National Aeronautics and Space Administration

Sensing Our Planet







NASA Earth Science Research Features **2014**

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

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Front cover images

Top row, left to right:

The dark ring in this image from the Hubble Space Telescope shows gravitational lensing, evidence of dark matter. See the related article, "A speed bump in space-time," on page 6. (Courtesy NASA, European Space Agency, and M. J. Jee)

This aerial photograph of the incoming tides of the Sea of Cortez was taken May 12, 2014, nearly two months after the gates of Morelos Dam between Arizona and Mexico were lifted to allow a surge of water to flood the dry riverbed of the lower Colorado. The event was part of an historic experiment called Minute 319. See the related article, "Connecting the drops," on page 10. (Courtesy F. Zamora/Sonoran Institute/LightHawk)

Zebra stripes come in different patterns, unique to each individual. They are social animals that live in harems. Here two stand in the Okavango Delta, Botswana. Unlike horses or donkeys, zebras have never been truly domesticated. See the related article, "Zebras without borders," on page 22. (Courtesy M. Munneke)

A prescribed fire is applied to a *Pinus nigra* stand in Portugal. See the related article, "Strange bedfellows," on page 40. (Courtesy P. Fernandes)

Bottom row, left to right:

Scientist Hans Røy opens a core sample drilled from the Pacific Ocean seafloor. This sediment can be tens of millions of years old, and contains microbes that provide clues into how organisms survive with no light and little oxygen. See the related article, "Microbes in the murk," on page 14. (Courtesy B. B. Jørgensen)

Assam tea is known for producing a reddish cup of tea with an astringent flavor. It is grown exclusively in the Assam region of India. See the related article, "The price of tea," on page 2. (Courtesy T. Ducasse)

A pressure ridge forms on the sea ice near Scott Base in Antarctica. These form when separate ice floes collide and pile up on each other. Lenticular clouds are seen above. See the related article, "Unexpected ice," on page 28. (Courtesy M. Studinger, NASA)

Back cover images

Top row, left to right:

The NASA Terra satellite captured this true-color image of Hurricane Nadine in the Atlantic Ocean on September 16, 2012. See the related article, "Profiles in intensity," on page 44. (Courtesy Land Atmosphere Near-Real Time Capability for EOS [LANCE] System, NASA GSFC)

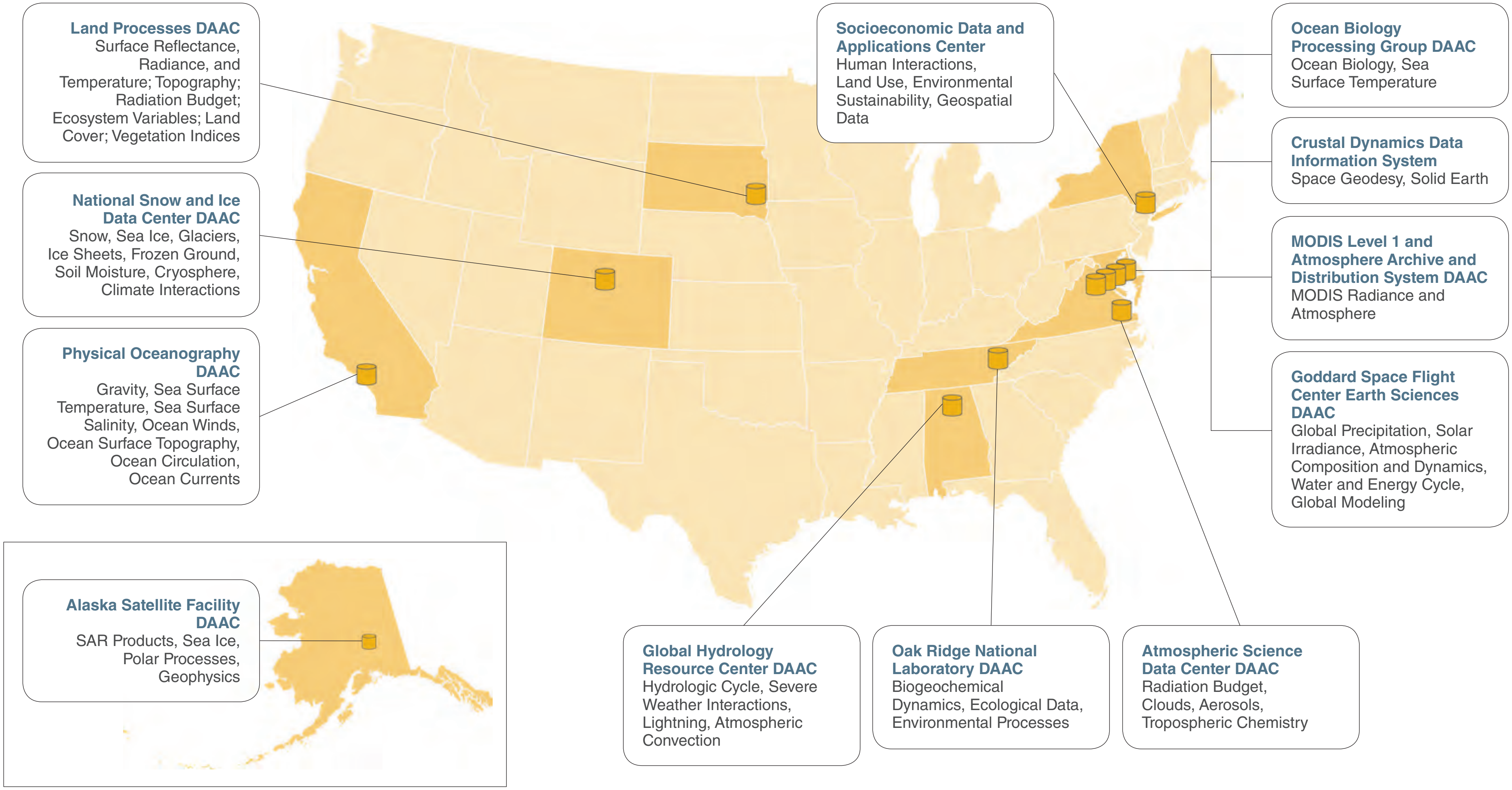
Many locations north of the equator, such as Guyana, tend to receive more rain than locations in the southern tropics. See the related article, "Rooting out rainfall," on page 48. (Courtesy T. Rampersad)

Bottom row, left to right:

A weather radar sits on a shipping container on Addu Atoll in the Indian Ocean where the Madden-Julian Oscillation spawns. Convective clouds form in the background. See the related article, "A baffling signal in the tropics," on page 18. (Courtesy E. Maloney/Colorado State University)

Researchers Matt Pritchard and Gabriel Gonzalez examine a large crack caused by an earthquake in the Atacama Desert of northern Chile. A major earthquake can cause volcanic unrest hundreds of miles from its epicenter. See the related article, "Shake, rattle, and sink," on page 32. (Courtesy M. Pritchard/R. Allmendinger)

In Naruto, Japan, a boundary between different water masses appears as a sliver of still water beyond turbulent waters. The stratification of disparate densities creates varying momentums within the ocean waters. See the related article, "Salt of the sea," on page 36. (Courtesy ume-y/Flickr)



About the EOSDIS Distributed Active Archive Centers (DAACs)

The articles in this issue arose from research that used data archived and managed by NASA Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs). The DAACs, managed by NASA's Earth Science Data and Information System Project (ESDIS), offer more than 6,800 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 Earthdata 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 2014* are available online at the NASA Earthdata Web site (http://earthdata.nasa.gov/sensing-our-planet). Electronic versions of the full publication are 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 water. Several stories for 2014 spotlight how satellite and ground observations can help researchers understand Earth's water cycle, including rainfall patterns, ocean currents and salinity, and ice.

