National Aeronautics and Space Administration

# Sensing Our Planet

## NASA Earth Science Research Features *2013*

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

www.nasa.gov

## Front cover images

### Top row, left to right:

Retirees perform tai chi during a smoggy day in Fuyang, China in January 2013. See the related article, “Crazy bad air,” on page 38. (Courtesy ImagineChina)

The Atchafalaya River delta meets the Gulf of Mexico. The view is upriver to the northwest. See the related article, “A tale of two rivers,” on page 34. (Courtesy A. Belala/U.S. Army Corps of Engineers)

A tsunami strikes northeast Japan after the 2011 Tohoku Earthquake, generating waves up to 133 feet high along some areas of the coast. Although the Japan Meteorological Agency issued a warning, the tsunami was responsible for more deaths and more damage than the earthquake itself. See the related article, “Sizing a tsunami,” on page 30. (Courtesy S. Tomizawa)

Sensors sniff out the comings and goings of carbon dioxide at the Missouri Ozarks AmeriFlux site. See the related article, “The secrets of leaves,” on page 26. (Courtesy M. Burden, University of Missouri)

### Bottom row, left to right:

Long-spined sea urchins nest on a depleted kelp bed off the coast of eastern Tasmania. Lush sea kelp forests turn into barren fields of rock once the sea urchins take over. See the related article, “Pedestrians of Eddy Avenue,” on page 14. (Courtesy S. Ling)

Ice re-grows in a lead between two sea ice floes in the Beaufort Sea, Arctic Ocean, in March 2013. See the related article, “Signs of snow,” on page 22. (Courtesy S. L. Farrell)

Thermophilic bacteria give Grand Prismatic Spring in Yellowstone National Park its many hues. See the related article, “Not so big, not so hot,” on page 2. (Courtesy A. Mancia)

## Back cover images

### Top row, left to right:

High, wispy cirrus clouds stream over Big Bend National Park in Texas, USA. Many of the cirrus shown here have been pulled by the wind in such a way that they resemble horses’ tails. See the related article, “Making heads of mares’ tails,” on page 18. (Courtesy M. H. Whitten)

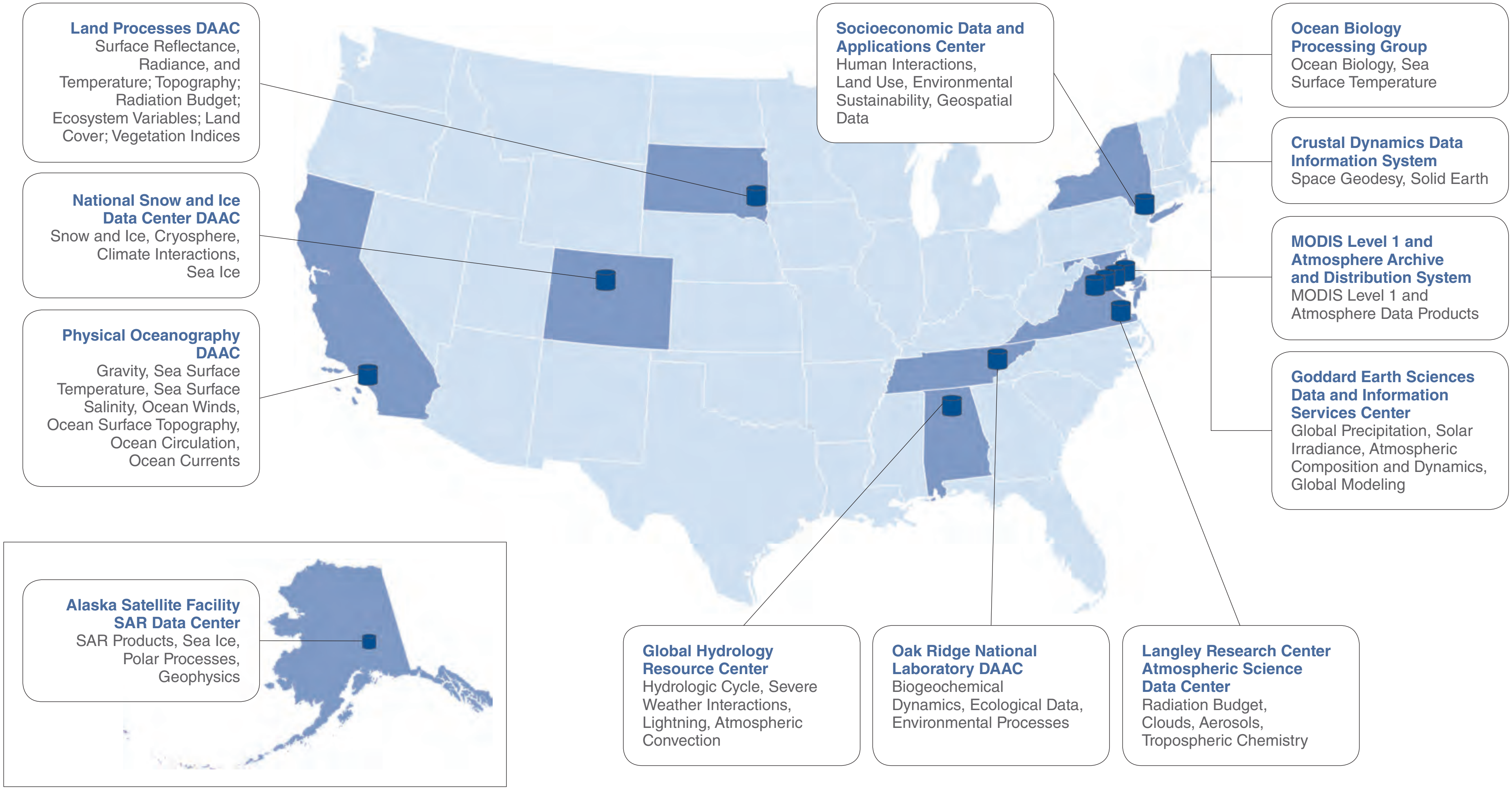
This false-color satellite image shows sea ice in the Chukchi and Beaufort seas (red) near Barrow, Alaska. Dark areas indicate cracks, or leads, in the sea ice while gray streaks show vapor plumes upwelling from the leads. Red-orange shades indicate snow cover. The image was created with data acquired by the MODIS Terra satellite on March 24, 2012. See the related article, “Mercury raining,” on page 42. (Courtesy NASA, Nghiem et al. 2013)

### Bottom row, left to right:

The strong La Niña in 2010 and 2011 produced torrential rain that inundated many low-lying areas around the globe. Floodwaters completely engulfed this house in Bangkok, Thailand. See the related article, “When oceans drop,” on page 10. (Courtesy R. J. Maurer, U.S. Marine Corps)

Contrails, or condensation trails, form when water vapor from airline exhaust condenses and freezes, forming clouds made of ice crystals. Scientists study contrails because, like naturally occurring clouds, they may contribute to a warming or cooling effect in Earth’s atmosphere. See the related article, “On the trail of contrails,” on page 48. (Courtesy J. Thomissen)

Rime frost covers both ends of a capped column snowflake, captured at 300 micrometers under an electron microscope. See the related article, “Cold, symmetric, and cryptic,” on page 6. (Courtesy P. Erbe, U.S. Department of Agriculture, Agricultural Research Service, Electron Microscopy Unit)



## About the EOSDIS Distributed Active Archive Centers (DAACs)

The articles in this issue arose from research that used data from 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 5,000 Earth system science data products and associated services to a wide community of users. ESDIS develops and operates EOSDIS, a distributed system of data centers 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 52)

NASA Earth Data Web site
http://earthdata.nasa.gov

NASA Earth Science Web site
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 2013* are available online at the NASA Earth Data Web site (http://earthdata.nasa.gov/sensing-our-planet). A PDF of the full publication is also available on the site.

For additional print copies of this publication, please e-mail nsidc@nsidc.org.

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

The design featured in this issue represents clouds. Several stories for 2013 spotlight how satellite and ground observations can help researchers understand how clouds and particles in Earth's atmosphere affect the planet's energy budget and air quality. See "Cold, symmetric, and cryptic," page 6; "Making heads of mares' tails," page 18; "Crazy bad air," page 38; "Mercury raining," page 42; and "On the trail of contrails," page 48.

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## Acknowledgements

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We especially thank our featured investigators for their time and assistance.

## Writing, editing, and design

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# Sensing Our Planet

## NASA Earth Science Research Features *2013*

# Not so big, not so hot

> “Thermal anomalies often precede eruptions, but it is usually after the fact that we realize this.”
>
> Greg Vaughan
> U.S. Geological Survey

by Jane Beitler

Yellowstone National Park puts on a thrilling show. Geysers steam and spout, steam vents hiss, mudpots spew, and hot springs color their waters with intense yellows, blues, oranges, and greens. Visitors soon learn they are standing on a volcano that has not erupted for about 70,000 years, but still could.

Preventing volcanoes from erupting is beyond human control, but scientists can monitor for the signs of a coming eruption. Changes in heat may be one of those signs. “Yellowstone is one of the places where Earth is letting out a lot of its internal heat,” said Greg Vaughan, a U.S. Geological Survey researcher who has studied Yellowstone. All of this hot action on the surface can be read as a report on the restless lava and pressures far below ground.

## An eye to the surface

People like to talk about the potential for a massive eruption at Yellowstone, wiping out the


Thermophilic bacteria give Grand Prismatic Spring in Yellowstone National Park its many hues. (Courtesy A. Mancia)

park and large areas of the three states it straddles, but scientists say that is unlikely. "There have been some very big eruptions there in the past, but many more that were not as big. If there were ever to be another eruption in Yellowstone, it is more likely to be one of those not-so-super eruptions," Vaughan said.

Yellowstone, like some other active volcanoes, is monitored by a group of scientists who watch for signals that precede eruptions. They use ground instruments to monitor Yellowstone's 1,000 to 3,000 annual earthquakes, and both ground and satellite observations to spot bulges or subsidence on the surface that indicate magma or hot fluids moving underground, like gophers burrowing under your lawn.

Thermal features like Old Faithful's clockwork eruptions also hint of the hot magma that causes groundwater to spout boiling plumes into the air. Yet most of Yellowstone's thermal features are less consistent or stable than Old Faithful. "The National Park Service monitors these features and how they change," Vaughan said. "They disappear and move around. New ones pop up where they have never been before. The Park Service needs to understand how this ever-changing thermal activity affects visitor safety, and park infrastructure—for example, if they are going to build a new road."

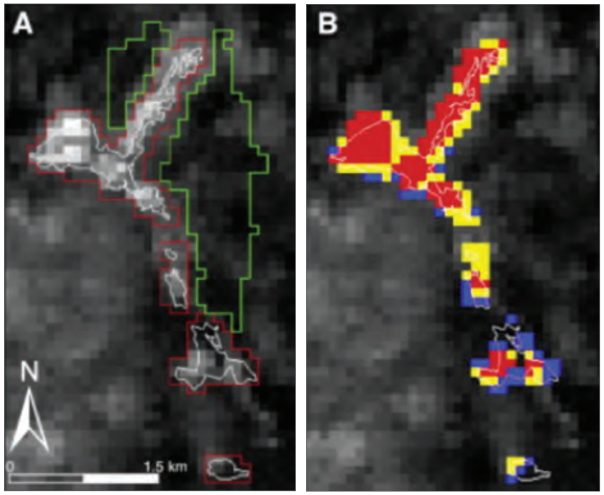
Vaughan is interested in what changes in thermal activity can say about volcanoes. "Thermal anomalies often precede eruptions, but it is usually after the fact that we realize this," he said. While the park has placed sensors at some locations, it is impossible to monitor on foot Yellowstone's more than 10,000 geothermal features spread over 3,472 square miles. Most volcanoes in the world are not monitored, nor do they sit within a popular park. They may have limited or no instrument networks to alert scientists of their growing wrath. "For a lot of volcanoes, a satellite image might be the first indication of an eruption," Vaughan said.


A rainbow stretches over Castle Geyser in the early evening. (Courtesy C. Tidball)

## Heat and space

Thermal infrared satellite images have long been used to detect volcanoes erupting in remote, unmonitored locations. When Redoubt Volcano in the Aleutian Islands erupted in 2009, scientists used infrared data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument and other sensors to monitor, in near-real time, the heat that signaled the growth, collapse, and cooling of the lava dome within Redoubt's crater.

More recently, researchers have been looking at changes in surface heat that can be a precursor to an eruption. Rick Wessels at the Alaska Volcano Observatory said that satellite monitoring of thermal activity can be useful in cool climates, where the heat of the thermal features stands out against a cold background. "This method works when you have such a good temperature contrast," Wessels said. "It doesn't work in the tropics, where thermal activity is such a small feature on an already warm background."



The figure at left from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument shows nighttime temperature at Heart Lake Geyser Basin on January 28, 2010. The thermal areas are outlined in white; the ASTER pixel areas encompassing the thermal area are outlined in red. Non-thermal background temperature pixels are outlined in green. The figure at right shows how the thermal pixels vary from thermal background: blue pixels are average, yellow are two standard deviations greater, and red are four standard deviations greater. North is up; pixels are 90 meters resolution. (Courtesy R. G. Vaughan et al., 2012, *Journal of Volcanology and Geothermal Research*)

After the Redoubt eruption, Wessels looked back through satellite data for thermal signals before the eruption. "With Redoubt, we were able to see slight hints going on in midwinter, but we didn't catch it at the time. We saw it later, going back through ten months of data," he said. He retrieved data from clear winter nights, which provide the best thermal contrast, from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra satellite, distributed by the Land Processes Distributed Active Archive Center. ASTER picked up subtle anomalies in the surface temperature of Redoubt's crater a few months before the eruption.

## Hot and cold

Thermal monitoring is one more way to spot volcanoes that need watching, and to refine eruption predictions. Wessels said, "Most volcanoes give us a few weeks warning. We've successfully forecast pending eruptions and have been able to get people out of the way for the last ten to fifteen years." The exact date of a coming eruption remains hard to figure, and narrowing that window would help emergency managers. "We'd like to be able to predict eruptions in the next few days rather than in the next few months," he said.

Vaughan thought that Yellowstone would make a good case study for detecting thermal precursors of an eruption. Yellowstone's high elevation, ranging from 5,000 to 11,000 feet, gives its thermal features that cool background, especially at night when the sun is not warming the surface. Still, Vaughan and his colleagues at the Park Service were looking at some relatively subtle features, at the scale of satellite imagery. Vaughan said, "Trying to detect thermal features that are not that hot, maybe just boiling, and that are small, pushes the limits of this method."

The MODIS instrument, also on the Terra satellite, crosses most of Earth twice a day, once during the day and once at night. This high frequency of data is ideal for monitoring larger features, but not for small ones like geysers. Yellowstone's thermal features range from a few centimeters to tens of meters across. MODIS thermal infrared pixels are 1,000 meters across. ASTER thermal infrared images have 90-meter pixels, but ASTER does not acquire data constantly, only on request.

Vaughan planned to use MODIS with its high frequency and coverage, but lower resolution, to measure the background temperatures of the Yellowstone area. This would give him data on normal surface temperatures in the area over the last decade. Subtracting this background from the thermal areas would help him distinguish the hot features from normal variations in temperature, caused for example by variations in snowpack, and to see more clearly where temperatures spiked from increased activity or new, unknown features. Using wintertime scenes helped increase the contrast even more. The research team was able to compare these thermal data to data from ground instruments and airborne studies.

## An eye on change

Still, Yellowstone's features were so small, their impact to even an ASTER scene was subtle, like throwing a cup of boiling water into a swimming pool of cold water. Is the park heating up, cooling down, or staying the same? The heat data confirm that Yellowstone's volcano is chugging steadily along. "Over the years we've been looking, there has not been any real change," Vaughan said. "There are variations on a smaller scale, but for the park as a whole, no detectable thermal changes. That question is really only answerable over a longer time scale." Yet the study provides a framework for monitoring changes in these subtle features, which might someday be automated to alert scientists when volcanoes stir.

More immediately, the results help Yellowstone's park managers. "ASTER has been useful for assessing and updating maps of specific thermal areas in the park," Vaughan said. "We found hot areas with ASTER that were not on the thermal area maps."

With some luck humans will enjoy the wonders of Yellowstone for many generations, and it will continue to teach scientists too. Vaughan said, "Yellowstone has the largest concentration of thermal features in the world. They are not constant; they are changing. It's important to monitor how they change, to protect resources and people."

*To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/2013/not-big-not-hot*

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## For more information

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

NASA MODIS Level 1 and Atmosphere Archive and Distribution System (MODAPS LAADS)
http://laadsweb.nascom.nasa.gov

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
http://asterweb.jpl.nasa.gov

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

## About the remote sensing data used

| | | |
|---|---|---|
| Satellites | Terra | Terra |
| Sensors | Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) | Moderate Resolution Imaging Spectroradiometer (MODIS) |
| Data sets | ASTER Level 1B thermal infrared (TIR) data:<br>AST_L1B radiometrically calibrated, geometrically corrected at-sensor radiance<br>AST09T atmospherically corrected at-surface TIR radiance<br>AST05 surface emissivity<br>AST08 surface kinetic temperature data | MOD02 Level 1B Calibrated Radiances<br>MOD03 Geolocation |
| Resolution | 90 meter | 1 kilometer |
| Parameters | Radiance | Radiance, geolocation |
| Data centers | NASA Land Processes DAAC (LP DAAC) | NASA MODIS Level 1 and Atmosphere Archive and Distribution System (MODAPS LAADS) |

ASTER emissivity data for various areas of Yellowstone were derived from the North American ASTER Land Surface Emissivity Database (NAALSED), available from the LP DAAC.

## About the scientists

R. Greg Vaughan is a research scientist at the U.S. Geological Survey (USGS) Astrogeology Science Center. His research interests include understanding the surface expression of volcanic and geothermal systems and how they change in response to volcanic, tectonic, and hydrological processes. The USGS and NASA supported his research. Read more at http://astrogeology.usgs.gov/people/greg-vaughan. (Photograph courtesy R. G. Vaughan)

Rick Wessels is a research geophysicist for the Alaska Volcano Observatory at the USGS in Anchorage. His research focuses on understanding volcano and glacier dynamics using remote sensing. The USGS, the American Recovery and Reinvestment Act, and the National Oceanic and Atmospheric Administration supported his research. (Photograph courtesy R. Wessels)

# Cold, symmetric, and cryptic

> “We are building this column of understanding of snowfall and snowfall characteristics from the top of the cloud all the way to the ground.”
>
> Patrick Gatlin
> NASA Marshall Space Flight Center

by Natasha Vizcarra

Snowflakes have intrigued many for centuries, but it has been an especially befuddling ride for remote sensing scientists. Aiming a microwave radiometer at a rainstorm gives them streams of beautiful data. Pointing it at a snowstorm sends the instrument into conniptions. “Scientists have the technology to study rain from space, but we’re forty years behind for snow,” said Gail Skofronick-Jackson, who studies remote sensing of snowfall. “Raindrops are spherical when small, or shaped like burger buns when large.” This simplicity allows satellites to recognize raindrops from 200 miles away. “Snow is trickier to detect because, as you know, it has so many shapes,” she said.

Skofronick-Jackson and about a hundred other scientists in the NASA Global Precipitation

A dog explores a park during a blizzard in the town of Abbotsford, British Columbia, Canada. (Courtesy J. Moore)

Mission Cold-season Precipitation Experiment (GCPEx) are using instruments that can, among other things, tell the difference between raindrops and snowflakes. If they succeed, the Global Precipitation Measurement satellite mission will use GCPEx data to measure snowfall worldwide, bringing crucial data to meteorologists, freshwater resource managers, and climate researchers. The big hurdle, however, is teaching it how to see snow.

## Decoding snowflakes

Scientists and snow enthusiasts have gotten closer to understanding snowflakes with every advance in technology. In 1635, mathematician René Descartes sketched snowflakes he had examined with the naked eye, noting shapes like capped columns and the rare twelve-sided snowflake. Thirty years later, philosopher Robert Hooke drew snowflakes he had observed under a microscope. American farmer Wilson Bentley rigged a microscope to a large format camera in the 1880s, amassing 5,000 images of snowflakes as a hobby until his death in 1931, and not finding any two alike.

