost is continuous, meaning most of the region's ground remains frozen. Arctic tundra is usually treeless, populated by low-lying vegetation that can survive the gelid habitat and short growing seasons. In contrast, the discontinuous permafrost found across southern Siberia exists only in portions or in sporadic areas, making the region more hospitable to swampy taiga forests.

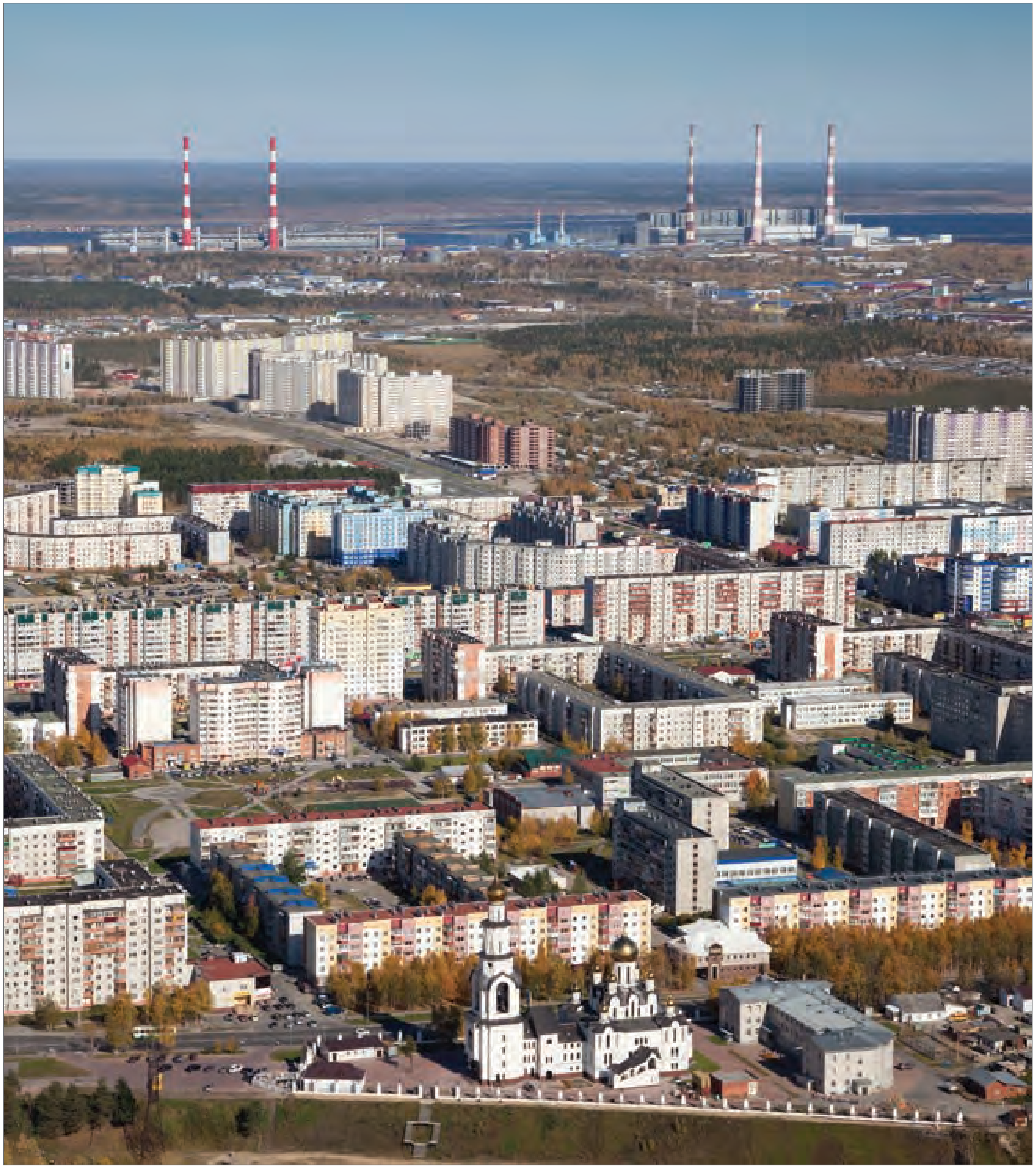
Reindeer scamper across the treeless Arctic tundra, left. Swampy forests, or taiga, are common across sub-Arctic Russia, right. (Courtesy V. Sagaydashin, left, and I. I. Savin, right)

Overlying many permafrost areas is a thin active layer that thaws seasonally, allowing plants and trees to grow. Larch trees thrive in permafrost regions because their root systems are broad instead of deep, thus remaining in the active layer. Whether continuous or discontinuous, permafrost requires low temperatures to remain stable, and anything built atop it—roads, pipelines, or cities—can disturb this stability.