Acknowledgements

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Sensing Our Planet

NASA Earth Science Research Features 2014

The price of tea

“The tea industry wants to come up with new technologies to effectively monitor and manage these plantations.”

Rishiraj Dutta
Asian Disaster Preparedness Center

by Laura Naranjo

“The best tea must have creases like the leather boots of Tartar horsemen, curl like the dewlap of a mighty bullock, unfold like a mist rising out of a ravine, gleam like a lake touched by a zephyr, and be wet and soft like earth newly swept by rain,” wrote the great Chinese tea sage, Lu Yu. More than 1,200 years since Lu Yu wrote these words, people can still be very serious about the pleasures of tea.

Whether consumed British-style with milk, Moroccan-style with mint, or with yak butter

Assam tea is known for producing a reddish cup of tea with an astringent flavor. It is grown exclusively in the Assam region of India. (Courtesy T. Ducasse) and salt in Tibet, the basis for tea is simple: nothing more than hot water and the leaves of a shrub. Growing and producing those tea leaves, however, is anything but simple. Much of the industry remains labor intensive, and as plantations age, tea quality and crop yield have declined. In India, the industry has struggled to modernize and remain competitive. A new breed of tea sages is now waxing scientific instead of poetic on the quality of tea.

Aging plantations

Tea production is a relative newcomer to India's agricultural scene, introduced by the British in the early 1800s to compete with China. In less than 200 years, the tea industry has become India's second largest employer and is a mainstay in the country's economy. India is home to nearly 1,600 plantations that grow an extensive variety of black and green teas. Many plantations have been producing tea for 50 to 100 years or more, and their harvesting and production methods are steeped in tradition. Yet their very age may contribute to the problems the industry now faces.

"The big production period for plantations is between 20 and 40 years," said Rishiraj Dutta, one of the researchers who studied ways to modernize India's aging tea industry. "Most of the plantations in India are more than 60 years old. So their productivity levels and tea quality are starting to decline." Plant age, soil depletion, and increasing pest infestations are making it difficult for plantations to continue producing the quality and quantity of tea that they have in the past.

Dutta and his colleagues hoped to use remote sensing to help get the most out of tea plants. Qualities of specific tea varieties, such as Darjeeling's astringent muskiness, or the bold

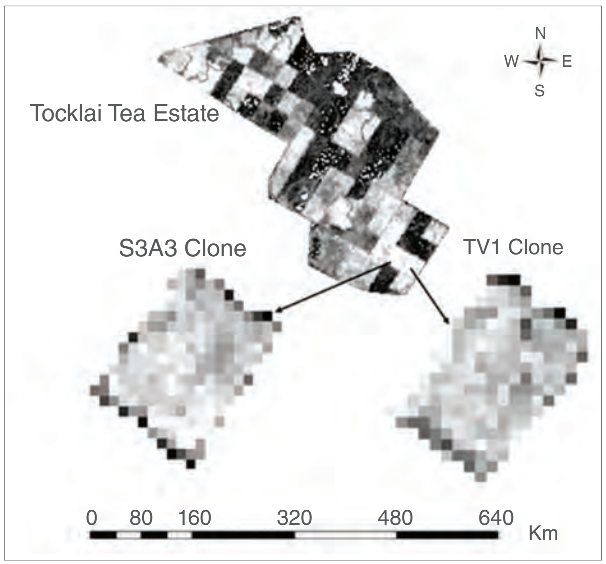
Most tea leaves are still harvested by hand. Tea trees are pruned to waist height so pluckers can easily reach the leaves. (Courtesy M. Williams)

flavor of Assam tea, rely heavily on specific chemicals within the tea leaves. "The tea industry wants to come up with new technologies to effectively monitor and manage these plantations. That's where this research started," Dutta said. Could multispectral remote sensing permit plantation managers to monitor the chemistry of tea leaves from space?

First flush

From the first shoots of spring through the series of summer harvests, called flushes, tea

Tea is the most widely consumed beverage in the world, and is typically grown on massive plantations such as this one in Munnar, India. (Courtesy J. Dohnal)



This Normalized Difference Vegetation Index (NDVI) map shows the sections of two particular tea clones on the Tocklai Tea Estate, in Assam, Northeast India. Researchers observed the two clones to see how certain amounts of chemicals in the leaves, such as caffeine or catechins, affected their spectral reflectance in the image. Data are from the NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). (Courtesy R. Dutta et al., 2011, *Food Chemistry*)

production is tightly controlled to nurture and retain the finest tea qualities. Specific chemicals in the leaves determine tea quality, including the flavor, color, appearance, mouthfeel, and the brightness of the brewed product. A class of compounds called polyphenols has a large influence: Catechins and tannins contribute an astringent taste, and theaflavins play a role in flavor and color. Tannin levels also generate the mouthfeel of tea—whether it feels smooth or rough in the mouth. One of the most well-known compounds, caffeine, helps determine the briskness of tea. Combined, these constituents create a tea's overall flavor.

The chemical makeup of tea leaves develops as the plants grow, meaning the qualities of each flush differ. The first flush of certain varieties, such as Darjeeling, is highly valued. Yet other varieties are considered best during their second flush. Likewise, the subsequent third and fourth flushes will have slightly different qualities and flavors as each of the chemicals increases or decreases. "We considered the first flush and the second flush for this study. We can see the difference in the chemical parameters in the green leaves, as well as with the black tea," Dutta said. Ideally, these chemical differences reveal variations in catechins, tannins, and caffeine content of the leaves from flush to flush.

Dutta and his colleagues focused on two particular tea clones on a plantation that is part of the Tocklai Experimental Station in the Jorhat district of Assam, India. They planned to use a satellite instrument to measure the Normalized Difference Vegetation Index (NDVI), which is a visual indicator of vegetation abundance and health. Remotely sensed NDVI reveals how the leaf canopy reflects light at different frequencies across the electromagnetic spectrum, many of which are invisible to the human eye. In this case, Dutta also hoped it would help distinguish the chemical components in the leaves that were responsible for tea quality.

Producing the perfect tea

Remotely sensed NDVI, however, would only work for observing plants in the field. The researchers still needed to analyze the final tea product to make a correlation between satellite and ground data. For the most accurate results, they would have to harvest and process a batch of tea samples under the same rigorous conditions the plantations used. Between April 20 and June 15, 2009, they had one kilogram of tea leaves carefully plucked. "Quality differences also depend on how we collect the leaves," Dutta said. "So we retained the same sets of pluckers for the entire plucking period to maintain the leaf fineness." The researchers then reproduced standard tea processing commonly used in the industry.