It was Bentley who realized why identical snowflakes were hard to find. A snowflake's size and shape, Bentley thought, must be influenced by varying temperatures it travels through, from the snow cloud to the ground. Japanese physicist Ukichiro Nakaya proved this in the 1940s after photographing thousands of artificially grown snowflakes in his refrigerated laboratory in Sapporo.

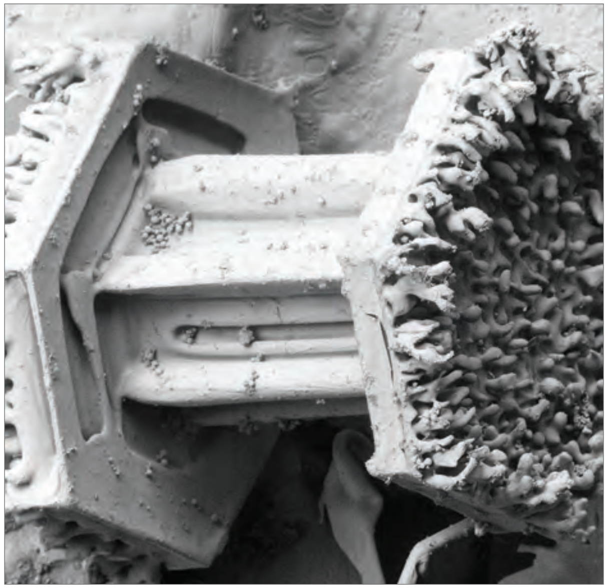
Nakaya discovered that specific conditions produced certain kinds of snowflakes. At -2 degrees Celsius, a bit below freezing, he grew thin, plate-like snowflakes. At -5 degrees Celsius he got thin, needle-like snowflakes. Cranking his apparatus to the coldest setting at -25 degrees Celsius produced thicker plate-like and columnar snowflakes. Intricate snow crystals with radiating, fern-like branches blossomed with humidity, and simple hexagons formed under dry conditions. Nakaya wrote that snowflakes were like "letters from the sky," bearing stories about the meteorological conditions they were born in.

## The whole elephant

Scientists had to wait a few more decades before they could use snowflake morphology to predict snowstorms. Today's meteorologists use weather models that rely on snowflake shapes catalogued in the 1970s. However, snowstorm forecasts remain iffy because scientists still have much to learn about snowfall, including how fast or slow different snowflakes whip about inside storm clouds or the best way to define the speed at which they fall from the sky. The sheer variety of snowflake shapes and how much water each shape holds also continue to throw off weather radars and satellite radiometers.

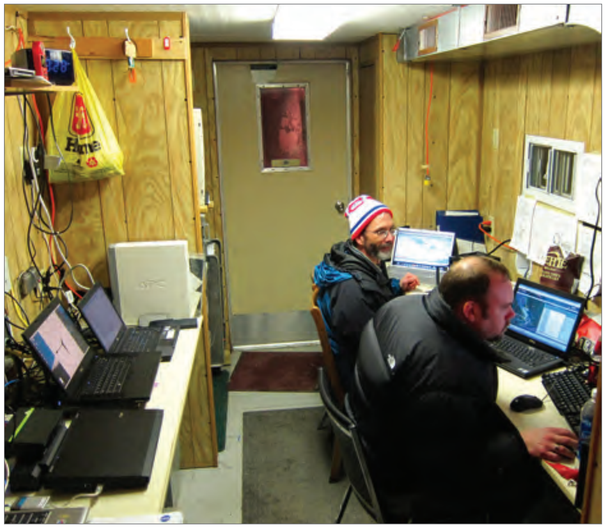
Not so with rain. Scientists sent the first weather satellites into space in the 1960s and by the 1990s had developed sophisticated sensors that measured rain and mapped out the churning innards of hurricanes. The NASA Tropical Rainfall Measuring Mission (TRMM) satellite helped atmospheric scientists improve weather forecasts and fine-tune flood and drought prediction. But because TRMM is designed for rain, it only orbits the tropics where warm equatorial waters spawn the biggest, most destructive storms.

Scientists need a satellite that would do for snowstorms, what TRMM does for rainstorms—one that scans Earth's snow-covered mountain regions and the frigid poles. "To see snow, a satellite must be specially designed for snow," Skofronick-Jackson said. To do that, scientists have to feed the satellite more data on falling snow.

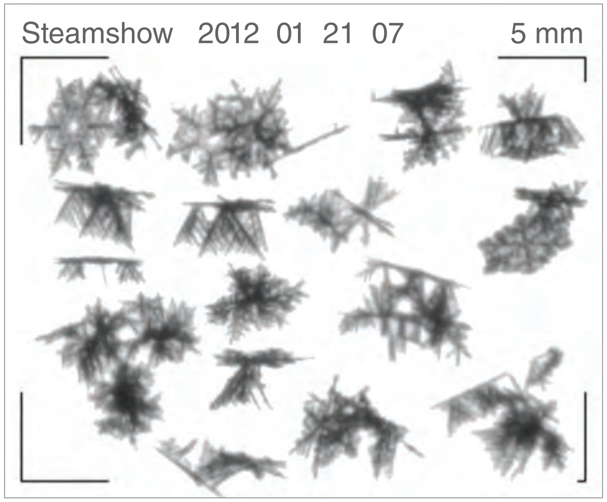


Rime frost covers both ends of a capped column snowflake, captured at 300 micrometers under an electron microscope. (Courtesy P. Erbe, U.S. Department of Agriculture, Agricultural Research Service, Electron Microscopy Unit)

So GCPEx scientists hunkered down in the Canadian countryside and aimed radars and other sensors at passing snowstorms. They launched instrument-loaded aircraft into snow clouds while a satellite simulator watched from Earth's lower stratosphere. Reminiscent of the tale of the blind men and the elephant, where blind men feel different parts of the animal to describe the whole elephant, GCPEx scientists set out to observe as many parts of a snowstorm as they could. Walter Petersen, GCPEx ground validation chief, said, "We essentially tried to follow snowflakes from the clouds to the ground."



GCPEx scientists Norm Wood (left) and Tristan L' Ecuyer monitor flights and weather in the mission operations trailer—which can be very cold at times. (Courtesy NASA/C. Kidd)



This image of falling snowflakes was taken by the Snow Video Imager (SVI) at Steamshow Fairgrounds, one of the auxiliary ground sites for the GCPEx campaign. The SVI is set up about a foot off the ground and the snowflakes fall from top to bottom through the frame. They can be seen here in different three-dimensional orientations at 5x magnification. (Courtesy NASA/L. Bliven)

## A golden storm

In Egbert, Ontario, researchers tracked storms from a cramped and barely heated trailer beginning January 17, 2012. By the tail end of the campaign, they had only sampled mild snowstorms and lake-effect storms from cold winds blowing over warmer Lake Huron. GCPEx researcher Patrick Gatlin said, “We were still waiting for that one, classic winter storm.” They wanted a synoptic storm, at least 600 miles across and churning with complexities. On February 24, they got their wish.

As the storm approached Egbert, three aircraft were already en route. The NASA DC-8 airplane flew high above the storm carrying the Airborne Precipitation Radar-2 and the Conical Scanning Millimeter-wave Imaging Radiometer, instruments similar to those that would fly in space. “The DC-8 is our proxy satellite,” Petersen said. “It collects data that will help us connect what we see from space to what is going on in the storm and on the ground.”

In the snowing clouds, the University of North Dakota’s Citation and the Canadian National Research Council’s Convair flew spirals in and under the storm and dog bone patterns along the snow band. These aircraft flew meteorological sensors and probes that measured snowflake size and water content, as well as temperature and cloud water. On land, an array of twenty instruments measured the physical aspects of the snow. How much did it weigh? How fast did it fall? What kinds of snowflake shapes were falling and how much water did they hold?

“We are building this column of understanding of snowfall and snowfall characteristics from the top of the cloud all the way to the ground,” Gatlin said. The storm was just what they needed to wrap up the campaign. “It was the golden storm,” Gatlin said. “Everything came together at once; all the aircraft flew and all the ground sensors were working and collected a lot of data.”

## Like a shaken snow globe

The researchers are on track to use the data to prep the Global Precipitation Mission (GPM) Core Observatory satellite that launches in 2014. The satellite will be the first to recognize and measure snow from space, and do so before snow lands on the ground. “That’s what’s so different about this satellite. We specifically designed it to make global measurements of snow before it hits Earth’s surface,” Skofronick-Jackson said. “Satellites have difficulties measuring snow in mountainous regions. So it’s great to be able to measure snow before you have to deal with these surface features.”

Scientists currently measure snow using snow pillows, platforms on the ground that weigh snow pack. Unfortunately, the snow pillows are sparse, and it is hard to tease out global trends from the data. There are satellites that measure snow cover worldwide but these run into problems when flying over forests. “If the snow lands on the trees or falls through the trees, that affects the satellite’s ability to measure snow,” Skofronick-Jackson said. “The same goes for snowpack that gets a heavy crust of ice on top of it from repeated melting and refreezing.”

The GPM Core Observatory, which will also measure rain, will not identify every single snowflake shape that it sees, but “in a bulk sense, will know whether they are all needles, mostly hexagonal plates, or all dendrites which are the pretty ones you normally see,” Skofronick-Jackson said. It will still take scientists several years to catch up to where rain measurement is right now. "But we are starting that process with this satellite," she said. "After the field campaign, we re-recognized that snow is a complex process, and being able to understand it and estimate falling snow from spaceborne instruments is going to be a process for several generations of scientists to come."

*To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/2013/cold-symmetric-cryptic*

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## About the data used

| | |
|---|---|
| Sensors | Various aircraft microphysical probes, thermodynamic sensors, radiometers, profilers, radars, disdrometers, and precipitation gauges |
| Data sets | Airborne Precipitation Radar version 2 (APR-2)<br>Conical Scanning Millimeter-wave Imaging Radiometer (CoSMIR)<br>Aircraft mounted particle probes and thermodynamic sensors (UND Citation and CNRC Convair 580)<br>Dual frequency dual polarimetric Doppler radar (D3R)<br>Environment Canada C-band dual-polarimetric Doppler radar at King City, Ontario<br>Advanced Microwave Radiometer for Rain Identification (ADMIRARI)<br>Centre for Atmospheric Research Experiments (CARE) vertical profiling radiometer and X-band radar<br>Disdrometers, precipitation gauges and meteorological conditions at each ground site |
| Data center | NASA Global Hydrology Resource Center (GHRC) |

## About the scientists

Patrick Gatlin is a research meteorologist at the NASA Marshall Space Flight Center. His research interests focus on precipitation science. NASA supported his research. (Photograph courtesy NASA Marshall Space Flight Center)

Walter Petersen is chief of the Earth Sciences Office of Field Support at the NASA Goddard Space Flight Center Wallops Flight Facility. His research interests focus on space- and ground-based remote sensing of precipitation. NASA supported his research. (Photograph courtesy NASA Goddard Space Flight Center)

Gail Skofronick-Jackson is deputy project scientist of the NASA Global Precipitation Measuring mission. Her research interests include the use of microwave and millimeter-wave remote sensing techniques from aircraft, spacecraft, and the ground to study Earth's surface and atmosphere. NASA supported her research. Read more at http://www.nasa.gov/centers/goddard/about/people/GJackson.html. (Photograph courtesy NASA/R. Roth)

## For more information

NASA Global Hydrology Resource Center
http://ghrc.nsstc.nasa.gov
NASA GPM Cold-season Precipitation Experiment
http://pmm.nasa.gov/node/485

# When oceans drop

> “GRACE is our latest favorite toy. This idea that you can weigh a continent or weigh the ocean from outer space is kind of cool.”
>
> Josh Willis
> NASA Jet Propulsion Laboratory

by Laura Naranjo

“Sea level is one of the most important yardsticks for measuring how humans are changing the climate,” said Josh Willis, an oceanographer at the NASA Jet Propulsion Laboratory. He and colleague Carmen Boening have watched sea level creep upward at a slow but steady three millimeters per year. “We pay a lot of attention to this number,” Willis said, “so it was kind of surprising in 2010 and 2011 when we saw a dip, a reversal.” Sea level had suddenly dropped a half centimeter. What caused the drop? And did it mean sea level was no longer rising?

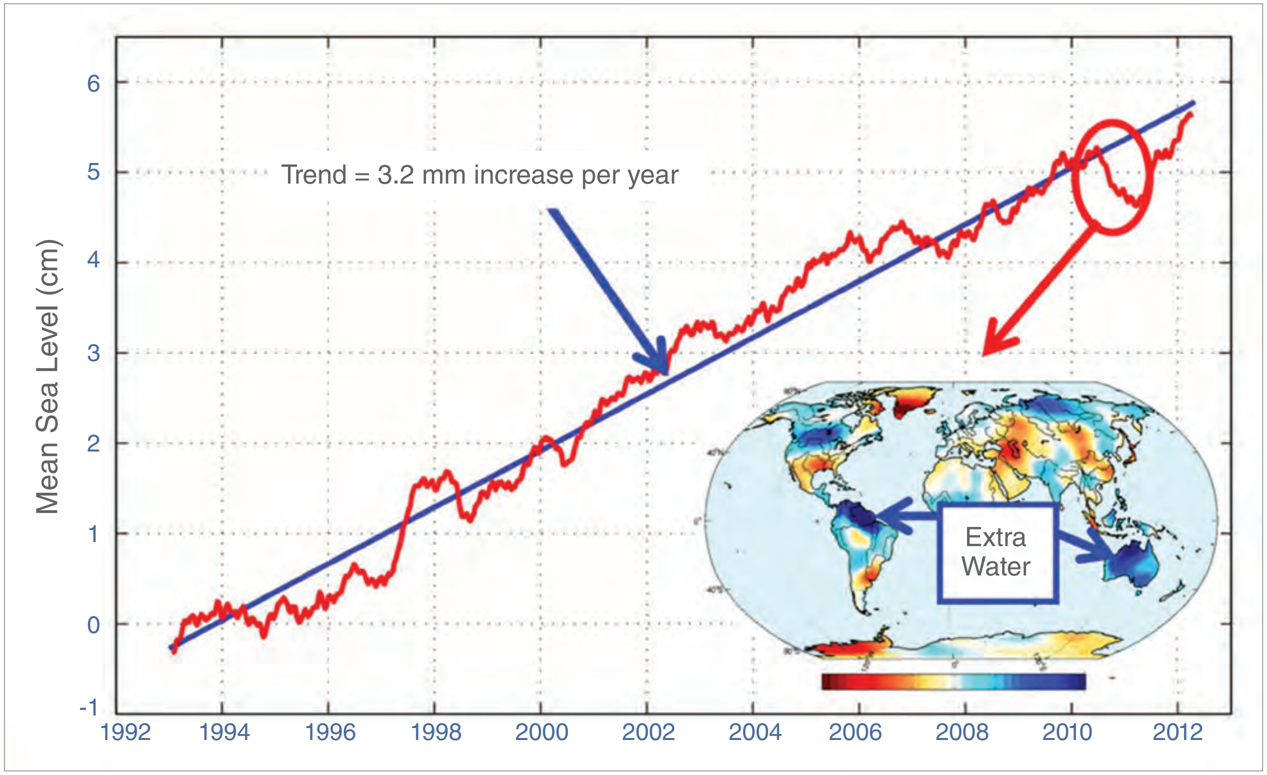
## Heat versus movement

Scientists long thought that global ocean levels changed primarily in response to temperature. Willis said, “We thought that sea level changes were simply the ocean heating up and expanding or cooling and shrinking.” As global temperatures have increased, the oceans have expanded,

The strong La Niña in 2010 and 2011 produced torrential rain that inundated many low-lying areas around the globe. Floodwaters completely engulfed this house in Bangkok, Thailand. (Courtesy R. J. Maurer, U.S. Marine Corps) ice has melted, and sea levels have crept upward. Low-lying island nations like Tuvalu in the South Pacific are already losing ground as rising seawater erodes coastlines and contaminates fresh inland water supplies.

But global oceans are also governed by shifts between El Niño and La Niña, a large-scale climate pattern in the Pacific Ocean. Called the El Niño Southern Oscillation (ENSO), this cycle has far-reaching impacts. A strong El Niño phase can cause drought as far away as Canada and Europe, and La Niña can send torrents of rain halfway around the world to Bangladesh. During the warmer El Niño phase, warm water pools in the eastern Pacific. The resulting impact on the jet stream fosters warm, dry weather around much of the globe. During the cooler La Niña phase, the eastern Pacific cools, changing the jet stream so that it carries wet and cool weather to many regions.

South American sailors documented this pattern more than one hundred years ago, noticing changes in water temperature along the coast of Ecuador and Peru. The oceans swing between the two phases about every three to five years. Such a pulse of heat and movement in the oceans is nothing out of the ordinary. However, the 2010 La Niña was the strongest in eighty years, devastating parts of Colombia, South Africa, Southeast Asia, and Australia with heavy rain and flooding. So scientists wondered if La Niña was behind the sea level drop. Boening said, “This drop could have two reasons. Either the ocean was cooling a lot, or there was less water in the ocean.” Could ENSO cool and shrink oceans enough to create a half-centimeter drop? If not, did the shift between El Niño and La Niña somehow move that much water out of the ocean?



This plot shows ocean levels since 1993. The red line shows sea level rise and the blue line indicates the trend. The red circle shows the sudden dip in 2010 and 2011, and the arrow points to a map of where that missing water went: primarily to Australia and northern South America (indicated by blue arrows on the inset map). While the ocean lost water, the continents experienced a gain because of increased rainfall brought on by the 2010/2011 La Niña. By mid 2012, global mean sea level had recovered by more than the five millimeters it dropped. (Courtesy NASA JPL)

## Jason and the Argonauts

Boening and Willis had eighteen years of sea level data from a series of remote-sensing missions: TOPEX/Poseidon and its follow-on missions, Jason-1 and Jason-2. “Satellite altimetry measures the total sea surface height,” Boening said, “and so it measures the changes in sea level.” Those records indicated that sea level steadily rose an average of three millimeters per year. The dramatic drop during 2010 had not only negated the average annual 3.2 millimeter rise, but dropped sea level an additional two millimeters.

To see if sudden cooling was to blame, the researchers turned to temperature data, which proved trickier to obtain. Willis said, “With satellites we can only see the temperature of the ocean surface. But sea level rise really comes from warming through the whole depth of the water.” So to complement the data from the mythically named satellites, the researchers turned to a global network of ocean floats, deployed by the Argo program. “Argo floats drift around at about 1,000 meters, and then dive down to about 2,000 meters, which is about the top half of the ocean,” Willis said. “As they come back up, they

This comparison photograph of the Gurra floodplain in Australia, northeast of Adelaide, was taken in February 2012. The inset photograph was taken in February 2011, when rains inundated the plain. (Courtesy C. Nickolai)

measure temperature and salinity." More than 3,000 floats had been deployed by 2007, providing the deeper temperatures researchers needed to see if oceans had cooled and contracted.

Between Jason-1, Jason-2, and the floating Argonauts, Boening and Willis found that while this La Niña was extraordinarily strong, temperature data ruled out ocean cooling as the culprit behind the drop in sea level. This meant that water had disappeared from the ocean, and the researchers needed to find out where it went.

## The weight of water

If the water was no longer in the ocean, then it must have ended up somewhere on land. It was not feasible for researchers to inspect every drainage basin, or examine water volume for every river across the globe. But they could try to find changes in weight around Earth. Five millimeters of global ocean water weighs about 1.5 trillion tons, and that much water cannot just disappear. A set of twin satellites, called the Gravity Recovery and Climate Experiment (GRACE), provided researchers with a fresh measurement of Earth's surface: gravity. Gravity exerts more pull on things that weigh more, so the scientists thought they could use the gravity measurements to locate the weight missing from the oceans. Willis said, "GRACE is our latest favorite toy. This idea that you can weigh a continent or weigh the ocean from outer space is kind of cool."