As cities grow, natural vegetation is replaced by clusters of roads and buildings. Man-made landscapes of impervious surfaces and drier urban soils tend to absorb heat, meaning many cities become urban heat islands that are warmer than surrounding areas. In temperate climates, urban heat islands warm the air, making sweltering summer heat even more oppressive. In the Arctic, heat islands also warm the soil, which may thaw the underlying permafrost and have far-reaching effects on tundra and taiga landscapes. Modern Surgut, for instance, is only 50 years old, but is already warming. "Surgut is now about 10 degrees Celsius [18 degrees Fahrenheit] above normal, which means that ecosystems around the city have a climate that could otherwise only be found 600 kilometers [373 miles] to the south," Esau said. Even small settlements and industrial areas are 1 to 2 degrees Celsius (2 to 4 degrees Fahrenheit) warmer, particularly during long polar summer days.

Researchers needed vegetation data to map the heat island effect relative to the surrounding Arctic environments. Because meteorological stations are sparse at such high latitudes, the researchers relied on the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument flying on the NASA Terra satellite. MODIS data from 2000 to 2014 offered a detailed view of greenness, or vegetation health, across Siberia. Changes in greenness provide a proxy for each city's footprint. To measure this footprint, the researchers included a 40-kilometer (25-mile) ring around each city, broken into concentric, 5-kilometer (3-mile) rings centered around the city core.

Over the 15-year period, the data showed a trend of warmth creeping north. Taiga in the southern portions of West Siberia warmed, causing trees



to die and turn brown. By contrast, the northern tundra became greener. Shrubs and grasses filtered in, and even larch trees were popping up in the typically treeless tundra. Siberian larch, a staple of taiga forests, require long cold winters, so a northward shift heralded broader change. Miles said, "This sparse larch forest now occupies a big area on the North Siberian Plain, on the border between the tundra and the boreal forest."

Booming and blooming

Amid these sweeping shifts, Esau and his colleagues discovered that all of the cities and their surrounding 40-kilometer rings had become greener. "We were really puzzled about this development. It was unexpected," Esau said. The older and more established a city was, the greener it appeared over the 15-year record. Northern tundra and northern cities alike were greening. And greening cities like Surgut, located in the taiga, stood out amid swaths of brown.

The construction boom included not just buildings, but pleasant and environmentally welcoming spaces, such as parks and tree-lined streets. "This increased greenness of the cities was very much because of change in the attitude toward the environment," Esau said. "Now practically every city in this region implements one or another kind of green space development program."

Residents use these parks and green spaces year-round, according to Natasha Rubanova, who grew up in Surgut, though she now lives in Massachusetts. "There is roller skating, jogging, cycling, walking dogs, taking kids to

After a massive oil and gas development boom in northern West Siberia, Surgut has grown to become the oil capital of Russia. (Courtesy V. Melnikov, Shutterstock) playgrounds. Some people even sun bathe," she said. Throughout the short summers, the city also uses parks for festivals and celebrations.

Similar to other cities elsewhere around the world, people in Siberia are shaping their own environment, carving a human habitat and sense of home out of an otherwise harsh landscape. But the heat island effect does not stop at city limits. Changes in vegetation slowly bleed outward, leaving a larger stamp on the landscape. While increasing greenness itself did not cause the heat island effect, it pinpointed where dramatic changes were happening. The real cause of the Arctic's urban heat islands lay a bit deeper: the permafrost they were built on.

Extracting an ecosystem

Construction on Arctic permafrost poses unique problems because the active layer's freeze-thaw cycle creates an unstable surface. "To build something there, you need to create some higher ground, otherwise, it's always boggy and muddy there," Esau said. So developers extract sand and gravel from river beds to create a base layer. Then, foundation piles are driven into the permafrost, sometimes more than 15 meters (49 feet) deep, which bear the weight of the building. Buildings are then perched atop the stilt-like piles, insulating frozen ground from heat generated in the buildings.

"But sand has a different thermal property than the normal soil found in this area," Esau said. Unlike permafrost, which is impermeable, sand allows water to drain through. Sandy surfaces are drier and warmer than the frozen ground beneath, and contribute to the urban heat island effect. "This effect is larger than the city itself, because sandy and artificial surfaces destroy natural vegetation patches," Esau said. "The effects proliferate around an area larger than the buildings themselves."

Siberian larch are deciduous conifers, dropping their needles each winter. Larch forests are spreading further north into the Siberian tundra. (Courtesy A. Salo)

As the researchers zoomed out from the city center, they saw shifts to what Esau calls alternative ecosystems. Shrubs and grasses were infiltrating the low-lying tundra, but in taiga forests, dying native vegetation was not always replaced by other species moving in. Thawing permafrost leaves behind a water-logged environment that not many plants are adapted to survive in. "More than 30 percent of the territory is bogs, swamps, mires," Esau said.