Once the leaves were processed and graded for quality, they assessed the chemical contents of final black tea and green tea products. For the NDVI analysis, they chose imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), an instrument aboard the NASA Terra satellite. The image captured leaf conditions during the second flush when they had collected the leaves.

By comparing the chemistry of the processed leaves with the NDVI analysis of the plantation fields, Dutta and his colleagues found that they could use remote sensing to detect the changes in caffeine, catechins, and various theaflavins that influenced a tea's appearance and flavor. Remote sensing could reduce the amount of hand sampling in the field by monitoring the desired leaf qualities across large sections of tea destined to be harvested in each flush.

Quantifying quality

India produces approximately a quarter of the world's tea, and the tea industry is trying to modernize its practices to keep up with that demand. Plucking tea bushes will likely remain labor intensive, as machine harvesting damages the leaves. Dutta's study proved that satellite imagery can help estate managers track the overall health of the plantations and tea leaf quality. "They want new techniques where it would be cost-efficient for them, and reduce the labor," Dutta said.

Dutta has also applied remote sensing to monitor the replanting of tea. Estate managers cope with not only aging plantations but also the effects of climate change. Tea thrives best in humid, subtropical climates with wet growing seasons. Historically, natural rainfall watered India's plantations, but as climate change shifts rainfall patterns and amounts, some managers must either replant sturdier tea clones or install expensive irrigation systems to water their tea bushes. "These are very old plants, so they are not able to adapt much to the changing environment," Dutta said.

Tracking the growth of replanted tea bushes is an intensive process, but it is critical if a plantation owner wants to continue producing tea. Replanting is completed one section at a time in a process that can take two years or more. Managers must remove old plants, refresh and prepare the soil, and then plant tens of thousands of new seedlings, often alongside other plants that help deter pests. "Once you replant, it takes almost three to four years to get your first production," Dutta said. Estate managers could employ remote sensing to monitor the leaf qualities from seedling plants to first harvest, and identify sections where crop yield might be highest, or where new growth might be stunted by lack of water or pest infestations.

Applying remote sensing allows plantation managers to track tea quality and plant growth, and is one more tool they can use to reduce costs and remain competitive. "If we can manage the plantations well, then they will sustain and produce tea for more than one hundred years into the future," Dutta said.

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/price-tea

About the remote sensing data

Satellite	Terra
Sensor	NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
Data set	ASTER L1B
Spatial coverage	60 x 60 kilometers
Parameter	Reflectance
Data center	NASA Land Processes Distributed Active Archive Center (LP DAAC)

About the scientists

Rishiraj Dutta is a technical officer with the Thailand office of the Asian Disaster Preparedness Center, and has worked with research programs on climate change, agriculture, and food security. He holds a PhD in applied geoinformation and Earth observation. The Tea Research Association supported his research. Read more at http://goo.gl/fiKvos. (Photograph courtesy R. Dutta)

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For more information

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

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

Tea Research Association
http://www.tocklai.net

A speed bump in space-time

"There is much more to the universe than meets the eye."

Rafael Lang
Purdue University

by Jane Beitler

Like many physicists today, Rafael Lang at Purdue University is on the hunt. As in a treasure hunt, the odds of finding the treasure may be slim, but the rewards are huge and the lure of the hunt irresistible. Lang said, "If we were to find something, it would be super, super exciting, another puzzle piece to open this new world."

They are looking for the rest of the universe's matter. Scientists have calculated that some 25 percent of the matter in the universe is not accounted for. They know something is out there because it is exerting gravitational pull on things that we can see. As light from distant stars passes through a galaxy, for example, the gravitational pull of the galaxy bends the light, as if it were passing through a lens. But when scientists

The dark ring in this image from the Hubble Space Telescope shows gravitational lensing, evidence of dark matter. (Courtesy NASA, European Space Agency, and M. J. Jee) measure the mass of the galaxy, and when they study this bending of light using space telescopes, there is more bending than there should be, so something else is out there, pulling. But they do not know what it is, or even what it is like. Maybe it could be passing through you right now as you sit. “There is much more to the universe than meets the eye,” Lang said.

What is the matter?

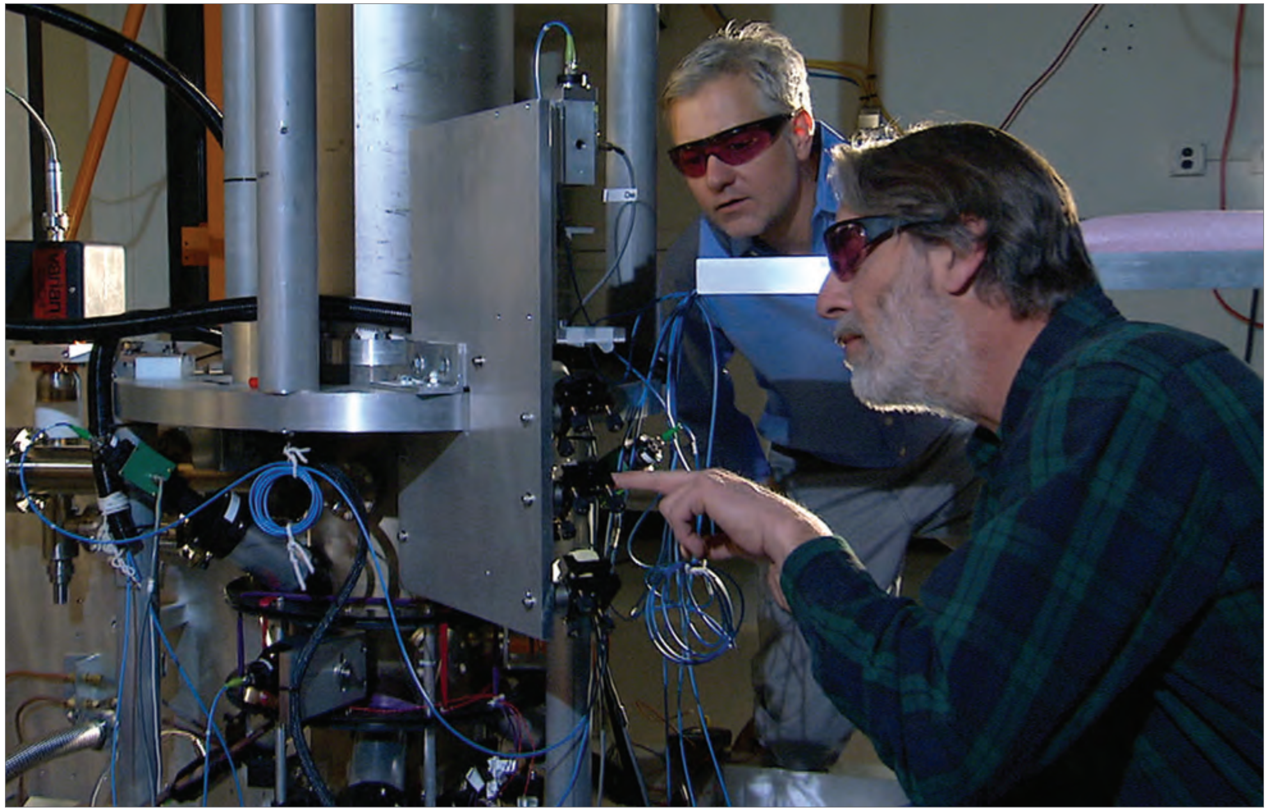
What Lang and others are looking for is a kind of matter that apparently does not reflect light. In our everyday understanding of the universe, we think of it being made of stuff that can be divided down into smaller and smaller components, until we reach some fundamental particles. Though these particles are too small to see with the naked eye, they can interact with us and so can be detected with instruments and experiments.