By looking at gravity measurements of oceans and land around the globe, the researchers could spot areas that weighed more in 2011. Boening said, "GRACE allowed us to actually track down the water to see where it went. And it turned out it was in northern South America, Southeast Asia, and Australia." The strong La Niña had affected the oceans to an unusual extent, not by cooling the water so much as by moving the water on to land. Rainfall follows warm pools of water, and during El Niño, more rain tends to fall over the Pacific Ocean. But during La Niña, cooler oceans push that rainfall over continents. The researchers then compared their GRACE findings to data from the Tropical Rainfall Measuring Mission (TRMM). "TRMM measures precipitation, so we could make sure that the changes we were seeing with GRACE lined up with the precipitation that was measured in these areas during that time," she said. Indeed, torrential rains had fallen over Southeast Asia, parts of South America, and eastern Australia, which suffered its worst floods in more than one hundred years.

"So it turns out that the atmosphere is good at picking up this water, carrying it a little ways, and then dumping it back down," Willis said. "That's a big part of why sea level goes up and down every year."

## The rise marches on

Scientists had suspected that the ENSO cycle was capable of such dramatic water transport, but previously did not have the direct proof GRACE provided. They now know that thermal expansion only accounts for 10 to 20 percent of these kinds of sea level changes. Willis said, "It wasn't until this last switch from El Niño to La Niña that we had good enough data: sea level from altimeters, temperature data in the ocean, and gravity data from GRACE. We really needed all three to be sure that this was caused by changes in mass and not by thermal expansion."

These more extensive observations have also proven that the sea level drop was only temporary. Even though La Niña-induced rainfall deposited massive amounts of water on land, it only takes six months to a year for that water to run back off into the ocean. "What we're seeing now, over the course of 2011 to 2012, is that sea level is going back up again," Boening said. Shifts in water storage caused by El Niño and La Niña are only short term against the ongoing backdrop of warming. "Even as sea level dropped a little bit, we had huge amounts of melting in Greenland and Antarctica. So the things that are causing long term sea level rise are still chugging right along," Willis said.

Still, knowing where Earth's water is, whether it is in the oceans, falling as rain, or frozen in ice sheets, is crucial for monitoring global ocean levels. Boening said, "As we gather more and more observations, we are able to understand these fluctuations better, and also make our predictions of sea level rise better."

*To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/2013/when-oceans-drop*

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## About the remote sensing data used

| | | |
|---|---|---|
| Satellites | Gravity Recovery and Climate Experiment (GRACE) | Tropical Rainfall Measuring Mission (TRMM) |
| Sensors | K-Band Ranging System | TRMM Microwave Imager |
| Data sets | JPL GSM RL05 | 3B42: 3-hour 0.25 x 0.25 degree merged TRMM and other satellite estimates |
| Resolution | 300 kilometer by 300 kilometer | 0.25 degree x 0.25 degree |
| Parameters | Gravity fields | Precipitation |
| Data centers | NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) | NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) |

The researchers used sea surface height data processed by the CU Sea Level Research Group, based on TOPEX/Poseidon and Jason-1 and -2 data from PO.DAAC. Data from Argo floats were provided by the International Argo Project.

## About the scientists

Carmen Boening is a climate researcher at the NASA Jet Propulsion Laboratory (JPL) and part of the Gravity Recovery and Climate Experiment (GRACE) team. She studies ocean-climate interactions and their role in sea level rise. NASA supported her research. Read more at http://science.jpl.nasa.gov/people/Boening. (Photograph courtesy NASA JPL)

Josh Willis is a project scientist for the Jason-3 mission at the NASA Jet Propulsion Laboratory (JPL). He studies global ocean warming, sea level rise, and large-scale changes in the ocean and its circulation on interannual to decadal time scales. NASA supported his research. Read more at http://science.jpl.nasa.gov/people/Willis. (Photograph courtesy NASA JPL)

## For more information

NASA Goddard Earth Sciences Data and Information Services Center (GES DISC)
http://daac.gsfc.nasa.gov
NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)
http://podaac.jpl.nasa.gov
Gravity Recovery and Climate Experiment (GRACE)
http://podaac.jpl.nasa.gov/GRACE
Jason-1 Mission
http://podaac.jpl.nasa.gov/Jason1
Jason-2 Mission
http://podaac.jpl.nasa.gov/OceanSurfaceTopography/OSTM-JASON2
TOPEX/Poseidon Mission
http://podaac.jpl.nasa.gov/TOPEX-POSEIDON
Tropical Rainfall Measuring Mission (TRMM)
http://trmm.gsfc.nasa.gov

# Pedestrians of Eddy Avenue

> “We have a nutrient source that is self contained, can endure for a long time, and be exploited by different fish populations.”
>
> Peter Oke
>
> Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research

by Agnieszka Gautier

Cruising south on the East Australian Current (EAC), the long-spined sea urchin, *Centrostephanous rodgersii*, has ventured further into Tasmania’s warming waters, affecting a lucrative seafood industry, and leveling sea kelp forests into barren fields. These porcupines of the sea gnaw off the anchors of giant kelp, uprooting the entire plant. Nearly 95 percent of the giant forests have vanished. Within a decade all may disappear, and with them the sea snails, rock lobsters, and abalone that shelter within their canopies.

“The temperatures off the east of Tasmania are some of the fastest rising in the world,” said Iain Suthers, a professor at the University of New South Wales (UNSW). Average winter sea temperatures have warmed to 12 degrees Celsius (54 degrees Fahrenheit), the survival threshold for spawning sea urchin, allowing them to reproduce longer. “This isn’t unique to the EAC. All poleward boundary currents are strengthening,” Suthers said. Boundary currents interact with coastlines, and unlike their eastern counterpart, western boundary currents move poleward within strong, deep, and narrow channels.

Long-spined sea urchins nest on a depleted kelp bed off the coast of eastern Tasmania. Lush sea kelp forests turn into barren fields of rock once the sea urchins take over. (Courtesy S. Ling)

Subtle shifts in ocean temperature significantly disrupt established food chains. As an underwater highway, the EAC transports warm, low-nutrient waters from the Coral Sea southward into the Tasman Sea, displacing cold, nutrient-rich waters. It now extends further south by 350 kilometers (220 miles). "Species are being transported well outside of their range," said Suthers. "The identification of Eddy Avenue is just one piece of the jigsaw to explain recent events."

## Sighting the site

Eddy Avenue—playfully named after an actual street in Sydney, Australia, where all the researchers once waited for the bus—is a region within the Tasman Sea with an unusually high number of eddy formations. Eddies are little worlds of intense biological and physical productivity. "We suspect that commercial fishermen know eddies well and truly. They can look for certain features and efficiently target their catch," Oke said. "We're just filling in a bit of a gap."

Everett and his team set out to locate and quantify the eddies within the Tasman Sea, and then link ocean circulation to different biological elements: phytoplankton, zooplankton, and fisheries. Eddy Avenue was not part of the initial plan. "But when we started, Eddy Avenue jumped out," said Jason Everett, a postdoctoral researcher at UNSW. Located close to the southeast coast of Australia, Eddy Avenue has 20 to 30 percent more eddies than the surrounding waters. Here, the eddies deviate from the global average with higher sea levels, faster rotations, and more chlorophyll, which means more nutrients to support a food chain.

Eddies are rotating blobs of water with warm or cold cores. They are the ocean's high or low pressure systems, instrumental in transporting heat within the ocean. "They're basically ocean weather," said Peter Oke, a research scientist with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for Marine and Atmospheric Research. Eddies form out of instabilities. Most result when the wavelike path of a current circles back onto itself, pinching off into spinning cylinders of water.

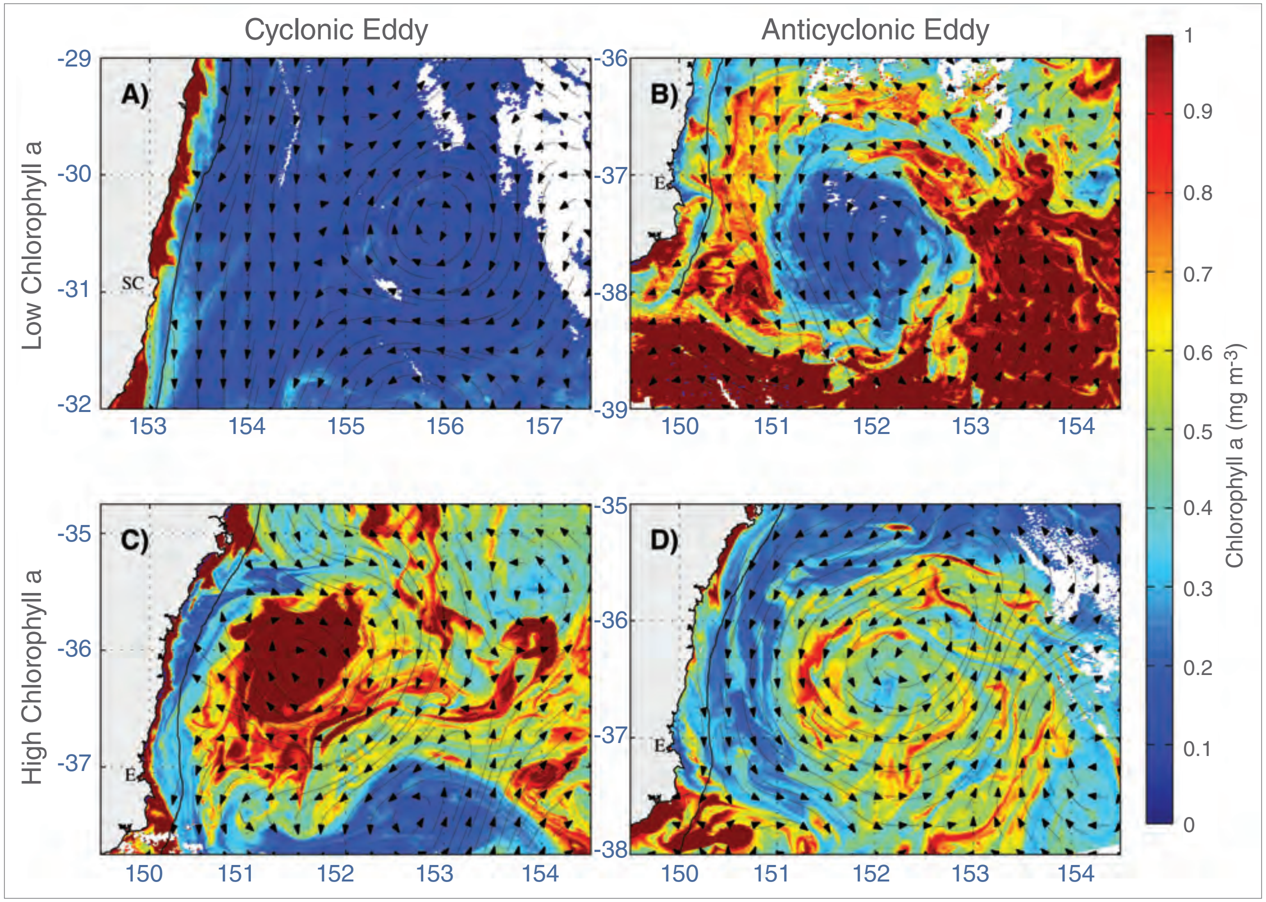
To understand the high incidence of eddies in Eddy Avenue, one has to understand the EAC. "In the Tasman Sea, the eddies get spun up quickly after the EAC leaves the coast," Oke said. Typical eddies rotate at ten centimeters per second, but within Eddy Avenue they rotate at fifty centimeters per second, a slow walking speed. "When the current separates from the coast, it gets complicated. It starts to wobble; it meanders. Rather than going in a relatively straight path like the Gulf Stream in the North Atlantic, it walks like a drunk man." Not only does the EAC wobble, it U-turns. "Every boundary current has its own peculiarities. They're like people," Suthers said. "They have their own idiosyncrasies. The EAC is a bit anomalous." About two-thirds of the current retroflects back up into the eastern Pacific, breaking up the EAC further. "It really is a current of eddies." Such instabilities saturate Eddy Avenue with eddies.

## Eddy biology

Eddy Avenue helps shed light on the migration of species out of their usual bounds. As key players in heat transportation, eddies provide nutrients for phytoplankton, photosynthesizing microscopic organisms, often green from the chlorophyll pigment present in their cells. Not all eddies do this, however. Two types exist: cyclonic and anticyclonic. The centers of cyclonic eddies dimple the ocean surface. The direction an eddy swirls depends on the hemisphere. In the southern hemisphere, clockwise rotation pulls deep water up the center, forming a cold depression of higher density water. The upwelling brings nutrients, submerged as decayed organic matter, into the light zone where it can be used by phytoplankton for growth and reproduction. "These cyclonic eddies are really the basis of the food chain," Suthers said.


The research team hauls in a fine mesh net to sample live salps during their asexual solitary stage, keeping them for only a few hours to determine their growth and fecundity. These gelatinous, barrel-shaped filter feeders are supremely abundant with an asexual stage that can release 240 buds in a week. They feed on a virtually unlimited carbon resource and thrive in rich phytoplankton areas. (Courtesy I. Suthers)

Down under, anticyclonic eddies dot the ocean like pimples, pulling warm, low-density surface water into their core through a counterclockwise rotation. The differences in height and temperature allowed the team to take a broad look at the Tasman Sea with satellite altimetry and sea-surface temperature (SST) to map the circulation of the eddies. By applying ocean color data, which detects chlorophyll concentrations, they could estimate productivity levels. Green areas



These satellite images present the complex qualities of cyclonic and anticyclonic eddies within Eddy Avenue, proving they are not simply cold core and warm core, respectively. Geostrophic currents (from altimetry; black arrows) confirm the type of eddy based on ocean circulation. To find out what the biology was doing, the researchers used the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the NASA Aqua satellite to track concentrations of chlorophyll a (shading). (Courtesy P. Oke)

are phytoplankton hot zones. Brown and blue represent fallow ocean fields.

Using satellite data from 1993 to 2008, the researchers charted the frequency and quantity of eddies within the Tasman Sea. They identified 30,000 eddies with over half being anticyclonic. The unproductive warm cores were expected to have low chlorophyll, while chlorophyll should have clouded the centers of cyclonic eddies. Sometimes this was the case, but Eddy Avenue complicated matters. “Now we’re starting to understand eddies aren’t simply warm or cold core,” Suthers said.

## Eddy chameleon

Sometimes cyclonic eddies had no cold core. As the EAC leaves the coast of Australia and breaks down into eddies, often a trace lingers—a fast slither weaving in and out of eddies. When it comes into contact with a cyclonic eddy, it floods it, capping it with warm water. “The importance here is if you were to look at SST from satellite data, you might not see the cyclonic eddies,” Oke said. “It’s only by pulling other data types, the satellite altimetry and ocean color, that we can go ‘Ah that’s warm, but it’s still a cyclonic eddy.’” Though this has happened before, the researchers had not seen it on this scale.

Suthers said, “Cyclonic eddies are far more involved. If you look at a pair of twins, the big bald twin is the anticyclonic eddy and then you’ve got the cyclonic twin that has a range of colors, sizes, and personalities. They’re far more biologically interesting.” Both types of eddies interact with the continental shelf, but cyclonic eddies are able to entrain nutrient-rich water from the shelf, resulting in higher chlorophyll concentrations. Anticyclonic, for reasons yet undetermined, do not. “We didn’t expect that from the cyclonic eddies,” Everett said. “Our research points to two processes. You get uplifting, but closer to the coast within Eddy Avenue, there’s a second process: the entrainment of shelf water.”

Researchers once considered entrainment as a death trap, believing that when spawned fish were dragged from the coast, they would die. But entrainment provides a nutrient-rich environment with fewer predators. “Larval fish are growing faster and bigger within these smaller, coastal cyclonic eddies,” Everett said. “We’re in a neat position to see this in Eddy Avenue because of the number of eddies.” All eddies propagate to the west. This is partially due to Earth’s rotation. To the west is Australia. So the eddies just bobble there. Bumping up against the coast, they sweep in high-nutrient water, over and over. It is a productive environment—little plankton incubators, if you like. "We have a nutrient source that is self contained, can endure for a long time, and be exploited by different fish populations," Oke said.

## A light on Eddy Avenue

The identification of Eddy Avenue has highlighted entrainment to explain high chlorophyll levels, but a missing link still exists. "It's quite easy to sample fish or zooplankton on the coast and then sample them in an eddy close by to show that the species are the same," Everett said, "but it's much harder to show that they actually came from the eddy nearby." Making that final connection is the next step.

For now the researchers are left with a bit of optimism. "Up until now, global climate models (GCMs) assumed that with global warming these would be less productive because the warmer layer of water would isolate upwelling and cap deep nutrient-rich water," said Suthers. Eddy Avenue has unlocked another possibility. As currents increase, more energy will propagate south. "Eddies will either have to get bigger or there will be more of them," Everett said. "We aren't sure which at this stage." More eddies and bigger eddies point to the possibility of more chlorophyll, perhaps pulling more carbon out of the atmosphere into phytoplankton and sustaining fisheries. "That was something that came from this research," Suthers said. "You bet, we've got a serious eddy production off the east coast of Australia and now it's being incorporated, being realized, into GCMs."

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## About the remote sensing data used

| | |
|---|---|
| Satellite | Aqua |
| Sensor | Moderate Resolution Imaging Spectroradiometer (MODIS) |
| Data set | Level 3 Ocean Color Web |
| Resolution | 4 kilometer |
| Parameter | Chlorophyll a concentration |
| Data center | NASA Ocean Biology Processing Group (OBPG) |

## About the scientists

Jason Everett splits his time as a postdoctoral researcher at the University of New South Wales and at the University of Technology in Sydney, Australia. Everett is interested in how oceanographic features influence the productivity of phytoplankton and zooplankton communities. The Australian Research Council Discovery Project supported his research. See http://www.famer.unsw.edu.au/staff/jason.html. (Photograph courtesy J. Everett)

Peter Oke is a research scientist at Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research in Hobart, Australia. Oke undertakes research in oceanography, using observations and numerical models to investigate ocean dynamics. The Australian Research Council Discovery Project supported his research. See http://www.marine.csiro.au/~oke060. (Photograph courtesy P. Oke)

Iain Suthers is a professor in the School of Biological, Earth and Environmental Sciences at the University of New South Wales and is partly based at the Sydney Institute of Marine Science. Suthers explores the basis and sustainability of estuarine and coastal ecosystems. The Australian Research Council Discovery Project supported his research. See http://www.bees.unsw.edu.au/iain-suthers. (Photograph courtesy I. Suthers)

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NASA Ocean Biology Processing Group. MODIS Level 3 Ocean Color Web. 2012. Greenbelt, Maryland USA. http://oceancolor.gsfc.nasa.gov.

## For more information

NASA Ocean Biology Processing Group
http://earthdata.nasa.gov/data/data-centers/obpg
Moderate Resolution Imaging Spectroradiometer (MODIS)
http://modis.gsfc.nasa.gov

# Making heads of mares’ tails

> “The warming effect of cirrus is six times larger than you would get by doubling all the carbon dioxide in the atmosphere.”
>
> Tristan L’ Ecuyer
> University of Wisconsin-Madison

by Karla LeFevre

For centuries, many a sailor has learned to heed the message of high, windswept clouds to batten down their hatches. As the proverb goes, “Mares’ tails and mackerel scales make lofty ships to carry low sails.” Together, wispy cirrus clouds resembling horse tails and patchy cirrocumulus signal that a rain storm is on its way.

But scientists are interested in other messages these high altitude clouds can share. Thick, low clouds like cumulus reflect incoming sunlight while thin, high clouds like cirrus trap the sun’s thermal energy in Earth’s atmosphere. For researchers Tristan L’ Ecuyer and Graeme Stephens who study how much heat the planet holds or sends back to space, known as Earth’s energy budget, this is an important distinction. Which type wins overall? That is an ongoing scientific debate, but L’ Ecuyer and Stephens are chipping away at the answer. What scientists do not debate is that cirrus are no ordinary clouds. Understanding them may be key to understanding how Earth is going to handle continued warming.

## Cloud computing

Most cirrus stream out of the chimneys of tropical cyclones or form at the top of boiling thunderstorms, and can stretch over entire

High, wispy cirrus clouds stream over Big Bend National Park in Texas, USA. Many of the cirrus shown here have been pulled by the wind in such a way that they resemble horses’ tails. (Courtesy M. H. Whitten) continents when pulled by the jet stream. They are made of millions of tiny ice crystals of varying shapes, like disks and rods, and are sometimes so thin they are almost transparent. These features give cirrus an uncanny ability to allow solar radiation into the atmosphere, yet prevent it from reflecting back out into space.