Islands in a regime

Even as the effects of urban heat islands radiate to the surrounding environment, cities themselves feel the effects. In a few Arctic cities, some foundations are cracking and buildings are crumbling, ultimately forcing residents to move. But rising temperatures are not entirely to blame, according to Nikolay Shiklomanov, a professor at George Washington University who studies Arctic climate change and urban infrastructure. Each city is a complex system, making it difficult to predict how buildings, roads, and utilities collectively impact the sensitive thermal regime of permafrost. "That's really difficult to model or

This map shows trends in vegetation (Normalized Difference Vegetation Index, NDVI) in West Siberia between 2000 and 2014. Greens indicate increasing greening; browns indicate browning. The southern portion of northern West Siberia browned as forested taiga biomes became stressed by rising temperatures. The northern portion warmed and greened, with small shrubs, grasses, and even larch trees spreading north into the tundra. Data are from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the NASA Terra satellite. (Courtesy I. Esau, et al., 2016, *Atmospheric Chemistry and Physics*)

test at the scale of the city," he said. "When you sprinkle people on top of that, their activities make interactions between an urban system and permafrost much more complex. For example, plowing roads can mess with the ground temperature field."

In addition, construction on permafrost tends to have a shorter life span, and Russia's Arctic settlements grapple with aging infrastructure and lack of maintenance, often a result of the economic malaise following the 1991 dissolution of the Soviet Union. "While climate-induced permafrost changes have some impact, a good deal of these deformations were probably initiated by human factors," Shiklomanov said. For instance, leaking pipes or even substandard construction can promote permafrost thaw. "During the Soviet time, there were strict standards of permafrost construction," Shiklomanov said. "Now standards largely are up to individual builders."

Shiklomanov looked at data stretching back through the 20th century, isolating Arctic climate changes across Siberia. He and his colleagues then looked into the future, compiling results from six different climate models to analyze the weight-bearing capacity of the cities' pile foundations. As temperatures increase, the bearing capacity of piles decreases significantly because they were designed for certain temperatures and can be negatively affected by warming. By 2050, buildings in many Siberian cities may begin to crumble or fall apart as the underlying permafrost degrades and piles give way.

Evidence indicates the Arctic will only continue to warm. "As climate change progresses, it will play a bigger role," Shiklomanov said. "So right now, while it's not the primary reason for deterioration of urban infrastructure, it definitely made things worse. As warming progresses, it has the potential to become a prime reason for decreased stability of structures on permafrost." This means rising temperatures can potentially impact many of the 40 million people who consider Siberia home. Will engineers and urban planners innovate ways to mitigate the heat island effect in the Arctic? Or will they adapt construction methods to accommodate a thawing environment? Siberia's fate has changed in the past, and its future is not set in stone—or permafrost.

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/a-spread-of-green.

About the remote sensing data

Satellite	Terra
Sensor	Moderate Resolution Imaging Spectroradiometer (MODIS)
Data set	Vegetation Indices 16-Day L3 Global 250m (MOD13Q1)
Resolution	250 meter
Parameter	Normalized Difference Vegetation Index (NDVI)
DAAC	NASA Land Processes Distributed Active Archive Center (LP DAAC)

About the scientists

Igor Esau is a research director for the Climate Processes Group at the Nansen Environmental and Remote Sensing Center (NERSC) and an adjunct professor at University in Bergen, Norway. He studies the planetary boundary layer, ecosystems, Arctic climate trends, and anthropogenic effects. The Belmont Forum, the Norwegian Research Council, and the Bjerknes Centre for Climate Research supported his research. Read more at https://goo.gl/S5ZwDe. (Photograph courtesy NERSC)

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Nikolay Shiklomanov is an associate professor in the Department of Geography at George Washington University. He studies the Arctic environment, climate variability and change, and socioeconomic problems associated with development in Arctic regions. The National Science Foundation and the Russian Science Foundation supported his research. Read more at https://goo.gl/3kAZHx. (Photograph courtesy George Washington University)

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For more information

NASA Land Processes Distributed Active Archive Center (LP DAAC)
https://lpdaac.usgs.gov
NASA Moderate Resolution Imaging Spectroradiometer (MODIS)
https://modis.gsfc.nasa.gov
Anthropogenic Heat Islands in the Arctic (HIARC)
http://hiarc.nersc.no

About the NASA Earth Observing System DAACs

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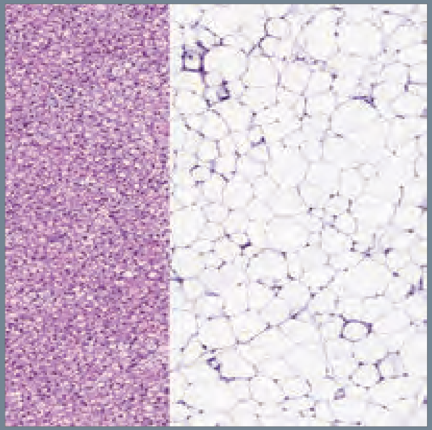

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