But the missing matter eludes detection by the usual means. Scientists have nicknamed it dark matter. They are sure it exists, but they know almost nothing about it.

“Dark matter is transcendent. There is dark matter in your office. Think of it like matter that is everywhere,” Lang said.

Several theories have been put forth about the nature of dark matter. Then physicists design experiments that confirm or disprove these theories. “You need to have ideas on how to search for it. If you don’t try to find it you’ll never know,” Lang said.

Until recently it has been generally accepted that dark matter is particulate in nature. Lang has been on a team looking for evidence of dark matter particles. “We look for evidence of change. Like I can look at that sofa: if there are cat hairs on it, then I know the cat has been there, the cat has left something behind,” Lang said. Researchers may construct complex, specialized research instruments based on these theories that detect interactions between dark matter and other matter.

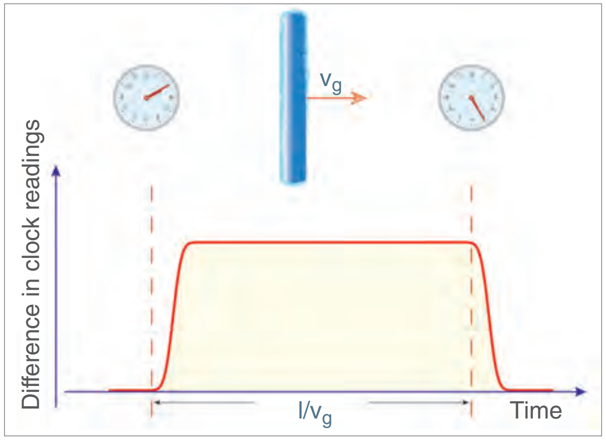


National Institute of Standards and Technology (NIST) physicists Steve Jefferts (foreground) and Tom Heavner examine the NIST-F2 cesium fountain atomic clock. Cesium clocks are one of the most accurate types of atomic clocks. (Courtesy NIST)

Defective knowledge

However, other researchers have postulated that dark matter is something else entirely, that it is not particulate. Instead, what if it is some kind of irregularity in the fabric of space and time? They call this a topological defect, thought to be caused when the universe was cooling, a sort of crack in space.

Lang gave an analogy. “There’s a wedding and a hundred people are sitting at this big round table. Somebody starts eating the salad. They pick up the fork on their left, so the person next to them has to pick up the fork on the left. Now the bride also starts eating, picking up the fork on the right, so everybody around the bride picks up the right fork. At some point in between this poor guy will be sitting with no fork; on his other side



This illustration shows how atomic clocks could be used to detect dark matter as the clocks pass through a topological defect. Before the arrival of a topological defect, the apparent time difference between the clocks is zero. As the topological defect passes the first clock, the two clocks de-synchronize. Then, as the topological defect passes the second clock, the de-sychronization disappears. (Courtesy A. Derevianko and M. Pospelov)

will be someone with two forks. Those two guys are called a topological defect. There's nothing special going on around the left, the right, but where those two guys are sitting, there's a disruption of the forks."

Physicist Andrei Derevianko at the University of Nevada, Reno thinks that dark matter may be organized as a large, gas-like collection of topological defects. If so, Derevianko and colleague Maxim Pospelov at the University of Victoria have proposed to detect it with instruments that are already available: atomic clocks.

A wrinkle in time

Atomic clocks are extremely accurate timepieces. A traditional clock may use a spring and balance wheel oscillating to mark time. An atomic clock counts the oscillations of an atomic electronic cloud. The atomic clocks that currently set the time standard for the U.S. use a fountain of cesium atoms to determine the exact length of a second; these clocks neither gain nor lose a second over about 100 million years, though even more accurate clocks do exist.

Geoff Blewitt at the Nevada Bureau of Mines and Geology explained how an array of atomic clocks could possibly detect dark matter. He said, "It might look like a wall between two parts of the universe. As the Earth is going around in our solar system and galaxy, we are passing through these walls once in a while. The laws of physics change very slightly as we pass through. This will affect an atomic clock. Andrei's concept is that we could look for variations in atomic clock time."

Derevianko and Pospelov have proposed that based on observations and simulations, astronomers have a good idea of how dark matter moves around the solar system. The defects would fly through the Earth at galactic velocities, approximately 300 kilometers (186 miles) per second. The dark matter would shift atomic frequencies, and as a clock swept through, it would become temporarily out of time with other atomic clocks. So they proposed to comb through atomic clock data to look for these out-of-sync nano-moments.

"You look for ways to find too many or not enough forks, you look for atomic clocks that eat the salad twice as fast because they have two forks, or don't eat the salad because they have no forks, that's what you look for," Lang said.

Satellites and dark matter

While arrays of atomic clocks exist on the Earth's surface, researchers were more intrigued by the array of atomic clocks in space. Thirty Global Positioning System (GPS) satellites each carry four atomic clocks on board. GPS receivers on the ground use these time signals from GPS satellites to triangulate their position on the Earth. The greater spatial distribution of the clocks on the satellites gives researchers a much larger picture in which to look for these tiny, temporary time discrepancies. Blewitt said, "Based on Earth's rotation, one of our topological defects would pass through in 200 to 300 seconds. So we should look for glitches in satellite clocks, a pattern, a sweep across the whole constellation."

"We have all the technology in place because of the other applications of GPS. We have tremendous data to look at, really good data going back ten years," Blewitt said.

Initially the team has been looking at GPS data from the International Global Navigation Satellite System Service (IGS) data archive at the NASA Crustal Dynamic Data Information System (CDDIS). "They publish data for every 30 seconds. We can do better than that," Blewitt said. "GPS can give you data every second, so it's really no problem to estimate every fifteen seconds." As a next step, they are starting to look at the high-rate GPS data archive at CDDIS, which includes GPS, Russian Global Navigation Satellite System (GLONASS) satellites, and Europe's Galileo satellites, sampled every second and distributed in near-real time.

Lang said, "That's where their idea is so beautiful and fresh, and so generic. Plus it's easy. All those atomic clocks are out there."

So far the idea is holding up. If the researchers continue to see promising information in the data, they might further refine their search. For example, some of the clocks on GPS satellites are rubidium clocks, and some are cesium clocks. They might constrain their data to the more accurate cesium clocks, and possibly propose the development of a larger network of the most accurate clocks.