Like large lids over the atmosphere, cirrus effectively prevent warm air from rising. Stephens and L' Ecuyer found they do this especially well over warm surfaces. Stephens, a senior scientist at the NASA Jet Propulsion Laboratory, said, "Think about high, cold cirrus at 14 kilometers [9 miles] sitting above the tropics over a 300 degree Kelvin [80 degree Fahrenheit] ocean temperature. That's when they're most effective at trapping heat."

The power to trap heat means they can also squelch storms. Storms build when warm air rises over a pocket of cold air like a conveyer belt, causing the cycle of convection. When that warm air finds its higher spot in the atmosphere, it condenses into rain or ice droplets, depending on the altitude. But cirrus clouds hamper this cycling of air, and much of the precipitation that should follow. More heat and less rain may be a welcome change for seafarers, but it means cirrus also create a powerful form of positive feedback to a warming climate.

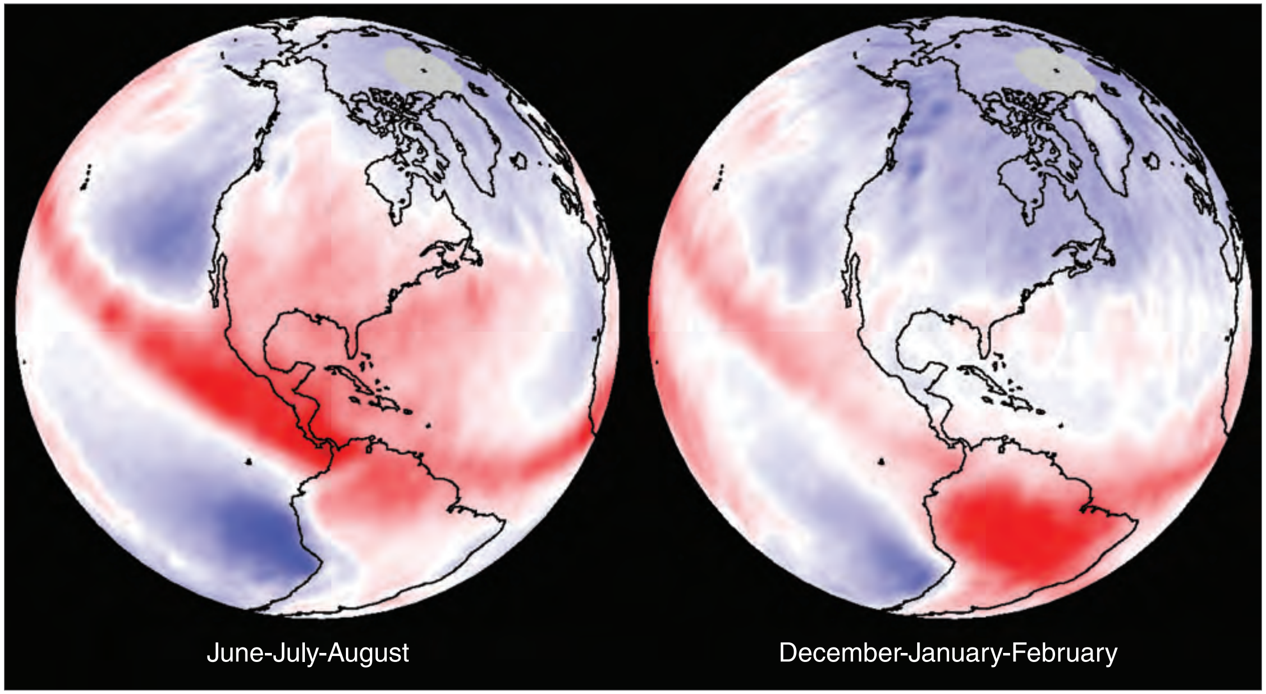
Put a cloud below the cirrus, however, and the dynamic changes. "What happens now that you have a cloud below the cirrus?" Stephens said. "It reduces the ability of the cirrus to trap heat. So the greenhouse effect of a cirrus cloud depends on what's below it." This complicates the already perplexing task of mapping clouds on a global scale, which is exactly what scientists need to do to calculate the sway clouds hold over the energy budget. Yet Stephens and L' Ecuyer took it a step further to capture a profile of clouds throughout the entire atmosphere, from top to bottom. Stephens said, "We needed to know: Is it just cirrus and one cloud layer below, or cirrus and two cloud layers? And how high are they?"

High, cold cirrus and lower, puffy cumulus clouds hover above homes in Eyemouth, Scotland. (Copyright G. White)

## Portrait of a cloud

Answering those complex questions required digging into data from not just one satellite, but three. They began their search with the NASA/French Space Agency CALIPSO satellite, otherwise known as the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation satellite. Onboard, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument was designed to size up a cloud by pointing its laser at it and measuring the light that bounces back, what scientists refer to as lidar backscatter. L' Ecuyer, an assistant professor of atmospheric physics at the University of Wisconsin-Madison, explained how this works. "Suppose you turn on your headlights when it's foggy outside. You can tell how much fog there is essentially by seeing how much light gets reflected back at you." In a similar way, the CALIOP instrument measures the thickness of clouds from space, and is particularly adept at sensing the finer particles of cirrus clouds. It can also penetrate through thin cirrus clouds to see what lies below.

Flying nearby on the CloudSat satellite was the perfect complement. Its Cloud Profiling Radar instrument was designed to measure another type of backscatter: radio waves. With radio waves, the researchers could begin to make out larger particles like snow and ice within a cloud, especially those in thicker clouds like puffy cumulus. They then combined these data with readings of optical thickness, yet another assessment of how bright



These images show the effects of clouds on the atmosphere. Red areas indicate places where clouds heat the atmosphere and blue areas are places where they cool it. The measurements show that the low clouds typically found off the west coasts of continents tend to cool the atmosphere while deeper clouds near the equator and over the Amazon tend to heat it. Likewise shallower clouds that occur during winter storms tend to cool the atmosphere while summertime thunderstorms have strong warming effects. Thus, the atmosphere over North America is warmed by clouds in summer months and cooled during winter months. The gray area around the pole indicates where measurements are not available. Data are from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and other NASA A-Train satellites. (Courtesy T. L' Ecuyer/NASA Langley Research Center Atmospheric Science Data Center [LaRC ASDC])

clouds are, from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite.

Together, the new data were groundbreaking. Not only could the researchers identify different types of clouds, but they could also track and catalog a vertical view of cloud layers, which helped them understand much more about cirrus than was previously known. L' Ecuyer said, "We now know how often there's a cirrus cloud in every environment on the globe. And maybe more importantly, we know how high and how cold they are."

## Modeling mares' tails

That information was a giant step toward refining their computerized cloud models, which is what they rely on to calculate the net effect of all clouds on Earth's energy budget. These models helped sort out surprising patterns about cloud behavior. It turns out the higher and thinner the cloud, the more heat it will trap. "It's counterintuitive," Stephens said. "You think big, thick clouds would be a thicker blanket, but they reflect a lot of sunlight, actually. The thin, cold cirrus have a disproportionately higher greenhouse effect."

In fact, their findings confirmed the importance of these wispy, sometimes barely visible cirrus clouds to climate. L' Ecuyer said, "The warming effect of cirrus is six times larger than you would get by doubling all the carbon dioxide in the atmosphere."

When the effects of low clouds were factored in, though, their models revealed that clouds continue to have a cooling effect overall, at least in today's climate. The next step is to learn how the heating or cooling effect of clouds might change in the future. Computer models will help predict this, but scientists caution they need continual testing and honing. Because clouds play a large role in determining the global climate, an enormous amount of data must go into analyzing them, and there is no shortage of factors to consider. That means that even with massive amounts of data from the most sophisticated instruments available, there are a great number of unknowns.

"That's the problem," Stephens said. "Just a small change in clouds can almost completely offset the warming, or reinforce it strongly." This sensitivity in current climate models is now pushing them to analyze data on other factors that influence cloud formation and behavior. Stephens said, "How do aerosols, for example—like pollution, dust, and other particles—affect this balance? And how does this affect the overall ability to produce precipitation?"

Until they can answer those questions, however, they will rely on the new benchmark their study has set for current models. And in the meantime, the advent of still more sophisticated instruments combined with a longer data record will help scientists continue to decode the messages clouds tell us in the future. Will a warming planet bring more clouds, and will these be warming cirrus clouds or cooling cumulus clouds? L' Ecuyer said, "What we've done is figure out what clouds do in today's climate, but what ways will clouds change in a warmer climate?"

*To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/2013/making-heads-mares-tails*

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## About the remote sensing data used

| | |
|---|---|
| Satellite | Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) |
| Sensor | Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) |
| Data set | Level-3 Lidar Backscatter, Vertical Feature Mask (VFM) |
| Resolution | 2 degrees latitude, 5 degrees longitude |
| Parameter | Lidar backscatter |
| Data center | NASA Langley Research Center Atmospheric Science Data Center (LaRC ASDC) |
| Processed CloudSat backscatter data and MODIS radiance data were obtained from the CloudSat Data Processing Center. | |

## About the scientists

Tristan L' Ecuyer is an assistant professor in the Department of Atmospheric and Oceanic Sciences at the University of Wisconsin-Madison. His research focuses on using satellite measurements and field observations to improve our understanding of the global energy and water cycles. NASA supported his research. Read more at http://www.aos.wisc.edu/~tristan. (Photograph courtesy T. L' Ecuyer/University of Wisconsin-Madison)

Graeme Stephens is the director of the Center for Climate Sciences at the NASA Jet Propulsion Laboratory (JPL). His research focuses on atmospheric radiation and on using remote sensing to understand the role of hydrological processes in climate change. NASA supported his research. Read more at https://science.jpl.nasa.gov/people/Stephens. (Photograph courtesy G. Stephens/NASA JPL)

## For more information

NASA Langley Research Center Atmospheric Science Data Center (LaRC ASDC)
http://eosweb.larc.nasa.gov

NASA Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)
http://www-calipso.larc.nasa.gov/about

NASA CloudSat
http://www.nasa.gov/mission_pages/cloudsat/main

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

# Signs of snow

> “When might we lose the entire multiyear ice pack and transition to a seasonal ice pack?”
>
> Sinéad Farrell
> University of Maryland

by Jane Beitler

From the window of the NASA P-3 aircraft, researcher Sinéad Farrell could see the research camp on the Arctic ice pack below. The red tents of the camp specked the wind-carved snow atop the sea ice pack, where the researchers on the ground had marked out an ice survey line. The P-3 traced this line as it flew far overhead, while radar in its belly measured from the air what the people on the ground measured with shovels, rulers, and probes.

The goal was to test a way to measure the thickness of the ice cover that floats on the sea surface, and the snow laying on top of the ice, two largely missing variables in the store of observations about a warming Arctic. Researchers like Farrell wonder how soon the Arctic might lose all of its summer ice cover. They knew they needed to know more than just the surface extent of the ice to answer that question.

## The world is watching

The loss of Arctic sea ice signals the warming that has been stronger in the Arctic than anywhere else on Earth. At the end of summer 2012, sea ice had shrunk to half its former extent compared to the average from 1979 to 2000, more than a million square miles less. The ice

Ice re-grows in a lead between two sea ice floes in the Beaufort Sea, Arctic Ocean, in March 2013. (Courtesy S. L. Farrell) had shrunk faster than computer climate models had predicted. While the world's citizens watched the news to see what would happen each year with sea ice, the world's scientists worked together to study the changes.

Farrell, a scientist at the University of Maryland and at the National Oceanic and Atmospheric Administration, was part of an experiment to measure ice thickness, and the depth of snow on the ice. The research camp had been established by a consortium of Danish research institutions and partnered by the U.S. Cold Regions Research and Engineering Laboratory. The aircraft she was riding was from a larger NASA mission called IceBridge because it bridges a multiyear gap in observations between two satellites. "The point of IceBridge was to continue to monitor polar regions in critical areas of change," said Farrell, who is also a member of the NASA Operation IceBridge Science Team. So the data gap is being filled with airplanes carrying arrays of sensors to measure sea ice, glaciers, and ice sheets.

Scientists knew that sea ice in the Arctic would continue to decline, but not exactly how the decline would progress. "We knew the ice pack was retreating in areas, but we didn't know how it was changing in thickness," Farrell said.

The thickness of sea ice is related to its age. "Multiyear ice is ice that survived the summer melt. It was the predominant ice type in the 1980s and 1990s," Farrell said. Ice that does not melt completely in summer thickens again during the following winter. But now sea ice in the Arctic mainly consists of new ice that froze in one season. "When might we lose the entire multiyear ice pack and transition to a seasonal ice pack?" Farrell asked.

Ice thickness matters a lot to the persistence of summer sea ice. Farrell said, "During the summer, the ice is melting and breaking up and then you have more intense storms coming through the region. The thinner the ice, we believe the more vulnerable it is to storms that break it up."

The first ICESat satellite provided some of the first remote sensing data on ice thickness, from 2003 until it stopped collecting data in 2009. "We have satellite data from the 1970s about the areal extent of the ice, but not about its volume or thickness," Farrell said. "We had some data from submarines, but no data across the entire Arctic Ocean."

## On top of it all

Along with a laser altimeter to measure ice thickness, the P-3 aircraft carried an experimental snow depth radar, designed by the University of Kansas. The altimeter can measure the height of the ice sticking up above the ocean surface, which is then multiplied by a factor to calculate how deep the ice extends below the surface. Snow depth is important to this equation. "The ice is floating on the ocean, but it is weighted down by the snow accumulated on top of the ice floes," Farrell said. "It pushes them down further into the water. Knowing the weight of the snow is important to measuring the thickness of the sea ice."

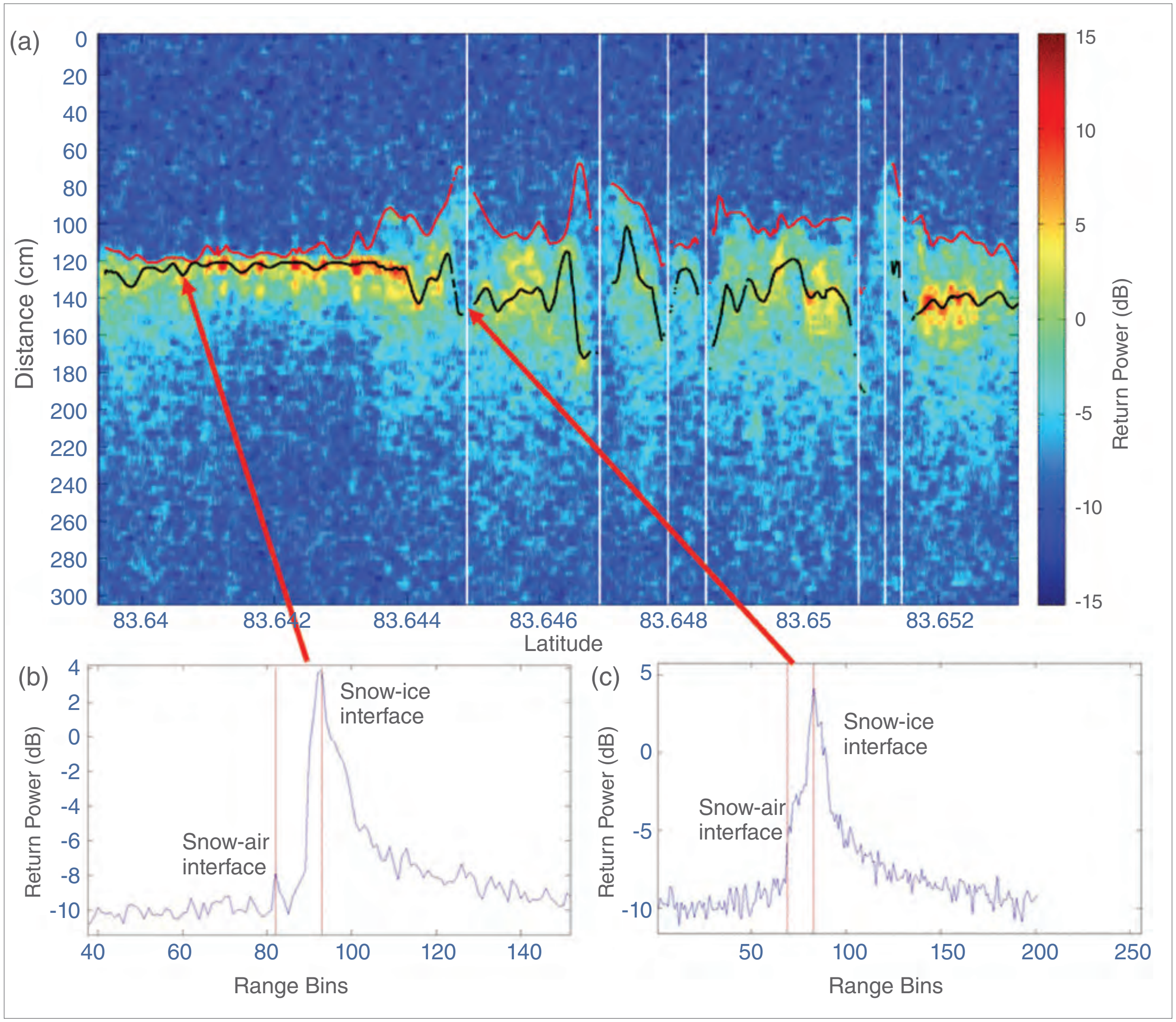
Snow also plays a role in the exchange of heat between the ocean and the atmosphere. Nathan Kurtz, a research scientist on the IceBridge team at the NASA Goddard Space Flight Center, said, "If you have snow on top of sea ice, the ice doesn't grow as fast; the snow insulates it."

Sea ice freezes not only because the air above it is cold, but also because the ocean below it is cold. Open water quickly releases its heat to the air. A thick layer of snow, even on thin ice, slows down the cooling of the ocean. But with no snow and thin ice, the ocean's heat more rapidly escapes. As the ice melts, the heat equation gets more complicated. Kurtz said, "In the summer when sea ice starts to melt, snow forms melt ponds, which also affect how much radiation is being absorbed. Not a lot is known about this."


The NASA P-3B aircraft arrives at Thule, Greenland. The aircraft carried Operation IceBridge instruments over the Arctic to study changes in sea ice, glaciers, and ice sheets. (Courtesy NASA/K. Krabill)

Kurtz's job is to wrangle useful measurements from the mission's several instruments. "We have a lot of data from IceBridge: laser altimeter, radar, visible images. All that is not very useable to scientists who are not experts on those instruments. So I turn it into a product, sea ice thickness and snow depth," Kurtz said.

In the case of the snow radar, this meant figuring out how to extract snow depth from the radar signal. "We knew it could work. Theoretically it should be easy, two peaks in the radar, but actually you rarely see that," he said. The signal for the top of the snow was weak, but Kurtz was



These figures illustrate the methods used to detect the depth of snow on ice using a special snow radar. Figure (a) is a processed snow radar echogram with air/snow (red) and snow/ice (black) interfaces indicated. Vertical white lines indicate where there was temporary loss of the snow radar signal along track. Figure (b) shows an individual snow radar return with clearly defined peaks in return power at the air–snow and snow–ice interfaces. Figure (c) shows an individual snow radar return with an indistinct air–snow interface. (Courtesy S. L. Farrell et al., 2012, *IEEE Transactions on Geoscience and Remote Sensing*)

able to tease out its signature, and he also figured out how to keep the data series consistent over time as the radar was improved. "It's such a hard measurement to get, but this study shows that the radar works really well. It is our best tool to measure snow depth."

Besides data from IceBridge, Kurtz also examined sea ice thickness data from Europe's Cryosat 2 satellite, ice measurements from Soviet ships, and on-the-ground snow measurements over the last fifty years. These data reinforced that snow depth and ice thickness have changed quite a bit, and helped the team set the changes in context. "In the past, multiyear ice stayed around," Kurtz said. "Now we have ice that comes and goes every year. Snow is much thinner on the ice that comes and goes, about half as deep."

## Beyond the method

Proving an accurate way to measure snow depth, and using that to improve ice thickness measurements, is only step one. With Arctic sea ice continuing its downward trend, Kurtz thinks the radar would be useful to fly every year. "It is expensive to fly," he said. "But there is also talk of putting the radar on unmanned aircraft." Others are looking at how the radar might fit on a small unmanned aircraft, and be operated remotely.

Step two for Kurtz is to get the snow depth and thickness data out to other researchers studying sea ice. He has been working on what he calls "quick look" data. He said, "The campaign flies in March, April, and May. Typically we don't see any of the data for half a year after that. With the quick look, it will be out right away, so the community can use this to forecast what the sea ice will be like over the summer." He has turned the data over to the NASA National Snow and Ice Data Center Distributed Active Archive Center, where other researchers can freely access the data.

Beyond the summer, Farrell sees the data being used to improve longer-term projections of sea ice. "Another interesting goal of IceBridge is to collect data that would better inform models that predict what would happen in the future, ten to twenty years out," she said. Modelers can use the detailed data to make the mathematical equations in their models more accurate, and thus provide better predictions of sea ice in the future. Losing more of this reflective cover will allow the ocean to absorb even more of summer's heat—which will likely be passed along to Earth's climate as a whole.

"The goal now is to gather as much information as we can on the health of the ice pack," Farrell said. "The Arctic plays a key role in the overall climate system, and we need to understand the changes going on there to understand the overall climate problem."

*To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/2013/signs-snow*

## About the data used

| | | |
|---|---|---|
| Platforms | Douglas DC-8 and P3B-Orion aircraft | Douglas DC-8 and P3B-Orion aircraft |
| Sensors | Airborne Topographic Mapper (ATM) | Radar echo sounders; wide-band snow depth radar |
| Data sets | IceBridge ATM L1B Qfit Elevation data | IceBridge Snow Radar L1B Geolocated Radar Echo Strength Profiles |
| Parameters | Ice sheet and sea ice elevation | Ice sheet topography, sea ice elevation, snow depth |
| Data centers | NASA National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC) | NASA NSIDC DAAC |

## About the scientists

Sinéad Louise Farrell is an assistant research scientist at the Earth System Science Interdisciplinary Center (ESSIC) at the University of Maryland, College Park and a visiting scientist at the National Oceanic and Atmospheric Administration (NOAA). Her research interests include remote sensing of polar regions using satellite and airborne altimetry. NASA and NOAA supported her research. Read more at http://www.star.nesdis.noaa.gov/star/Farrell_S.php. (Photograph courtesy NOAA STAR)

Nathan Kurtz is a postdoctoral researcher at the NASA Goddard Space Flight Center. His research interests include sea ice thickness, snow depth mapping, laser altimetry, radar altimetry, and sea ice thermodynamics. NASA supported his research. Read more at http://neptune.gsfc.nasa.gov/csb/personnel/index.php?id=453. (Photograph courtesy NASA)

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http://nsidc.org/daac
NASA Operation IceBridge
http://www.nasa.gov/mission_pages/icebridge
IceBridge Sea Ice Freeboard, Snow Depth, and Thickness Quick Look data
http://nsidc.org/data/docs/daac/icebridge/evaluation_products/sea-ice-freeboard-snowdepth-thickness-quicklook-index.html

# The secrets of leaves

“It’s extremely important that we understand how the carbon cycle is going to change as temperatures rise.”

Kevin Schaefer
University of Colorado Boulder

by Natasha Vizcarra

In the dense, dark night of the oak-hickory forest in the Ozarks, the soil breathes. Burrowing worms, twitchy protozoa, and roots of all sizes join the imperceptible breath that the forest soil takes, inhaling oxygen from air pockets in the earth and exhaling carbon dioxide that wafts up into the tree canopy. At sunrise, billions of forest leaves would take what the soil exhaled during nighttime and give something back, sucking in carbon dioxide for the hard work of photosynthesis, and releasing oxygen to complete the exchange.

Sensors sniff out the comings and goings of carbon dioxide at the Missouri Ozarks AmeriFlux site. (Courtesy M. Burden, University of Missouri)

This silent exchange between land and air is what scientists call a carbon flux, a key piece of Earth's much larger carbon cycle. Somewhere in this temperate forest is a 100-foot tower with prongs and probes that can measure these fluxes. Like a Godzilla-sized breathalyzer, it scans the air for answers. How strong was that waft of air? How much carbon dioxide was in it? How moist was it? How warm or cool?

Researchers such as Kevin Schaefer at the University of Colorado Boulder read these fluxes like a vital sign of the planet's health. They use computer models of the fluxes to understand how this exchange between land and the air will react to future scenarios, such as a much warmer Earth. Studies say that plants can grow up to 75 percent more if carbon dioxide doubles in the atmosphere. Will this and longer growing seasons be the norm, or will drought be a stronger player? How much will ecosystems change? Scientists are turning to these models for answers; yet how reliable are they to begin with? "We need models that we can trust today if we are going to make predictions about the future," Schaefer said. "But right now, these fluxes are a primary source of uncertainty in projections of future climate."

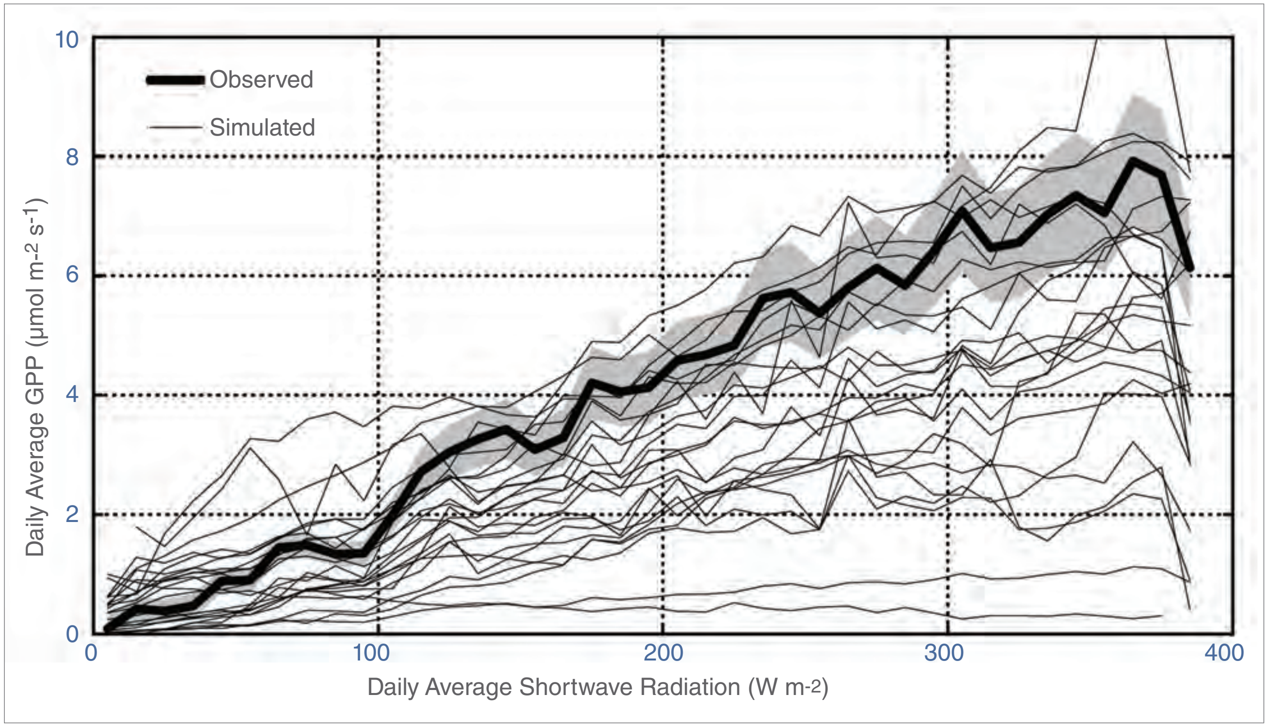
Forestry student Peyton Bennett captures photosynthesis measurements at the Ozarks AmeriFlux site. (Courtesy M. Burden, University of Missouri)

## Worms versus leaves

For carbon flux modelers, it all boils down to things that produce carbon dioxide, and things that absorb it. That means worms, rotting plants, decomposing critters, and all manner of bacteria that exhale carbon dioxide are thought of as respiration. On the other hand, the humble leaf gets its own label: photosynthesis. To measure flux, researchers subtract the amount of carbon dioxide absorbed by leaves during photosynthesis from the amount released during soil respiration. "You've got your tower and your vegetation, like a tree, and carbon dioxide is going up and down, being exchanged, and helped along by vertical wind," Schaefer said.

Many models simulate this recipe for carbon flux, some using satellite data, some built for crop prediction or timber inventory, and some designed for bigger carbon cycle models. In 2009, Schaefer was one of the leaders of a group of seventy volunteer scientists in scrutinizing some forty different models by comparing their simulated fluxes with actual fluxes observed by towers scattered all over the forests and grasslands of North America. After several years of comparing model against model, and simulations against observations, the researchers faced results that were disappointing. "Overall, the models did not perform that well, which was unfortunate, but true," Schaefer said.

However, odd results in the study gave them important clues on how to improve the models. "We thought some models would do better than others, but this was not the case," Schaefer said. "Rather, some tended to do better in some types



This graph shows simulated (gray lines) and observed (bold black line) Gross Primary Productivity (GPP) or photosynthesis as a function of daily average sunlight. The gray bar indicates uncertainty in the observed photosynthesis response to sunlight. Zero photosynthesis indicates winter and the peak indicates summer. Most modeled values did not match the observed values. (Courtesy K. Schaefer et al., 2012, *Journal of Geophysical Research*)

of landscapes than others." The models did best in forested sites, like the Ozarks flux tower site, but did badly in grassland sites. "They performed well in wet sites, but were the worst in dry sites," Schaefer said. The question was, why?

## All in the stomates

"We realized that the models needed to represent drought stress and humidity stress better," Schaefer said. "When leaves do the magic of photosynthesis, they open up their stomata, suck in carbon dioxide, and release water. When the soil is dry, plants cannot afford to lose water, so the stomata close down. But this also shuts down photosynthesis. And that's drought stress." Dry air causes the same reaction in leaves, called humidity stress.

The models need to better simulate the shutdown of photosynthesis during these two stresses. It is a crucial kink to fix. "It's extremely important that we understand how the carbon cycle is going to change as temperatures rise," Schaefer said. "We know that when it is hot enough, photosynthesis slows down. Does that mean respiration will overtake it in a much warmer climate?" Schaefer said, noting that this scenario means more carbon dioxide sticking around in the atmosphere.

The researchers also found that the models need to better simulate the peak of photosynthesis in the summer. Photosynthesis does not occur in certain areas in the winter, because low temperatures cause leaves to fall off and other plants to go dormant. "Photosynthesis peaks in the summer when the temperature is high, the air is moist, and it's the peak of the growing season," Schaefer said. Then photosynthesis drops off again in the fall when it gets cold and the leaves fall. "You've got this seasonal cycle," Schaefer said. "Photosynthesis starts at zero in winter, goes up in spring, peaks in summer, and then goes down in autumn. You can see this in the flux tower observations pretty plainly." Although the models simulated winter and summer correctly, none of them were able to estimate when photosynthesis started in the spring and none got the peak rate of photosynthesis quite right. "They were all over the place," Schaefer said. "Too high, too low, whatever."

## Randomness

After picking the models apart once more, the researchers found a flaw in the way they calculate the photosynthetic power of the entire canopy. "Most models calculate photosynthesis for a single leaf at the top of a tree's canopy, and scale it up for the rest of the canopy," Schaefer said. "So knowing the number of leaves is very important, knowing how photosynthesis scales up to all these leaves is important, and knowing what the photosynthetic capacity of that one leaf at the top is key."

In computer models, it may not be easy to estimate the photosynthetic capacity of hundreds of leaves based on one leaf at the top of the tree. "In real life it may depend on a lot of things the models may or may not have," Schaefer said. "Models tend not to be random. They move toward an average condition, whereas real life is more random. You are comparing real life to a model. It is hard to represent this randomness in computer models."

One of these random unknowns is how much nitrogen is contained in every single leaf in a canopy. "A single leaf's power to perform photosynthesis is essentially a measure of how much nitrogen it has," Schaefer said. Nitrogen is a key nutrient needed in photosynthesis. Plants get the nitrogen they need from the atmosphere, soil, and human activity, like fertilizer application and air pollution. "That is what is missing here," he said. "We need to get a better idea of that parameter, and it's not easy to measure in the field."

Carbon flux models have a way to go before they can simulate nature close enough to predict future fluxes. Schaefer and his colleagues are collaborating with ecologists and plant physiologists who have the leaf nitrogen and photosynthesis data that might be right for the models. He said, "Ecologists observe many, many things, and we have to communicate to them what things we think are most important to us as modelers." Then it is back to work on the models, which Schaefer describes as a continuous balancing act. "Models are like balloons," he said. "You push them in here and they bulge out on the other side. You fix one problem, you might break something else."

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## About the data used

| | |
|---|---|
| Sensor | Eddy covariance sensor from AmeriFlux |
| Data set | North America |
| Resolution | 1 kilometer |
| Parameter | Eddy covariance |
| Data center | NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) |

## About the scientist

Kevin Schaefer is a research scientist at the University of Colorado Boulder. His research includes permafrost carbon feedback, modeling of the terrestrial biosphere, biogeochemistry, and remote sensing of the active layer. NASA, the National Science Foundation, and the National Oceanic and Atmospheric Administration supported his research. Read more at http://nsidc.org/research/bios/schaefer.html. (Photograph courtesy N. Vizcarra)

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AmeriFlux
  http://ameriflux.ornl.gov
Modeling and Synthesis Thematic Data Center
  http://nacp.ornl.gov
North American Carbon Program
  http://www.nacarbon.org/nacp

# Sizing a tsunami

> "With GDGPS data, we can reliably estimate a tsunami's destructive potential within minutes, well before it reaches coastal areas."
>
> Tony Song
> NASA Jet Propulsion Laboratory

by Laura Naranjo

Few people are likely to forget the 2004 Sumatra Earthquake, which produced a devastating tsunami that killed more than 230,000 people across Southeast Asia. When an undersea earthquake strikes near a coastal area or a remote seafloor, the resulting large ocean waves can cause more damage than the earthquake. Although warning systems are in place along many coastal areas, current methods of predicting tsunamis are sometimes inadequate. In the case of the Sumatra Earthquake, there was no warning system at all for the entire Indian Ocean.

Researcher Tony Song at the NASA Jet Propulsion Laboratory (JPL) has been leading a team to develop a way to quickly measure and forecast tsunami size and direction using models coupled with a worldwide network of Global Navigation Satellite System (GNSS) satellites and ground receivers. GNSS can capture a variety of measurements, including land movement resulting from coastal or undersea earthquakes. These data could provide a more direct measurement of strength of the energy unleashed. If researchers can score the magnitude of an earthquake and the intensity of a hurricane, why not create a warning scale for tsunamis?

A tsunami strikes northeast Japan after the 2011 Tohoku Earthquake, generating waves up to 133 feet high along some areas of the coast. Although the Japan Meteorological Agency issued a warning, the tsunami was responsible for more deaths and more damage than the earthquake itself. (Courtesy S. Tomizawa)

## When Earth moves water

Traditionally, scientists have looked at the earthquake itself—using location, magnitude, and depth—to estimate the size and direction of the tsunami. As an oceanographer, Song knew that historic records had proven this method did not always work well. "The scale of the tsunami can be different from the earthquake scale," he said. "Sometimes it's the smaller earthquakes that can generate powerful tsunamis."

The key to understanding tsunami risk was not in the earthquake itself, but in the energy it releases into the ocean. On land, that energy dissipates once the shaking has stopped. But under water, the energy transfers through the ocean, producing waves that ripple across the seas for hundreds or even thousands of miles. Out on the open ocean, these waves may not be noticeable, but once they encounter land, they pile up, creating the devastating walls of water that crash inland.

Scientists suspected that measuring this transfer of energy might help improve tsunami prediction. Song and his colleagues theorized that if they could measure the ground displacement caused by a coastal or undersea earthquake, they could more accurately determine when a tsunami is likely, and where those waves might go. They also thought that GNSS could provide those missing measurements.

As part of the GNSS network, highly accurate Global Positioning System (GPS) receivers located all over the planet record movement in Earth's crust by triangulating signals with a constellation of satellites. Geodetic GNSS stations are much more precise than the GPS in phones and car navigation systems. For example, a consumer GPS device might be accurate to a few meters; geodetic GNSS can be accurate to a few centimeters, and in near-real time.

The hard part often involves collecting and processing that data in a timely manner, sometimes manually. For monitoring natural hazards, Song and his colleagues needed more timely data. So they developed a system to calculate the tsunami energy or scales directly from remotely retrieved real-time GNSS data in the Global Differential Global Positioning System (GDGPS), managed by JPL. GDGPS has more than 100 receivers worldwide, making it one of the largest real-time GPS systems in the world. "With GDGPS data, we can reliably estimate a tsunami's destructive potential within minutes, well before it reaches coastal areas," Song said.

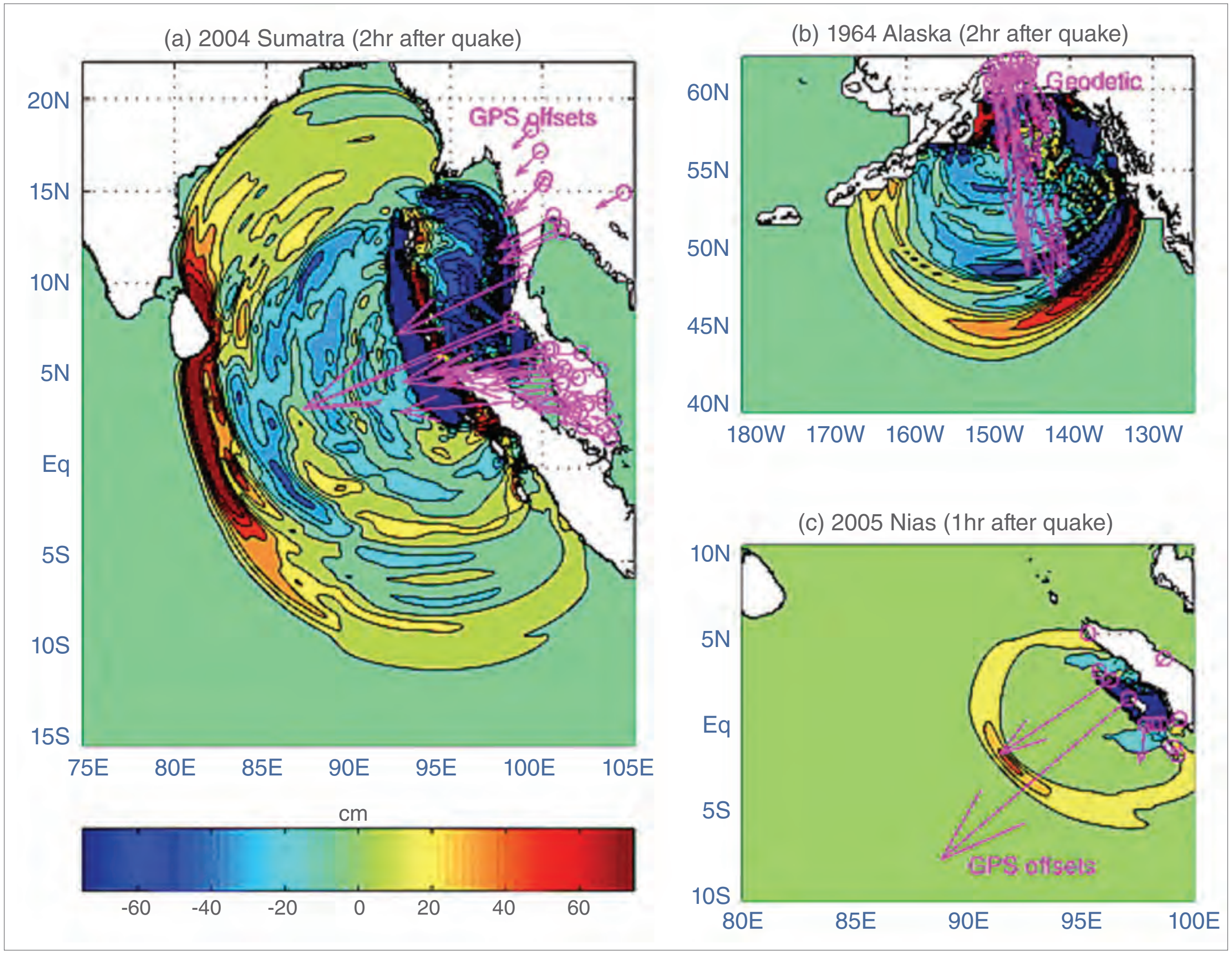
## Looking back to look ahead

Even if there were no receivers near an undersea earthquake, Song and his colleagues could still detect motion from afar and assess the tsunami likelihood. Although GNSS can only detect ground motion in the receiver's immediate vicinity, earthquakes generate such large-scale movement in Earth's crust that the displacement can be derived from distant receivers.