Blewitt said, "If we do it, it will be huge news. I'm not really expecting to see it; the chance of any one hypothesis working out is needle in a haystack. But you have to look."

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/speed-bump-space-time

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For more information

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

Global Navigation Satellite System (GNSS) data and product archive
http://cddis.gsfc.nasa.gov/Data_and_Derived_Products/GNSS/GNSS_data_and_product_archive.html

International Global Navigation Satellite System Service (IGS)
http://www.igs.org

About the data

Satellites	U.S. Global Positioning System (GPS), Russian Global Navigation Satellite System (GLONASS), European Space Agency Galileo
Sensors	Atomic clocks, GPS receivers
Data set	Daily 30-second data
Parameter	Time
Data center	NASA Crustal Dynamics Data Information System (CDDIS)

About the scientists

Geoffrey Blewitt is a research professor at the Nevada Bureau of Mines and Geology Seismological Laboratory. His research interests include physics, parameter estimation and stochastic modeling, geodesy, Global Positioning System (GPS) methodology, and GPS applications. NASA supported his research. Read more at http://goo.gl/YkzM7a. (Photograph courtesy G. Blewitt)

Andrei Derevianko is a professor of physics at the University of Nevada, Reno (UNR). His interests include quantum physics, atomic clocks, and fundamental symmetries. The National Science Foundation supported his research. Read more at http://goo.gl/NM5aqt. (Photograph courtesy UNR)

Rafael Lang is assistant professor of physics at Purdue University. His research interests include the nature of and detection of dark matter. The National Science Foundation supported his research. Read more at http://goo.gl/fDmYVI. (Photograph courtesy Purdue University)

Connecting the drops

"I'm amazed at the number of ways people have applied these data."

Peter Thornton
Oak Ridge National Laboratory

by Karla LeFevre

In 1869, John Wesley Powell led a team down the Colorado River to explore the last empty spot on the U.S. map. For ninety-eight days, they toiled in wooden rowboats, finally passing through the treacherous rapids of the Grand Canyon. After the trip, Powell predicted western states would be embroiled in water wars and widespread drought. In fact, the mighty river is now so overdrawn that it has reached its final outlet to the Pacific Ocean only a few times since 1960. The rich ecosystem the river once fed and the people who flourished from the delta are long gone.

Yet the Colorado River is just one of many beleaguered rivers in the United States, raising a question: Do we have enough water to meet our needs, now and in the future? Or is the dry Colorado River Delta a scene that will be played out again and again across the country as we continue to overuse our most precious resource? To help find the answers, 145 years after Powell's expedition, the United States Geological Survey

USGS scientists track the timing of the long-awaited return of the Colorado River to its parched delta in Mexico on March 24, 2014. (E. Kendy/The Nature Conservancy)

(USGS) is embarking upon the first National Water Census, a massive project that aims to take stock of our nation's water supply.

Balancing the water budget

Figuring out how much water is available across the U.S. is not simple. David Blodgett, a USGS civil engineer said, "When we say availability, it has to take into account ecological integrity and human needs along with climate change going into the future." That means estimating how much water will be available over the next fifty years.

To get that estimate, Blodgett said, they need to understand the ever-changing equation of water in versus water out. Like any household budget, a water budget is developed by balancing how much comes in, rain and snowfall in this case, with how much goes out, through runoff, evaporation, and evapotranspiration by trees and plants.

One of their first areas of focus is the Colorado River basin. The river and its tributaries have flowed for millions of years, carving out the Grand Canyon as it winds through a sprawling basin that spans seven states, from western Wyoming to California and into northern Mexico. Dozens of watersheds cross over state and county lines. Hundreds of thousands of pipelines siphon off water for various uses.

In spite of this demand, the Colorado River sustains ecosystems and agriculture in an arid part of the nation. It has made hot, high desert cities like Palisade, Colorado renowned for its plump peaches and thriving vineyards. But at the end of the river, the once-abundant delta is now two million acres of brackish mudflats and shrunken wetlands.

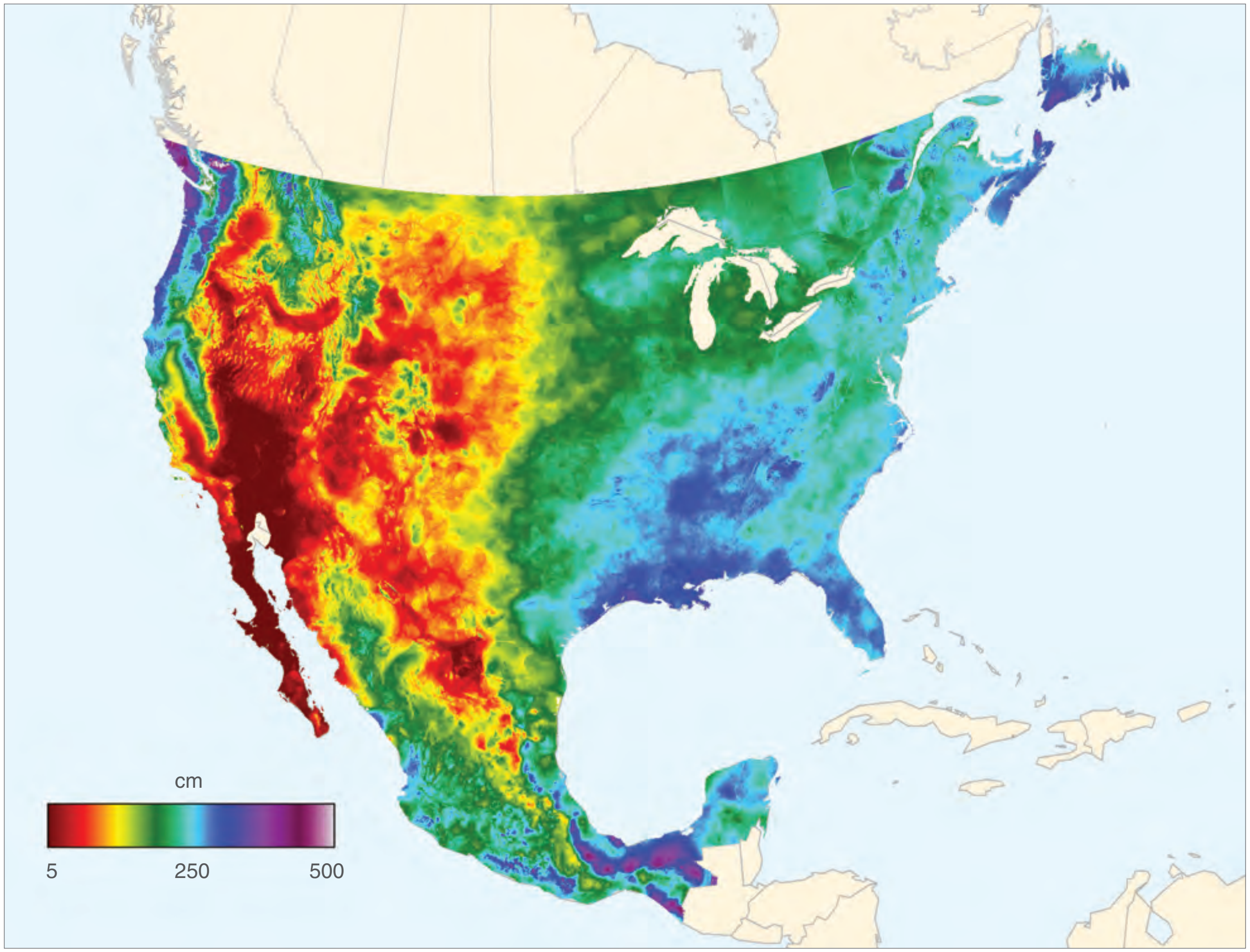
If such decline is preventable, or even reversible, ecologists need to know how much water it takes to sustain an ecosystem. "We need to understand what streams are suitable for what critters—fish, invertebrates, animals, plants—essentially, what the ecosystem type is," Blodgett said. If streams in a given region of the country typically flood each spring, then dry up by mid-summer, for example, that has implications for the types of plants and animals that can live there. "If we can get a national picture of stream flow character," he said, "then we can start to more intelligently say this is how much water we really need for this or that ecosystem to thrive." Likewise, water managers need stream flow data to estimate how much water will be available for their municipalities. The well-established USGS National Water Information System (NWIS) with its more than seven thousand stream gauges is already providing that piece of the water cycle equation.