To test his theory, Song looked back at three historic events: the 2005 Nias Earthquake, the 2004 Sumatra Earthquake, and the 1964 Alaska Earthquake, all major earthquakes of magnitude 8.7 or higher. "Tsunamis typically originate at undersea boundaries of tectonic plates near the edges of continents," he said. Previously, scientists thought the culprit behind tsunamis was the upward thrust caused when one tectonic plate collided with another during an earthquake, or the vertical displacement. But Song and his colleagues found that horizontal displacement, which caused more lateral movement along faults, also influenced waves. He said, "Our team found horizontal forces are responsible for two-thirds of the tsunami's height, and they generated five times more energy than the earthquake's vertical displacements." They also noted that horizontal forces best explained how the devastating 2004 tsunami spread across the Indian Ocean.

The 2010 Chile Earthquake triggered a tsunami that washed this house in Pelluhue off its foundation and into the street. (Courtesy Caritas Chile)

Song then compared their GNSS analyses to tsunami records from each of the three earthquakes. In each case, he found a match: the ground slip directions at the earthquake epicenter determined the direction of the waves. He also looked at seafloor displacement to calculate how strong the resulting tsunami might be. He said, "Based upon GPS displacement data and local topography data, we generated a new tsunami scale measurement from one to ten, much like



Scientist Tony Song used GPS to detect tsunami severity and direction after an earthquake. He tested his theory against three historic earthquakes and predicted the resulting tsunamis: (a) the 2004 Indian Ocean tsunami two hours after the quake, (b) the 1964 Alaska tsunami two hours after the quake, and (c) the 2005 Nias tsunami one hour after the quake. Pink arrows are the GPS displacement measurements (not scaled). (Courtesy T. Song, 2007, *Geophysical Research Letters*)

the Richter Scale used for earthquakes." Any tsunami measuring more than a five on this scale would merit a basin-wide warning. For instance, Song classified the tsunami generated by the 2004 Sumatra Earthquake as a 5.8, which would have sent warnings throughout the entire Indian Ocean.

Although GNSS data proved a strong indicator of tsunami wave size and direction, Song also merged his findings with other data to produce a model of the ocean environment through which the waves would be traveling. Song's colleague, oceanographer C. K. Shum, said, "Tony's method is innovative because it also includes the general ocean circulation models in addition to tsunami modeling, leading to more accurate tsunami prediction." By feeding these data into JPL's supercomputers, Song was able to generate results that validated his GNSS findings, and in less than twenty minutes.

## A new wave of data

Song's research had proven that GNSS-based tsunami detection is far more accurate than trying to predict a tsunami solely from the size and location of an earthquake. And when a magnitude 8.8 earthquake struck the coast of central Chile in February 2010, Song was also able to test his system's timeliness. Unlike hurricanes, which scientists can track for days before they strike land, tsunamis can strike within hours after an earthquake. Immediately following the 2010 earthquake, Song received data from a GDGPS station in Santiago, Chile. Although this was a large earthquake, the undersea fault transferred only a small amount of energy into the ocean, so Song and his colleagues calculated the tsunami scale at 4.8. This meant that the Chilean coast nearest the epicenter would bear the worst of the tsunami, while nations along the Pacific Rim would likely be safe. Song's scale proved accurate: unfortunately, Chile did experience destructive tsunami waves, while Japan and Hawaii suffered little damage.

"We were fortunate to have a station sufficiently close to the epicenter," said Yoaz Bar-Sever, JPL manager of the GDGPS system, who participated the 2010 Chile test. Bar-Sever said that more receivers around the world are needed to provide better coverage.

The 2011 Japanese tsunami gave them another chance to test their system—in retrospect. Song's team retrieved data from the Geospatial Information Authority of Japan, the largest GPS monitoring array in the world, and demonstrated that the existing Japanese GPS network could have determined the tsunami energy or scale more accurately for early warnings, instead of using of the earthquake's magnitude. Had the GPS system been used in an operational way, more lives could have been saved.

Developing the tsunami scale is just the first step in the process. "NASA is not developing the tsunami warning system," Song said, "but rather a tsunami detection system." Now Song is working on the next step: how to quickly relay the GNSS-derived tsunami scales to the agencies that do issue those warnings. He and his colleagues are collaborating with the Pacific Tsunami Warning Center (PTWC) in Hawaii, and the Pacific Marine Environmental Laboratory (PMEL) in Seattle. PTWC monitors earthquakes across most of the Pacific and Indian Oceans, and determines when to issue tsunami warnings, while PMEL focuses on tsunami observations and research development. Shum said, "Tony's wave energy detection system can be a useful tool, along with the available buoy data, to help a tsunami disaster center decide whether a tsunami threat is imminent or not."

Song, Shum, Bar-Sever, and their colleagues are still developing a way to integrate Song's tsunami scales into the PMEL and the PTWC systems. They hope that offering more accurate tsunami warnings to all Pacific Rim nations will reduce the number of false alarms, as well as save lives.

*To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/2013/sizing-tsunami*

## About the data used

| | |
|---|---|
| Satellite | Global Navigation Satellite System (GNSS) |
| Sensor | GNSS Receivers |
| Data set | GNSS Data Archive |
| Resolution | 30 second or more frequent |
| Parameter | Latitude and longitude |
| Data center | NASA Crustal Dynamics Data Information System (CDDIS) |

## About the scientists

Yoaz Bar-Sever is a principal engineer at the NASA Jet Propulsion Laboratory, where he is the program manager of the Global Differential GPS System. He has been involved in GPS technology development and its scientific applications. His key contributions cover the areas of GPS orbit and signal modeling for precision terrestrial and spaceborne GPS navigation. NASA supported his research. Read more at http://www.gdgps.net/about/index.html. (Photograph courtesy Y. Bar-Sever)

C. K. Shum is a professor and distinguished university scholar at the Division of Geodetic Science, School of Earth Sciences, Ohio State University (OSU). He studies satellite geodesy, sea level changes, satellite oceanography and hydrology, and geodynamics and ice mass balance. NASA and NSF supported his research. Read more at http://www.geology.ohio-state.edu/faculty_bios.php?id=83. (Photograph courtesy C. K. Shum, Ohio State University)

Tony Song is an oceanographer at the NASA Jet Propulsion Laboratory. He studies using GPS to detect tsunami scales and genesis, as well as researching ocean circulation, ocean modeling, and crustal oceanography. NASA supported his research. Read more at https://science.jpl.nasa.gov/people/Song. (Photograph courtesy T. Song, JPL)

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

NASA Global Differential GPS System (GDGPS)
http://www.gdgps.net

# A tale of two rivers

“People need to know how climate change is going to affect the water resources of Earth.”

Michael Jasinski
Goddard Space Flight Center

by Agnieszka Gautier

The Mississippi River threatens to leave New Orleans dry, diverting into the Atchafalaya River upstream of Baton Rouge. Over millennia, the Mississippi has made natural shifts, wandering hundreds of miles in grand arcs with ancient channels stretching into Texas. A shift may take hundreds, even thousands, of years, during which water patiently cuts the earth, scissoring a riverbed deep enough to eventually lure more water, more rivers until a giant boa constrictor surges.

Rising in northern Minnesota, the Big Brown picks up nutrient-rich sediment along its 2,300 mile-long journey south and deposits the slough into Louisiana’s wetlands. But before it enters the boot of Louisiana, it feels the tug of the

The Atchafalaya River delta meets the Gulf of Mexico. The view is upriver to the northwest. (Courtesy A. Belala/U.S. Army Corps of Engineers)

Atchafalaya River, a distributary on its right bank. By the 1940s, one-third of the great river had been captured. Now, if left to nature, the Atchafalaya threatens to swallow it whole, seizing the commercial value of the Mississippi. Between Baton Rouge and New Orleans dozens of industrial sites illuminate the river like a glowing sea slug, producing chemicals for such companies as Dow and Monsanto, processing agricultural products, refining 13 percent of the nation's gasoline and acting as a major U.S. shipping lane. Here, nature cannot be afforded; the greed of rivers must be attenuated.

## In control of nature

In the largest and most intensively managed floodway in the United States, the Mississippi meanders through an intricate lacework system of concrete dams and spillways, and earthen and rock levees that assist in navigating water. The United States Army Corp of Engineers (USACE) manages these controls for effective water application. "Still," said Hahn Jung, a postdoctoral fellow at the NASA Goddard Space Flight Center, "it is not well known how flooding water moves up and down this area scientifically." Without accurate data, the potential for a miscalculation increases—an impending danger for an unruly floodway so eager to tip its scales.

The better the science, the better the planning. Floodplains, with their multiple variables—soil type, sediment, man-made obstacles, and geomorphology of river rocks, tree roots, and other vegetation—cannot be accurately measured, but a model can offer a simplified representation of water dynamics. It can do a better job of predicting flow. It can better inform the Corps where water needs to go, and just how much. So to improve this science, Jung calibrated a hydrodynamic model using satellite data. He used the LISFLOOD-ACC model, a two-dimensional model that can simulate the flow of a river as well as its spread. "With LISFLOOD, I can provide daily, even hourly, measurements of discharge," Jung said, "something snapshot satellite imagery cannot." A non-calibrated model may falsely represent actual field conditions. But like all models, the LISFLOOD-ACC, reflects the complex reality of an immeasurable scenario, meaning models are not sophisticated enough to account for every nuance and trait within a river. Still they offer the ability to predict future behaviors.

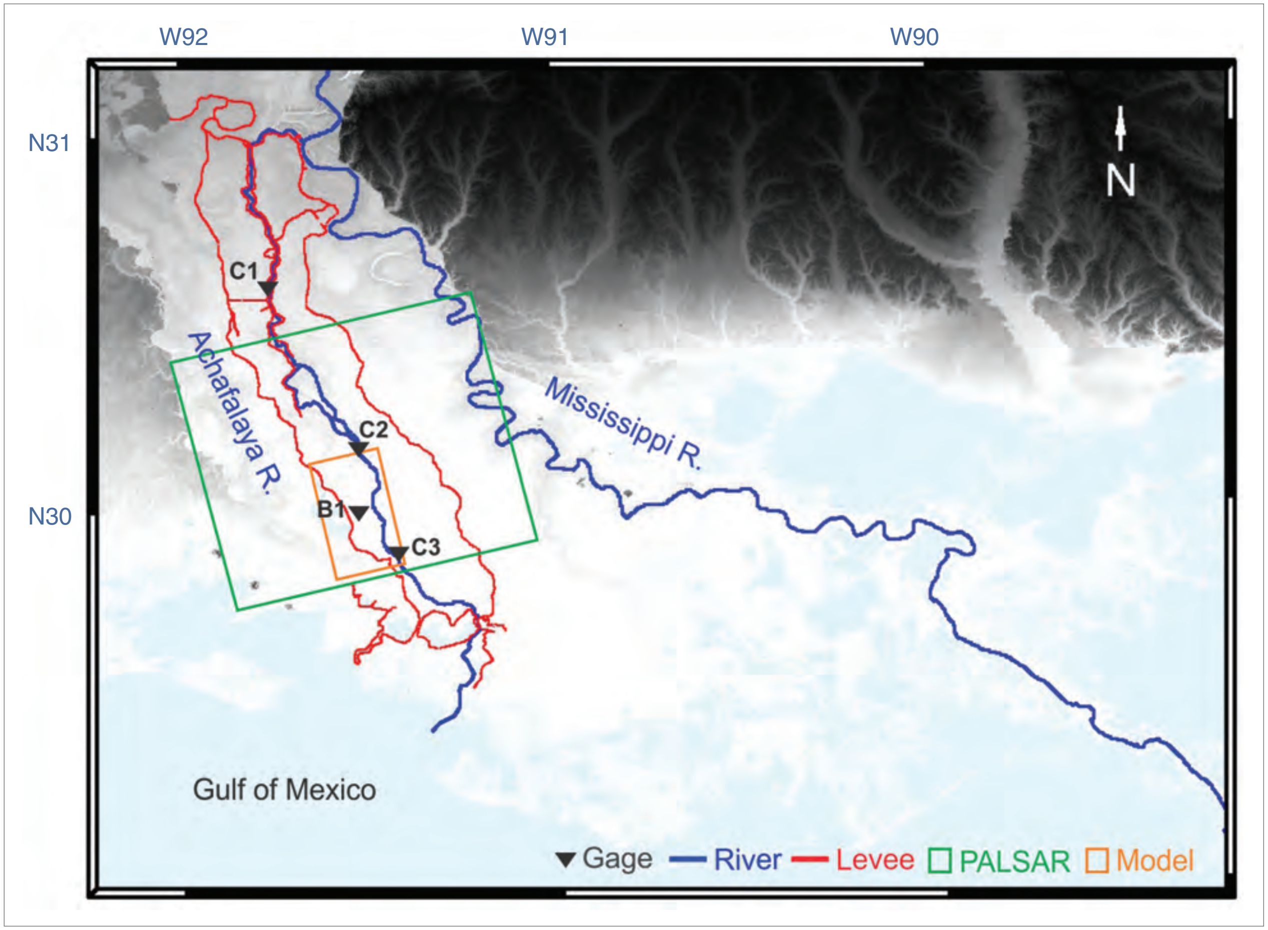
## A balancing act

The Atchafalaya flows west of the Mississippi. It is 20 feet lower and 150 miles closer to the Gulf. Water wants to go there. Connecting the two rivers, in the form of an H, is the Old River, the site where the Atchafalaya could capture the Mississippi. In 1963, the USACE constructed a seven-mile channel system of dams and spillways to relieve some of the Mississippi but not all. Should the shift happen anywhere, it would be here. In the spring of 1973, the Old River Control Structure (ORCS) nearly failed when the Mississippi swelled with unusually high snowfalls thawing in the north and persistent rains sluicing the south. Further down the river with deafening turbulence, the Morganza Spillway opened 42 of its 125 steel gates to assuage the ORCS's vibrating foundation. The only other time this spillway opened was in May 2011.

Controlling a flood is one thing, but maintaining a fragile ecosystem is another. Before the USACE was responsible for allocating the waters in the Atchafalaya basin, water went where it pleased and people accepted it. Now who gets what? Knowing how much water is where leads to better planning. "If you can target annual spring flows with a certain accuracy, then water resource engineers can better allocate and distribute that water," said Michael Jasinski, Jung's mentor and a NASA physical scientist specializing in hydrology.

During flooding, the Army Corps of Engineers conducts daily depth measurements along the intake side of The Old River Control Complex (ORCS), allowing for flow calculation. The ORCS is designed to channel as much as 30 percent of the Mississippi River's flow into the Gulf of Mexico through its eleven 44-foot wide gates across a 566-foot span that separates the Mississippi and the Atchafalaya Rivers. Although this helps relieve the Mississippi River, farms and nearby ecosystems may be flooded to avoid a catastrophic breach of the levee system. (Courtesy L. Cheung, USDA)

Easier said than done. Farmers ask to keep their soils saturated, not drenched. Shrimpers and fishermen benefit from low freshwater flooding, where nutrient-rich waters create enormous growth of shrimp that then feed trout, redfish and flounder, but municipalities, like the one in New Orleans, ask to keep levels high, countering saltwater intrusion into their drinking waters. Opening floodgates, as was done recently in May 2011, displaces larger animals. Deer struggle to find ground, levees trap alligators, and feral hogs



The Atchafalaya Basin Floodway System (ABFS) is bound on the east and west by levees in southern Louisiana. The upstream main channel in the basin diverts the Lower Mississippi River and flows out to the Gulf of Mexico. The orange rectangular box represents the model study area and the green diagonal box indicates the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) swath. Levees and gauges are marked with red lines and inverted black triangles. (Courtesy USGS National Geospatial Program and USGS Coastal and Marine Geology Program)

drown. And still conservationists say the wetlands need silt to replenish.

Since the 1600s, having been considered "wastelands" for centuries, more than half of these fragile ecosystems have been converted for other purposes. Wetlands function much like sponges, absorbing floodwaters, and then slowly releasing them. The largest swamp in the United States, the Atchafalaya flood basin combines wetlands and river deltas that buffer against major catastrophes. But levees steer Mississippi waters and nutrients away from wetlands, and without regular flooding, wetlands compact.

## The science of planning

Jung's calibrated model offers a foundation for studying river discharge worldwide. "Who ever thought you could measure discharge from space?" Jasinski said. "Twenty or so years ago, the only way to measure discharge, was to get in a boat and lower a flow meter." Satellites will not alleviate the need for in situ measurements in the U.S., as in situ measurements validate models; however, they will be invaluable in ungauged rivers in remote areas of the world. Further, gauges do not typically exist in floodplains.

This work looks forward to a NASA satellite due to launch in 2020. "A mission isn't just launched and then everybody rolls up their sleeves and starts using the data," Jasinski said. The Surface Water Ocean Topography (SWOT) mission will launch altimeters to look at the surface and slopes of rivers, floodplains, and oceans. Once the slopes within these water bodies are determined, models can be further applied to predict discharge or ocean circulation. "This is a bold cut, a new idea," Jasinski said. "We will have a satellite to target land, changes in water storage in lakes and reservoirs, and river discharge." Data will be available where it was not before. "This research isn't just about hydrodynamics," Jung said. "It has far greater implications and potential to prepare communities for upcoming climate change." Climate change affects Earth's water balance. Some areas will become drier, while others wetter. The key to planning is knowing how much freshwater water will go where.

Jung set out to calibrate the hydrodynamic model using a radar technique called interferometric synthetic aperture radar or InSAR. The Advanced Land Observing Satellite (ALOS) carries three sensors, including the Phased Array type

L-band Synthetic Aperture Radar (PALSAR), which offers landscape mapping and monitoring through InSAR. Change in elevation or surface deformation is detected by comparing satellite snapshots over time. ALOS PALSAR cycles every forty-six days, meaning two instantaneous snapshots of water levels could provide a change in the floodplain water elevation.

To get an accurate model, Jung ran the LISFLOOD-ACC for two months, trying to match the change of water elevation within his model to the results of the satellite data. One of the model's calibration parameters is Manning's Roughness, a friction coefficient based on the topography of the riverbed and floodplain. Smooth surfaces, like clay, have a low roughness, but a jagged bottom or something with trees in it will be high. More friction means slower discharge speeds and different water levels. The model is then set up using river gauge data that represent the shape of the channel and the amount of discharge for that particular spot. "Then you run your model," Jasinski said. "And you compare the heights you get for the floodplain with the change of heights from the ALOS PALSAR satellite data and the in situ data. You run it for a number of roughness values and when the value matches the satellite height to the model height, you get your calibrated model. It's a straightforward matching." The best match provides the most-comprehensive value for Manning's Roughness coefficient, and that's the model that can estimate river flow for any number of discharges.

This model, together with future satellite data, may aid in understanding other complex floodplains. "People need to know how climate change is going to affect the water resources of Earth and as a society, we need to adapt to that," Jasinski said. If, and many think when, the Atchafalaya captures the Mississippi, the cities of Baton Rouge and New Orleans need to brace themselves for the potential turn of the Big Brown.