Realizing rainfall

But there is more to the water budget than runoff. Rainfall, evaporation, and transpiration by plants need to be considered as well. Eventually groundwater will also be factored in, but for now it poses too many challenges, such as understanding the myriad rock properties surrounding groundwater wells. "Getting a spatial distribution of precipitation is hard, but getting a spatial distribution of ground water is even harder," Blodgett said. "So you begin with rainfall. If you don't have that right, you can't get the rest right."

One researcher who knows rainfall is Peter Thornton at the Oak Ridge National Laboratory, who developed a data set called Daymet. While working in Montana forests, he and his colleagues were struck by a lack of precipitation and temperature measurements, critical for understanding forest hydrology and productivity. Temperature data are especially helpful for estimating evaporation and transpiration rates. "We needed a way to connect the dots in between measurement stations," Thornton said.

This aerial photograph of the Colorado River Delta shows a rare sight: the Colorado River (top) flowing to meet the incoming tides of the Gulf of California, also known as the Sea of Cortez (bottom). The photograph was taken May 12, 2014, nearly two months after the gates of the Morelos Dam between Arizona and Mexico were lifted to allow a surge of water to flood the dry riverbed of the lower Colorado. The event was part of an historic experiment called Minute 319. (Courtesy F. Zamora/Sonoran Institute/LightHawk)



This Daymet map displays annual total precipitation for the U.S. and Mexico for 2012. Daymet is a model that incorporates temperature and precipitation measurements from multiple networks of ground stations to produce gridded estimates of daily weather parameters, such as humidity and shortwave radiation. (Courtesy P. Thornton/Oak Ridge National Laboratory)

Thornton realized he could garner observations of temperature and precipitation that were already being made in backyards and back lots across the country, and even in Mexico and Southern Canada. Many of these stations are part of a network of citizen scientists and farmers who monitor conditions on their property using instruments certified by the National Weather Service. By pulling these together with other national networks, Thornton and his team built an extensive map of ground stations across most of North America.

As a result, Daymet, which is available from the NASA Oak Ridge National Laboratory Distributed Active Archive Center, provides daily readings of rain and snowfall, as well as local temperatures and other meteorological data, such as how wet the soil is, daily humidity, and how much moisture is in the snowpack. "Daymet is the rainfall truth," Blodgett said. Thornton added, "Anyone can pull these data for their neighborhood to find out what the long-term temperature is like, or the extreme cold temperature in the last thirty years."

Accounting for ET

Next, Blodgett and his team focused on another major player, evapotranspiration or ET. This is the water lost either through evaporation to the atmosphere, such as through the many tens of thousands of irrigation ditches that cross the country, or through transpiration of plants and trees. For this piece of the hydrologic cycle, they are drawing on both USGS and NASA data.

"We're using remote sensing to get the big picture and then calibrating the remote sensing with these networks of very high accuracy and very high time resolution," he said. The ET database was built using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery that is cross-referenced with eddy flux tower data, measurements that tell them how much water moves through the atmosphere versus down through the ground. Combined, these elements—from stream flow to satellite imagery—are providing the most comprehensive picture of water availability to date.

Restoring water

In 2014 the USGS released a data portal that offers all National Water Census data in one place, including stream flow statistics, Daymet data, ET estimates, and reports on aquatic biology. This will allow anyone, from state water managers to local farmers, to build a budget for their watersheds to monitor changes between supply and demand and ultimately determine how much water is available. "What we're doing right now is providing the best information we can to help people answer that question," Blodgett said.

The team thinks that this surge of scientific measurements will lead to promising applications. "I'm amazed at the number of ways people have applied these data," Thornton said, regarding the Daymet data. "It has taken on a life of its own," he said. Studies using Daymet have ranged from the biodiversity of fireflies to the spread of insect and disease pathogens. "We've even generated this information for vintners so they can customize where they plant particular varietals on which slopes and which elevation and so on," Thornton said.

The data may even prove helpful for scientists working to restore impoverished ecosystems like the Colorado Delta. In spring 2014, scientists conducted an historic experiment by opening the gates of Morelos Dam between Arizona and Mexico long enough to allow a surge of water through. Their goal was to mimic the spring runoff that once refreshed the basin each year. Onlookers danced and played tubas as the first lip of the stream lined the dry river bed on its way through San Luis Río Colorado, Mexico. Two months later, the Colorado River reached the Sea of Cortez, its final outlet to the Pacific Ocean.

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/connecting-drops

About the data

Satellite		Terra
Sensors	Various meteorological sensors	Moderate Resolution Imaging Spectroradiometer (MODIS)
Data sets	Daymet daily surface weather data	Daily land surface temperature and emissivity
Resolution	1 kilometer	1 kilometer
Parameters	Temperature, precipitation, surface radiation, snow water equivalent, vapor pressure	Land surface temperature, emissivity
Data centers	NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC)	NASA Land Processes DAAC (LP DAAC)

About the scientists

David Blodgett is the team lead on the National Water Census Data Access Web Platform. His work focuses on geospatial and climate data standards, including Web service architecture and standards, as they relate to water resources modeling data. NASA supported his research. Read more at http://goo.gl/kMNXDg. (Photograph courtesy D. Blodgett/USGS National Water Census)

Peter Thornton is a scientist in the Ecosystem Simulation Science Group Environmental Sciences Division of the Oak Ridge National Laboratory. His research focuses on measuring how terrestrial ecosystems respond to climate change with a particular emphasis on water and carbon cycle interactions. NASA supported his research. Read more at http://goo.gl/PKX0Mf. (Photograph courtesy P. Thornton /Oak Ridge National Laboratory)

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http://daac.ornl.gov

DAYMET: Daily Surface Weather and Climatological Summaries
http://daymet.ornl.gov

United States Geological Survey (USGS) National Water Census
http://water.usgs.gov/watercensus

Microbes in the murk

“The biggest ecosystem on this planet—the most populated part of this planet—is the subsurface.”