## About the remote sensing data used

| | |
|---|---|
| Satellite | Advanced Land Observing Satellite (ALOS) |
| Sensor | Phased Array type L-band Synthetic Aperture Radar (PALSAR) |
| Data set | PALSAR Level 1.0 |
| Resolution | 20 to 50 meter |
| Parameter | Interferometric synthetic aperture radar (InSAR) |
| Data center | NASA Alaska Satellite Facility SAR Data Center (ASF SDC) |

## About the scientists

Michael Jasinski is a research hydrologist at the NASA Goddard Space Flight Center in Greenbelt, Maryland. His research ranges from hydrologic and hydrodynamic modeling to the retrieval of surface properties using satellite multispectral and altimetric observations. He is currently a member of the ICESat-2 Science Definition team. NASA supported his research. (Photograph courtesy M. Jasinski)

Hahn Chul Jung is a postdoctoral researcher at Hydrological Sciences Laboratory, NASA Goddard Space Flight Center in Greenbelt, Maryland. His research focuses on radar interferometry, wetland hydrology, hydrodynamic models, and flood inundation mapping. NASA supported his research. (Photograph courtesy H. C. Jung)

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## For more information

NASA Alaska Satellite Facility SAR Data Center (ASF SDC)
http://www.asf.alaska.edu

# Crazy bad air

> “There simply aren’t enough ground-based air quality monitors in many regions of the world.”
>
> Erica Zell
> Battelle Memorial Institute

by Natasha Vizcarra

It is obscure. It is scientific jargon. But to Chinese urbanites, PM2.5 is now as ubiquitous as tea. The term refers to airborne particles—from vehicle exhaust and from burning wood and coal—that are so small, several thousand could perch snugly on the pointy end of a sesame seed. These tiny particles can slip into your lungs and blood stream and aggravate heart disease and other illnesses. When PM2.5 levels in the cities rise, the chatter on Weibo, the Chinese version of Twitter, swells. Case in point: when concentrations rose to hazardous levels in Beijing on January 12, 2013, there were nearly 40 million messages on “pollution” and “PM2.5.”

“The term is technical and wonky,” said Angel Hsu, who studies Chinese environmental policy at Yale University. “But Chinese citizens have become very aware of air pollution issues, specially those involving fine particulate matter. I even saw an ad for a rock music festival called PM2.5.” Because of the extremely bad air days in Beijing, residents, visitors, scientists, and policymakers are discovering that open access

Retirees perform tai chi during a smoggy day in Fuyang, China in January 2013. (Courtesy ImagineChina) to air quality data could help warn people when everyone—children, the elderly and even healthy adults—should stay indoors because of dangerous pollution. The data are crucial in the dialogue between citizens and the government in cleaning up the air for years to come. Hsu said it all began in early October 2010 when Beijing residents looked out their windows and saw not the city's cosmopolitan skyline, but something that looked like a whole lot of *wu*.

## Beyond index

"*Wu* is the Mandarin word for fog," said Hsu. "Often, Chinese won't describe a poor air quality day as the result of air pollution, which is called *wuran*. They will say that it's fog." However, it was not a misty blanket of *wu*; it was *wuran* so dense that locals could not make out buildings a mere hundred feet away. The thick smog caused road accidents and flight cancellations in the city, and lingered in the area for about a month. Although Twitter is blocked in China, people found a way to check air quality readings tweeted from a monitor installed at the U.S. Embassy in Beijing and were shocked at the numbers that they saw on a particularly smoggy mid-November day.

The Air Quality Index (AQI) had surged to 557, way beyond the hazardous threshold of 500. AQI levels of 301 to 500 mean that children, older adults and people with heart or lung disease should remain indoors and that everybody else should not exercise outdoors. The embassy ran out of adjectives for AQI levels beyond 500, and had assigned the phrase "Crazy Bad" to AQI levels above 500. Of course, when embassy officials realized that the Crazy Bad AQI level had actually been reached, they quickly replaced it with the more benign "Beyond Index." However, word of the gaffe had already spread worldwide through news reports and social media sites. Residents were confused when they compared the U.S. Embassy's readings with the Chinese government's numbers, which said pollution levels were moderate. While the embassy's numbers were based on PM2.5 particles, the Chinese government's figures were based on PM10 particles, which are larger, coarser air particles, like dust. Government-approved data on PM2.5, which have greater health impacts than PM10, were simply not available to the public. Hsu said, "Many Chinese citizens felt something wasn't right. That's when they turned to the Internet. They really felt that the Chinese government was hiding information from them."

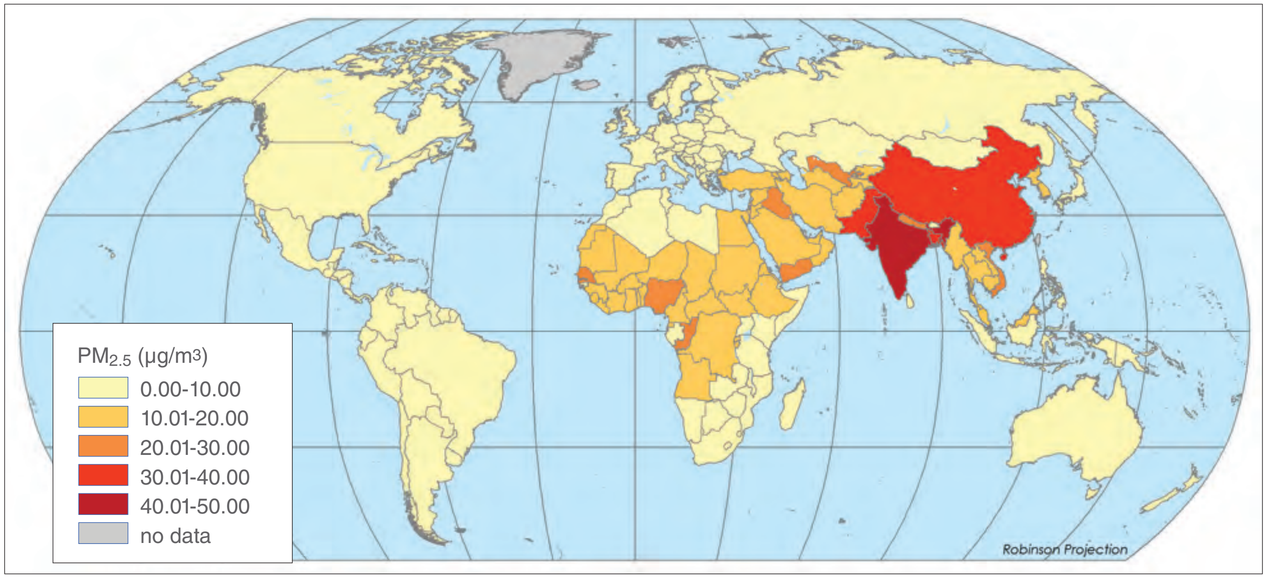
## People and pollution

China is not the only country that had not been offering PM2.5 data to its citizens. Erica Zell, an environmental engineer at Battelle Memorial Institute said, "There simply aren't enough ground-based air quality monitors in many regions of the world." Even where governments measure air quality, they may focus on different parameters, like $NO_x$ or PM10, or the measurements may not be well calibrated. Zell's colleague, Jill Engel-Cox, added, "Some countries do not have monitoring programs at all."

Although ground instruments like the one in the U.S. Embassy in Beijing are useful in alerting people to their daily exposure to PM2.5 pollution, data that span several years can say a lot about air pollution trends. Governments need these data trends to make decisions about air pollution policies. Zell, Engel-Cox, and colleague Stephanie Weber knew that there were not enough ground instruments in China and worldwide to tease out these trends. "We wanted to consistently measure air quality across the globe so policy makers can better address the sources of this both global and local problem," Engel-Cox said.

So they developed a way to use satellite and population density data to measure country-level PM2.5 all over the world for the last ten years. The researchers at Battelle collaborated with Aaron van Donkelaar and Randall Martin at Dalhousie University to make PM2.5 maps using aerosol optical depth (AOD) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-Angle Imaging Spectroradiometer (MISR) sensors on the NASA Terra satellite. They also used a world population data product from the NASA Socioeconomic Data and Applications Center to weigh the results by population distribution so that PM2.5 concentrations in more densely populated areas were more heavily weighted than concentrations in less populated areas. "Pollution concentrations are highest near population centers, since the industrial and transportation sectors are leading sources of emissions," Zell said.

The researchers then worked with Hsu and her colleagues at the Center for International Earth Science Information Network (CIESIN) at Columbia University to integrate these data into the 2012 Environmental Performance Index. Hsu said, "The index compares countries on a key set of environmental issues, air quality being one of them. While developing this index for the last twelve years, we did not have country-level PM2.5 data because not all countries are at the stage of development where they can measure it," Hsu said. "Using satellite data gave us a more consistent measure of PM2.5 at the country level, using the same data set and the same measures for each country." Their findings showed that while China's air pollution problems have been in the



This map shows average annual human exposure to $PM_{2.5}$ by country for 2010. Reds and oranges indicate the highest levels of exposure; India, Bangladesh, Pakistan, and China scored the worst. (Data courtesy NASA, van Donkelaar et al., 2010, processed by Battelle Memorial Institute)

spotlight in recent years, India had the worst air quality in the world, followed by Bangladesh and Pakistan. China came in fourth.

## Seeing through the smog

As news of the 2012 Environmental Performance Index results added to the PM2.5 chatter in social media, Chinese citizens seemed to be getting results from their Internet campaigns. In November 2011, a Chinese property tycoon launched a Weibo campaign calling for tighter air pollution monitoring procedures in the country. In two days, China's vice minister of environment conceded that Beijing relied on a "limited" system of pollution measurement.

Chinese citizens were also sharing other sources of data. In January 2012, Chinese filmmaker Michael Zhao launched a Web site featuring daily skyline images of major Chinese cities and other major cities in the world. The site, China Air Daily, also published the U.S. Embassy PM2.5 readings, along with views of the cities from space, using MODIS images from the NASA Land-Atmosphere Near Real-time Capability for EOS (LANCE) system. Zhao's site was featured in news stories around the world and drew even more attention to China's air quality woes.

Around this time, Hsu said, the Chinese government announced that it had been collecting PM2.5 data all along but had not seen the need to release it and that PM2.5 concentrations in China had actually decreased over the last ten years. "None of the data have been transparent," Hsu said. "So none of the citizens believed it. That was a big lesson for the Chinese government; transparency is absolutely essential for effective environmental management and communication."

## A wind shift

Finally, in January 2013, China began publishing PM2.5 air quality ratings for seventy-four of its cities. "It looks pretty consistent with how you would expect air quality to be in these cities—a lot of them are showing very severe PM2.5 pollution," Hsu said. China has also started to address some sources of pollution. A month after publishing PM2.5 data, the government announced a plan to curb emissions with a ban on sub-standard diesel-fueled vehicles.

Chinese citizens continue to be passionate about improving the air they breathe and compulsively check both official Chinese air quality readings and those tweeted by the U.S. Embassy in Beijing. On January 12, 2013, netizens noted that AQI readings at the U.S. Embassy in Beijing reached a staggering 755. The government did not publish the actual value, but only noted that it was "Beyond Index."

Hsu says it is a great start. She said, "Scientists say that if you start releasing PM2.5 data today, citizens will have a better idea of the dangers and the extent of the pollution that they are facing. Still, experts in China say it will take about twenty to thirty years to clean up the air in Beijing."

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## About the data used

| | | | |
|---|---|---|---|
| Satellites | | Terra | Terra |
| Sensors | | Moderate Resolution Imaging Spectroradiometer (MODIS) | Multi-angle Imaging Spectroradiometer (MISR) |
| Data sets | Global Rural-Urban Mapping Project, version 1 (GRUMPv1) | MODIS Level 2 Aerosol | MISR Level 2 Aerosol |
| Resolution | 30 arc-seconds, latitude/longitude | 10 kilometer | 16 x 16 array of 1.1 kilometer radiance pixels |
| Parameters | Human population density | Aerosol optical depth | Aerosol optical depth |
| Data centers | NASA Socioeconomic Data and Applications Center (SEDAC) | NASA MODIS Level 1 and Atmosphere Archive and Distribution System (MODAPS LAADS) | NASA Langley Research Center Atmospheric Science Data Center (LaRC ASDC) |

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## About the scientists

Jill Engel-Cox is a senior program manager at Battelle Memorial Institute. Her research focuses on applying complex environmental data to public policy as well as clear and useful communication of environmental data to policymakers, stakeholders, and the public. NASA supported her research. Read more at http://www.engel-cox.org/jill/resume.html. (Photograph courtesy J. Engel-Cox)

Angel Hsu is a postdoctoral associate and project manager of the Environmental Performance Measurement Program at the Yale School of Forestry and Environmental Studies in New Haven, Connecticut. Her research focuses on environmental performance measurement and data-driven approaches to environmental policy-making and governance. NASA supported her research. Read more at http://hsu.me. (Photograph courtesy D. Constable)

Erica Zell is a program manager at Battelle Memorial Institute. Her research focuses on the application of satellite data for environmental analysis and training, including environmental indicator design and air quality and climate change analysis; and geospatial analysis of environmental data for land use, ecosystems analysis, climate change, and renewable energy. The NASA Applied Sciences Program supported her research. (Photograph courtesy E. Zell)

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https://eosweb.larc.nasa.gov
NASA Land-Atmosphere Near Real-time Capability for EOS (LANCE)
http://earthdata.nasa.gov/data/near-real-time-data
Moderate Resolution Imaging Spectroradiometer (MODIS)
http://modis.gsfc.nasa.gov
Environmental Performance Index
http://sedac.ciesin.columbia.edu/data/collection/epi

# Mercury raining

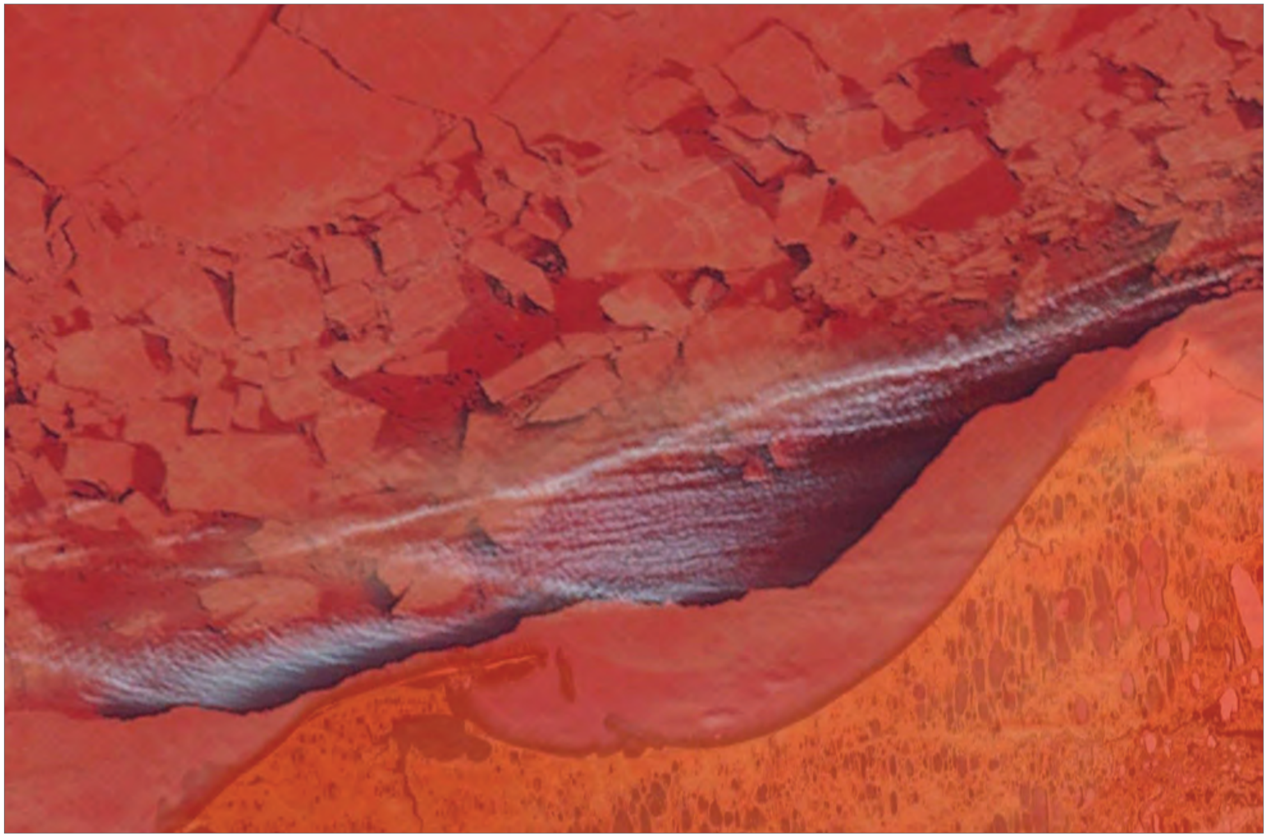
“If I told someone in a bar about this, they’d think I was crazy. You can’t see it without these instruments and satellites, but it’s there.”

Matthew Sturm
University of Alaska Fairbanks

by Karla LeFevre

Air Force pilots flying over the Arctic in the 1950s first noticed a brown haze and wondered “What the heck is that?” said researcher Paul Shepson. It turns out an element called bromine was partly to blame for the dirty hue. Today atmospheric chemists like Shepson know it is actually part of the Arctic atmosphere doing its own spring cleaning. “Mother Nature got a really good idea,” he said.

Every March in the Arctic, the atmosphere follows a certain cleaning regimen: combine upwelling bromine, plenty of cold air, and spring sunlight. When these ingredients mix,



This false-color satellite image shows sea ice in the Chukchi and Beaufort seas (red) near Barrow, Alaska. Dark areas indicate cracks, or leads, in the sea ice while gray streaks show vapor plumes upwelling from the leads. Red-orange shades indicate snow cover. The image was created with data acquired by the Terra MODIS satellite on March 24, 2012. (Courtesy NASA, Nghiem, et al. 2013) a chemical chain reaction ensues, and scrubs pollution out of the air. Scientists call this reaction a bromine explosion. The result? The atmosphere is much cleaner, but there is a catch. The cleaning process works so well that it causes a gaseous form of mercury to fall out of the sky.

So what happens to all that mercury? Does it get released back to the atmosphere, or does it stick around? That question led Shepson and colleagues to understand more about bromine explosions as the Arctic continues to warm and change.

## In search of salt

Barrow, Alaska is an ideal place to get a closer look at bromine explosions. At the northernmost tip of the U.S., this small town looks like an arrow pointing toward the Arctic Ocean. To the left and right are the Chukchi and Beaufort seas. In several ways, this makes Barrow a salty place, and sea salt contains bromine.

Frost flowers also contain it. These delicate, crystalline structures sprout on top of fresh sea ice when the air is calm and colder than the ice below. As if by magic, sea salt is pulled to the surface of the ice and forms a tiny root-like opening. Saturated water vapor then threads more salt up the opening into the freezing air until it builds on itself, eventually appearing as frost in full bloom. “Scientists are human like everyone else, and we’re attracted to bright, shiny things,” explained Shepson. But the flowers are more than beautiful. Frost flowers contain about three times as much salt as any other type of frost or surface, and possibly a lot of bromine.

Another potent source of bromine, they reasoned, might be the fresh sea ice. When ocean water freezes, salt accumulates into droplets called brine that can get trapped in watery pockets between ice crystals. If the ice is frozen long enough, say one to ten years, the brine eventually drains out. So an ideal place to measure bromine was over both new and old sea ice, over salty conditions and not-so-salty conditions. Huge cracks in the sea ice, called leads, were just the place.

One of local fame is the Barrow Lead. The Inupiaq people stand at the edge of this wide “whale road” every spring to hunt bowhead whales. Subsistence whale hunters like the Inupiaq can normally walk right from the shore on sturdy landfast ice, the ice attached to land, and set up their camps on heavy multiyear ice. But as recently as spring 2013, scientists at the University of Alaska Fairbanks reported finding zero multiyear ice in the Beaufort Sea. As Arctic sea ice conditions continue to change, scientists are grappling with how these changes will shape future conditions. Shepson said, “If we sample the air above all these surfaces that represent the old world, like the multiyear ice, and above lots of fresh, new ice like we have now, and over what represents the future—meaning open water—we can predict how climate change will impact the Arctic’s ability to clean itself.”

Son Nghiem, lead scientist for the bromine investigation, wondered if such change has led to more bromine explosions, and possibly more mercury ending up on the land or ocean. On the other hand, since bromine reactions require frigid temperatures, they might eventually stop altogether with a warmer Arctic. There was also the mercury. Does it change back into a gas and return to the atmosphere, or does it wind up in the food chain?


A field of frost flowers in full bloom catches the springtime sunlight. These freshwater frost flowers are similar in appearance to their salty, arctic counterparts. (Courtesy B. Berwyn/Summit County Citizens Voice)

## Searching high and low

These complex questions called for a complex approach. Nghiem said, “From the ground, to the air, to space, we measured it all.” Nearly thirty researchers conducted the Bromine, Ozone, and Mercury Experiment, or BROMEX, in spring 2012. They used half a dozen satellites to gather data over Barrow and the Chukchi and Beaufort seas for bromine, mercury, and other atmospheric markers like ozone. With an eye out for polar bears, they also set up instruments at field sites and combed the area for snow, ocean, and air samples.

Other measurements were riskier to gather. They needed to place instruments in the Barrow Lead just before the spring melt began breaking up the ice. Physical scientist Matthew Sturm knew the challenges firsthand from his days with the U.S. Coast Guard and U.S. Army. “It’s sort of like the winter world you’re used to,” he said, “except it’s things breaking up, and sliding around, and

From left to right, researchers Bill Simpson, Matthew Sturm, and Carl Kippe venture out into an open sea ice lead to collect water samples and measure upwelling vapor for its bromine content. (Courtesy D. Perovich/Cold Regions Research and Engineering Laboratory)

getting crunched up." His task was to somehow get two instrument-laden buoys to hitch a ride on chunks of ice as they floated down either side of the lead. "The goal was to put each instrument out far enough to see the bromine explosions, but not so far so that it couldn't talk back to us, and not so far that it would get swept away," he said. Adding to the challenge was the small window they would have. It had taken the team months to design and outfit the expensive instruments, but they would have just a few minutes to deploy them from a helicopter. Nghiem said, "Matthew knows Alaska like the back of his hand. It worked perfectly, and that is tremendous."

They also needed to gather air samples over remote areas with small aircraft. Fortunately, atmospheric chemist Shepson was also a skilled pilot. Spotting frost flowers during one flight, he banked to fly downwind from them for the best bromine measurements, always mindful of where to land his small plane in case of engine failure. "It's incredibly beautiful up there," he said. "Sometimes scary though. We flew over pretty unpopulated areas. Really unpopulated areas."

## Unexpected leads

As the researchers suspected, the data confirmed that more bromine explosions are occurring now than at any other time in the past twenty years—but not near frost flowers. "We were looking for a smoking gun," said Bill Simpson, a chemist at the University of Alaska Fairbanks. "We were expecting to see a huge amount of bromine coming from them, but it just wasn't there." Instead, it was the air above the tundra slightly inland that was steeped in bromine.

Simpson and his colleagues believe snow might be a factor in at least two ways. First, blowing snow carries sea salt from the top of the ice further inland than it otherwise might travel. Once on land, the snow blows across the surface and piles up in drifts. In this way, a small volume of salt gets spread over large distances, effectively covering the surface.

Samples also revealed that the snow cover is more acidic than other surfaces. And that acidity helps initiate the reaction by chemically unlocking the bromide in the salt, which is bromine in its nonreactive form, and releasing it to the atmosphere where it becomes reactive. "It's an amazing, invisible process," Sturm said. "If I told someone in a bar about this, they'd think I was crazy. You can't see it without these instruments and satellites, but it's there."

Whatever role snow plays, however, remains to be solved in the next round of studies. But the

Scientist Ignatius Rigor lies at the edge of a frozen sea ice lead to photograph frost flowers. In the background, a vapor plume can be seen along the horizon as it wafts up from an open crack further down the lead. (Courtesy C. Linder/chrislinder.com)

## About the remote sensing data used

| | | | | | | |
|---|---|---|---|---|---|---|
| Satellites | Terra | Terra, Aqua | Aura | Quick Scatterometer (QuikSCAT) | Defense Meteorological Satellite Program (DMSP) F17 | Aqua |
| Sensors | Moderate Resolution Imaging Spectroradiometer (MODIS) | MODIS | Ozone Monitoring Instrument (OMI) | SeaWinds | Special Sensor Microwave Imager/ Sounder (SSMIS) | Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) |
| Data sets | MODIS Level 2 Aerosol | MODIS Level-3 Sea Ice Extent, and Ice Surface Temperature | OMI Level 3 Backscatter | QuikSCAT Ku-band Backscatter | Near-Real-Time Brightness Temperatures | AMSR-E/Aqua Brightness Temperatures, Sea Ice Concentration, & Snow Depth |
| Resolution | 10 kilometer | 4 kilometer | 725 kilometer | 25 kilometer | 25 kilometer | 6.25–25 kilometer |
| Parameters | Aerosol optical depth | Sea ice extent, sea ice surface temperature | Bromine, aerosol optical depth | Sea ice extent, sea ice class distribution, melt on sea ice | Brightness temperatures | Brightness temperatures, sea ice concentration, snow depth |
| Data centers | NASA MODIS Level 1 and Atmosphere Archive and Distribution System (MODAPS LAADS) | NASA Land Atmosphere Near-real-time Capability for EOS (LANCE) | NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) | NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) | NASA National Snow and Ice Data Center (NSIDC) DAAC | NASA NSIDC DAAC |

team confirmed that mercury dropped on the surface does not go away; it accumulates. And since plankton and fish cannot digest it, it can get passed along the food chain to whales and of course people. Sturm said, “Mercury deposited in the Arctic could be coming from a power plant in Florida or from a volcano. But the Arctic can plate it out better than any other place.”

As long as there are intermittent cold spells, and some sea ice, it appears the Arctic atmosphere will continue cleaning itself of mercury and other pollutants. According to Nghiem, although the average temperature of the Arctic is indeed rising, unseasonal cold spells have become more common over the last decade, and they are sufficient for beginning the bromine chain reaction. Yet he remains optimistic that their research can help convince governments to limit mercury pollution where possible. Nghiem said, “With the scientific foundation to show this is happening, I hope it will be the basis for making the right decisions, and even help to expedite the right decisions.”

*To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/2013/mercury-raining*

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## For more information

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NASA MODIS Level 1 and Atmosphere Archive and Distribution System (MODAPS LAADS)
http://laadsweb.nascom.nasa.gov

NASA National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC)
http://nsidc.org/daac

NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)
http://podaac.jpl.nasa.gov

Implications of Arctic Sea Ice Reduction on Tropospheric Chemistry
http://seaice.apl.washington.edu/AirChemistry/index.html

## About the scientists

Son V. Nghiem is a senior research scientist at the NASA Jet Propulsion Laboratory. His research focuses on polarimetric scatterometry and scientific applications of scatterometry in land, ice, and snow processes. NASA supported his research. Read more at http://radar.jpl.nasa.gov/people/index.cfm?FuseAction=ShowPerson&pplID=12. (Photograph courtesy of S. V. Nghiem)

Paul Shepson is a professor of chemistry at Purdue University. His research focuses on the exchange of gases between the surface and the atmosphere in the Arctic and in mid-latitude forests. NASA supported his research. Read more at http://www.chem.purdue.edu/people/faculty/faculty.asp?itemID=59. (Photograph courtesy of P. Shepson)

Bill Simpson is a professor of physical chemistry at the University of Alaska Fairbanks. His research focuses on high latitude oxidation chemistry and snowpack photochemistry, and the development of instrumentation for detecting reactive radicals. NASA supported his research. Read more at http://www.gi.alaska.edu/profile/william-simpson. (Photograph courtesy B. Simpson)

Matthew Sturm is a professor of geophysics at the University of Alaska Fairbanks. His research focuses on snow and sea ice physics, and snow in high latitudes the world over, from the Arctic to Antarctica. NASA supported his research. Read more at http://polar.crrel.usace.army.mil/people/personnel_sid/sturm.matthew.html. (Photograph courtesy M. Sturm)

# On the trail of contrails

> “The contrails are trapping more heat in the atmosphere.”
>
> Douglas Spangenberg
> NASA

by Laura Naranjo

Most people have, at some point in their lives, lain on their backs and gazed up at the sky, scouting for clouds that look like puppies or leaping dolphins. Scientists Sarah Bedka and Douglas Spangenberg scan the skies for thin white lines that could be contrails. Contrails are the linear clouds etched across the skies by high-altitude airplanes as more than 90,000 flights per day crisscross the globe.

Whether natural or man-made, clouds can help warm or cool Earth: they reflect incoming sunlight and trap heat in the atmosphere. But until recently, scientists were uncertain how contrails

Contrails, or condensation trails, form when water vapor from airline exhaust condenses and freezes, forming clouds made of ice crystals. Scientists study contrails because, like naturally occurring clouds, they may contribute to a warming or cooling effect in Earth’s atmosphere. (Courtesy J. Thomissen) contributed to each of these effects. Bedka and Spangenberg are trying to find out how much contrails warm the atmosphere, and possibly to mitigate their effects. They helped develop a method that harnessed satellite data to spot contrails and calculate how much warming they might cause. Contrails likely have a small effect now, but increasing air traffic may change that.

## A trail of cloud

While it is easy to imagine that contrails are just dirty streams of pollutants billowing out of airplanes as they cross the sky, in reality they are mostly ice crystals. Water vapor is already present in the atmosphere, but when the extra vapor from the airplane exhaust rapidly saturates already moist air, the water condenses and freezes into minute ice crystals. In fact, the word contrail is short for "condensation trail."

On top of that, most commercial jets cruise at 26,000 feet or higher, where temperatures are cold enough that the large volumes of condensed vapor instantly freeze and form visible contrail clouds. Spangenberg said, "That's why contrails form at the high altitudes where the jet liners fly. Lower altitude aircraft are not going to create them because the temperature is not low enough." In very humid conditions, some aircraft may also produce wingtip vortices, or contrails that spiral out behind each wing. Low-flying planes at airshows often generate what look like contrails, but are simply special effects created by smoke.

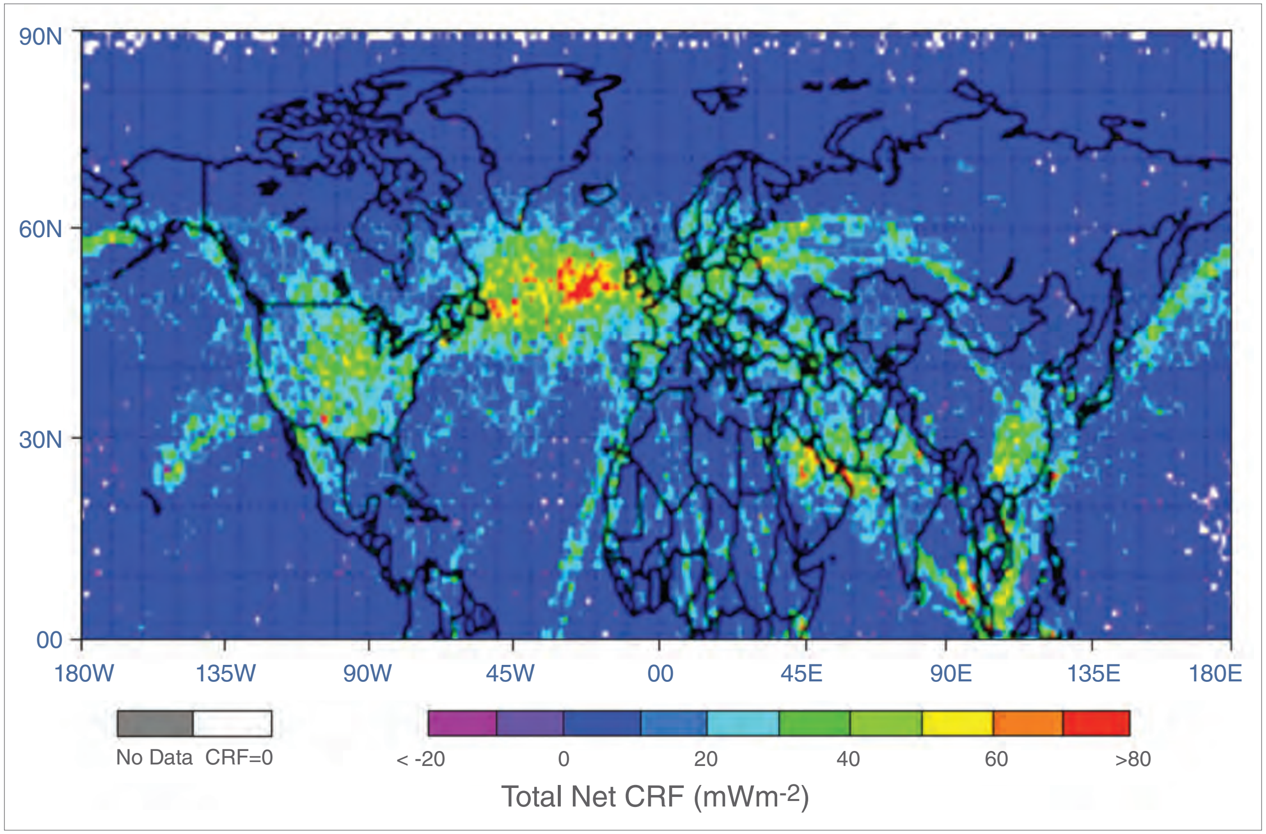
High in the atmosphere, clouds perform a dual role. White cloud tops act like mirrors, reflecting incoming sunlight back out into space and promoting a cooling effect. Clouds can also serve as a blanket, trapping heat emitted from Earth's surface, inducing a warming effect. The researchers needed to analyze both to understand whether contrails have a warming or cooling effect in Earth's atmosphere, what they call the net radiative effect.


The image on the left shows the sky above Würzburg, Germany, without contrails after air traffic was temporarily grounded in 2010. The image on the right shows the sky with regular air traffic on a day when conditions were right for contrails to form. (Courtesy M. Wegmann)

## Masking the spread

To figure out whether contrails contribute more to cooling or to warming, the scientists first needed to isolate contrails from other clouds. But contrails are tricky to identify because they do not always maintain a neat, linear formation that makes them easy to detect. On one hand, contrails must be large enough and persist long enough to be seen in satellite data. Spangenberg said, "Satellites won't be able to see the contrail until it's about one kilometer wide, which is the size of the image pixels." On the other hand, if contrails spread out too much or even merge, they start to mimic the broad layers of cirrus clouds that often occur naturally high in the atmosphere.

So Bedka and Spangenberg, along with their colleague at Science Systems and Applications Incorporated, David Duda, and Patrick Minnis at NASA Langley Research Center, needed to focus



This image shows radiative forcing from contrails (CRF) during January, April, July, and October 2006 from Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) data. Flight corridors over the north Atlantic, north Pacific, southwest Asia, and eastern Europe and Russia stand out remarkably well. (Courtesy D. Spangenberg, 2013, *Geophysical Research Letters*)

on specific contrails. They decided to include only contrails that persisted long enough to be visible in satellite data, yet maintained a linear shape. "It allowed us to apply an automated algorithm to detect those types of contrails," Bedka said. To find contrails, they analyzed satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the NASA Aqua satellite. After running the contrail detection algorithm, the results were matched to known flight paths. This allowed the researchers to find approximately 190 million pixels from linear contrails that they were searching for.

MODIS data also helped the researchers weed out other things on Earth's surface that look linear. Previous studies had produced false alarms, erroneously identifying a variety of features as contrails. "A lot of linear features aren't contrails, like coastlines, rivers, ship tracks, and all kinds of other things," Bedka said, "So we used additional information from the other MODIS bands to help filter those out."

## Airplanes and the atmosphere

The researchers found that contrails have an overall warming effect, acting like a light blanket. "The contrails are trapping more heat in the atmosphere compared to cooling from reflected sunlight," Spangenberg said. However, Bedka and Spangenberg said that the effect is still quite small. "When you consider all of the man-made radiative forcing and all the changes we're making that can affect climate, contrails are one of the smaller effects, compared to carbon dioxide and other emissions," Spangenberg said. "Globally, you would have to increase the contrail effect by roughly 100 times to get the same effect as all of the anthropogenic carbon dioxide in the atmosphere."

They also found that the environment in which the contrails occurred, such as other clouds in the atmosphere or Earth's surface itself, influenced a contrail's net radiative effect. "If planes fly through or over cirrus clouds that already exist naturally, you would minimize the radiative forcing from the contrails," Spangenberg said. Likewise, if contrails form in otherwise clear skies over a hot desert, or over warm low clouds, they will have a much greater radiative effect.

Yet while contrails may not increase atmospheric warming much on a global basis, the researchers discovered that contrails produced more significant regional warming. For instance, over the United States alone, more than 5,000 aircraft may be in the air at once. Many of these flights route through the large East Coast hubs, and generate a mesh of contrails that waft across the skies toward Europe. "We found that the North Atlantic tends to experience the greatest warming effect," Spangenberg said. "That's right along the corridors where planes are flying across the ocean." Another contrail hot spot includes central Europe, which also experiences heavy air traffic.

Bedka and Spangenberg caution that because they focused only on linear contrails, their results underestimate the total contrail effect on Earth's atmosphere. Spangenberg said, "We suspect there's at least a factor of three increase if we include the other types of contrails in our results, and their warming effect." Consequently, they are already conducting new studies that will include not just linear contrails but those that spread over time and become what are called contrail cirrus. "You really have to look at the evolution over time," Bedka said. "Because if the conditions in the atmosphere are right, contrails that start out linear can spread and merge with each other until they become large, relatively uniform areas of ice cloud."

And even though their research supplied a low estimate, it is still the first study that firmly quantifies the contrail effect using satellite data. "That's the unique part of it, that it's an observation-based approach," Spangenberg said. "Most of the other studies of contrails have been modeling-based approaches." Climate modelers finally have a specific set of results to help refine their estimates of contrail effects on the atmosphere. Likewise, researchers now have a basis to investigate the cloud forms that contrails may evolve into, and how that evolution contributes to warming or cooling in Earth's atmosphere. "With increasing air traffic, the effect of contrails has the potential to increase," he said.

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## About the remote sensing data used

| | |
|---|---|
| Satellite | Aqua |
| Sensor | Moderate Resolution Imaging Spectroradiometer (MODIS) |
| Data set | MODIS/Aqua Calibrated Radiances 5-Min L1B Swath 1km |
| Resolution | 1 kilometer |
| Parameter | Clouds |
| Data center | NASA MODIS Level 1 and Atmosphere Archive and Distribution System (MODAPS LAADS) |

## About the scientists

Sarah Bedka is a senior research scientist at Science Systems and Applications, Incorporated (SSAI). She studies infrared satellite data to better understand cloud micro-physical and macro-physical properties, including optically thin cirrus clouds and contrails, clouds over snow-covered surfaces, and cloud retrievals at night. The Aviation Climate Change Research Initiative (ACCRI) and the Department of Transportation (DOT) supported her research. (Photograph courtesy S. Bedka)

Douglas Spangenberg is a research scientist at SSAI. He develops software to display and analyze satellite data and validates satellite retrievals of cloud properties. He also studies ice buildup on aircraft flying though clouds and the cloud radiative forcing of jet contrails. The Aviation Climate Change Research Initiative (ACCRI) and the DOT supported his research. (Photograph courtesy D. Spangenberg)

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## For more information

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## Goddard Earth Sciences Data and Information Services Center

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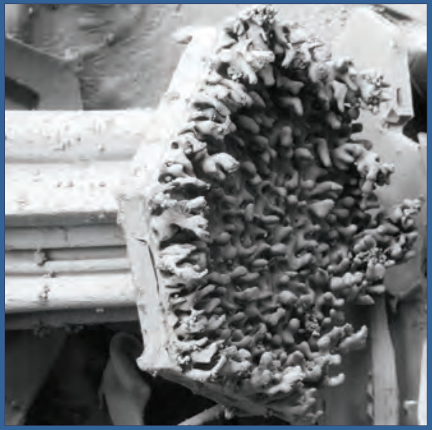

NASA's view from space reveals our dynamic planet

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