Hans Røy
Aarhus University, Denmark

by Laura Naranjo

Tucked beneath Earth’s rich surface layer, tiny organisms eke out a meager living, subsisting in complete darkness with very few food sources. Their existence defies how we often think of life, abounding with oxygen and light. Strangely enough, up to 30 percent of Earth’s life forms survive in these extreme places. These microscopic organisms, or microbes, cling to lava vents, linger in permafrost, and lurk in seabeds.

“The biggest ecosystem on this planet—the most populated part of this planet—is the subsurface,” said Hans Røy, a researcher at Denmark’s Aarhus University who studies aquatic ecology and

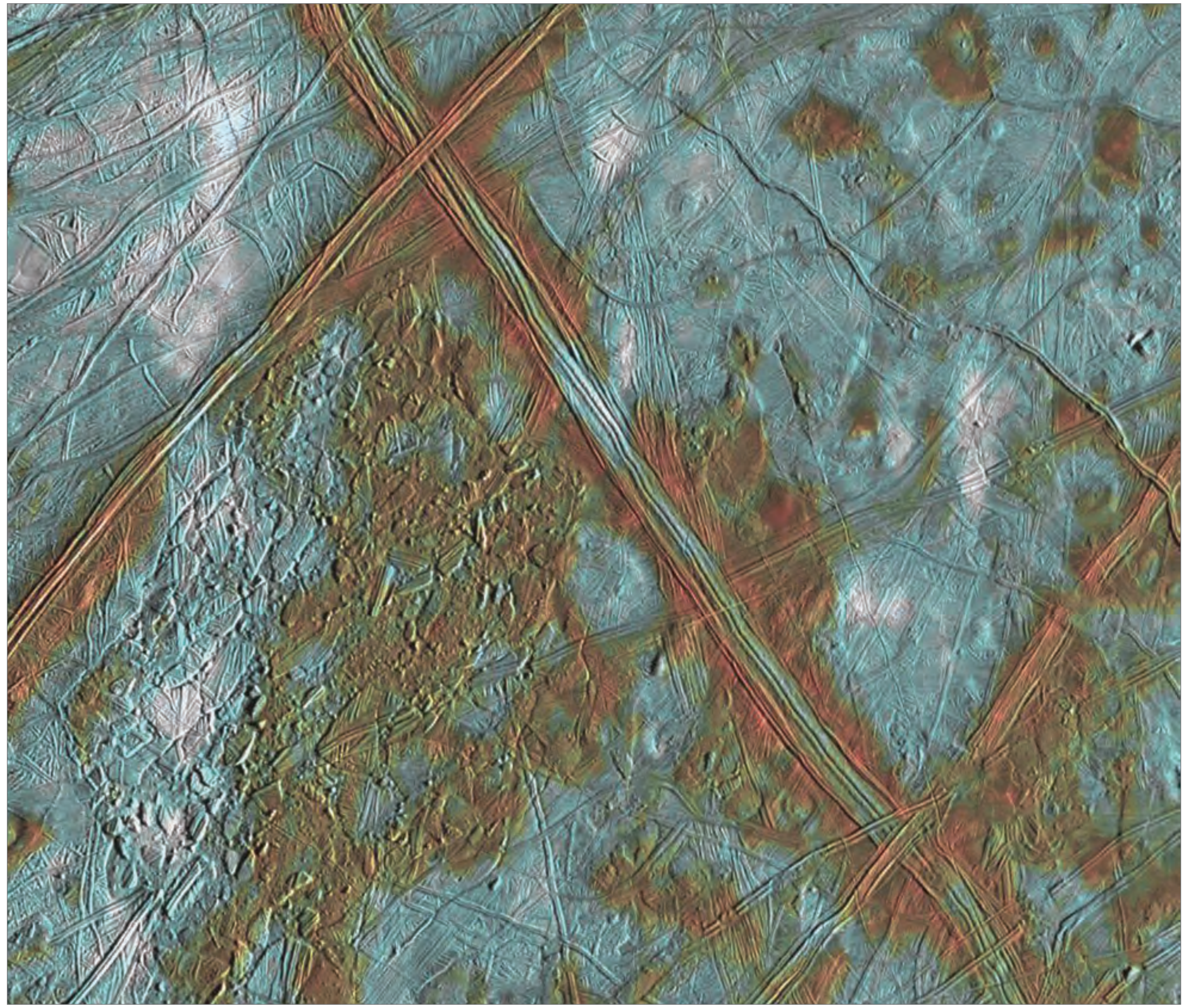
Scientist Hans Røy opens a core sample drilled from the Pacific Ocean seafloor. This sediment can be tens of millions of years old, and contains microbes that provide clues into how organisms survive with no light and little oxygen. (Courtesy B. B. Jørgensen) microbial food webs. Røy seeks out these microbes deep in the seabed, curious about how they survive. "We're interested in what sets the limits for life," he said. How do these organisms survive without food or energy sources? And are they clues to life in other extreme places, such as on other planets?

Searching the gyre

On Earth, scientists find some of the most energy-deprived environments in ocean gyres. Gyres are massive areas of relatively stationary water bound by currents, which sweep nutrients around the gyres rather than into them, rendering them more desolate than the neighboring ocean environments. A group of Røy's colleagues had discovered an oddity in the South Pacific Gyre: its remote and desolate seabed contained oxygen—and microbes—and they suspected the North Pacific Gyre might harbor similar conditions, as well.

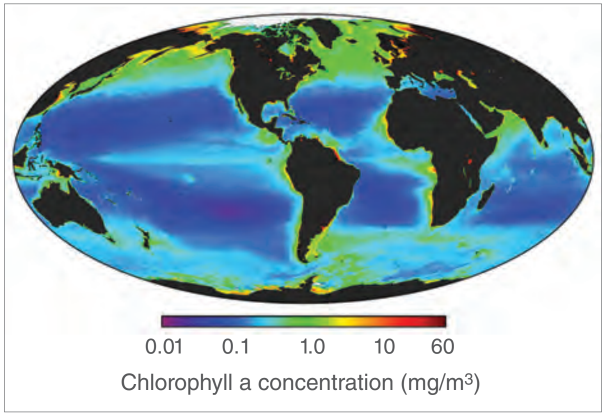
Røy and his colleagues spent forty-two days at sea, drilling cores in and around the bed of the North Pacific Gyre. The gyre covers a vast expanse of the ocean, nearly eight million square miles, slightly larger than the size of Russia. It stretches between the coasts of Southeast Asia and North America, and reaches from the equator to 50 degrees north. In fact, the North Pacific Gyre's isolated seabed was once considered a vast marine desert. Scientists have discovered that the gyre harbors life, including the microbes Røy was searching for, along with an unexpected amount of oxygen.

Most life, no matter how small or how deeply buried, requires at least minute amounts of energy. Subsurface microbes acquire this energy by consuming detritus, or the remains of dead



This image of Europa, one of Jupiter's moons, shows a region called the Conomara Chaos. The terrain is a jumble of ice rafts that scientists think might be evidence of liquid water below the surface. Studying Earth's energy-poor ecosystems can help scientists understand whether life could exist in similar environments on other planets. (Courtesy NASA Galileo Mission)

organisms, and in that process they deplete oxygen from the seabed. Therefore most of the seabed is anoxic, meaning it contains no oxygen. Oxygen typically exists only in the shallow upper layers of sediment. "In coastal waters, oxygen penetrates maybe 1 to 2 millimeters [0.04 to 0.08 inches] down," Røy said. "In normal ocean sediments, this may be 10 millimeters [0.4 inches]." Yet in the South Pacific Gyre, oxygen penetrated far deeper into the seabed.



This image shows global distribution of chlorophyll in the oceans. Purple indicates the least; red the most. Dark blue areas mark Earth's five major subtropical gyres. Data are from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS). (Courtesy SeaWiFS Project)

On their way to the North Pacific Gyre, Røy and his team drilled cores in the seabed at several locations as they traveled west along the equator.

Most of the seabed was indeed anoxic below the shallow top layer. However, once the ship veered north into the gyre, the cores told a different story, and they found conditions similar to the South Pacific Gyre. "Suddenly the entire sediment column is oxic, all the way down to the bedrock," Røy said.

In the gyre, one reason oxygen might penetrate so deeply is because algae in the surface waters simply do not produce enough detritus to filter down to the seabed. So along the research trip, he and his colleagues also checked primary productivity for the previous ten years around each core site using data from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) satellite instrument. Productivity indicates the rate at which algae and phytoplankton in the oceans convert solar energy into biomolecules, in much the same way a cornfield produces corn. Once the researchers entered the North Pacific Gyre, productivity dropped by 50 percent. But it was not nearly low enough to explain the lack of oxygen consumption in the seabed. Why were they finding oxygen in the cores of this extreme environment?

Life in slow motion

Oxygen persisted in the seabed not because of the lower primary productivity present in surface waters, but as a result of how slowly sediment and food were buried. The ocean within the gyre is remote and lacks currents, so the sedimentation rate is only 0.2 millimeters (0.04 inches) per 1,000 years, compared to 10 to 40 centimeters (4 to 16 inches) per 1,000 years along the continental shelves and slopes. "That organic material basically sits right on the surface for thousands of years. And everything that the bacteria can eat, gets eaten before the sediment slowly gets buried," Røy said.

Røy discovered that oxygen existed simply because there were few microbes to consume it. "It's kind of the other way around than you would think. The oxygen in the cores is there because nobody's using it," he said. "It's not really that the seabed microbes were super high adapted to lower energy, there were just a lot fewer of them." Other seabed environments typically contain far more organisms, which consume all the available food and oxygen, leaving most of the seabed anoxic.

In addition to the low population, these microbes live so slowly that they are not consuming even the trace amounts of oxygen and food that remained. They were consuming and respiring, but their metabolism had slowed down so much it could only be measured on a geologic timescale. "If you put a lid on the sediment and tried to suffocate the microbes, it would take 40,000 years," Røy said.

Ancient, dark, and deep

The microbes Røy explored also stretch our assumptions about how long organisms can survive. The North Pacific Gyre cores drilled into sediment dating back 86 million years. Were the microbes also that old? "We have no idea, no way of really investigating that. But they can not be less than 100 years old," Røy said. "But if they are so starved that they use enough energy to just barely keep themselves alive, well then there's really no upper limit to how old they could be."

If the microbes reproduced, even at very slow timescales, some microbes may indeed be distant descendants of ancestors that were alive when dinosaurs roamed the Earth. But it is also possible that some have subsisted in stasis, capable of resuming normal life functions once conditions change. Tori Hoehler, a specialist in space science and astrobiology, studies extreme microbial life forms on Earth to understand what life on other planets might look like. Hoehler said, "These guys down in the deep subsurface are metabolizing anywhere from ten thousand to a million times more slowly."

Other research teams have located ancient microbes in similar deep seabeds and provided them with richer food sources than those typically found in their spare natural habitat. These cells once again metabolized food, and emerged from a sort of suspended animation. This means that the North Pacific Gyre microbes might also revive if more nutrients became available to support them. "It seems that these microbes are sort of sitting there, ready to go," Hoehler said. "And that's at least some indication that they're not in a completely unrevivable state, and maybe they are just going very, very slowly."

Life on Earth and beyond

Studying these microbes gives scientists like Røy and Hoehler a chance to expand the known boundaries for life on Earth, and understand what life forms might thrive in extreme environments that appear uninhabitable. Yet scientists currently know so little about these conditions, even on Earth. Hoehler said, "A third of the life on our planet lives in a physiological state that we have very little insight into."

Exploring extreme environments can also clue scientists into where life on other planets might be found. While countless science fiction books and films have created wildly imaginative scenarios of what aliens might look and act like, it is far more likely that alien life will resemble the tiny humble microbes found deep in Earth's seafloor.

"The kinds of conditions we find deep in the subsurface may be more relevant to thinking about life in these other places," Hoehler said. For instance, it is believed that water exists deep in Europa or in the subsurface of Mars, in conditions similar to Earth's subsurface environment. "A first step in understanding that is knowing how life on Earth copes with limitation of energy," Hoehler said. "And what can that tell us about the prospects for life elsewhere?"

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/microbes-murk

About the remote sensing data

Satellite	GeoEye SeaStar
Sensor	Sea-Viewing Wide Field-of-View Sensor (SeaWiFS)
Data set	SeaWiFS Level 3
Resolution	9 x 9 kilometer
Parameters	Chlorophyll a and photosynthetically active radiation
Data center	NASA Ocean Biology Processing Group Distributed Active Archive Center (OBPG DAAC)

About the scientists

Tori Hoehler is a scientist with the Space Science and Astrobiology Division at NASA Ames Research Center in California. He studies microbial ecology and biogeochemistry, as well as subsurface and low energy ecosystems and planetary habitability. The NASA Astrobiology Institute and Exobiology Program supported his research. Read more at http://goo.gl/Ndpsqw. (Photograph courtesy B. Thamdrup)

Hans Røy is a researcher at Aarhus University in Denmark. He focuses the ecology of slow growing microorganisms below the surface of our planet, and on how these organisms influence the global element cycles. The Danish National Research Foundation, the German Max Planck Society and the National Science Foundation supported his research. Read more at http://goo.gl/45pLS7. (Photograph courtesy C. Pearce)

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

A baffling signal in the tropics

"These huge cloud systems are important elements in atmospheric heat exchange."

Robert A. Houze, Jr.
University of Washington

by Natasha Vizcarra

Hannah Barnes remembers the day she saw it spawning. She was sitting in a shipping container, under a radar, on a tiny island in the Indian Ocean. "There was a lot of rain and low, gray clouds. But it wasn't anything huge," she said. "I'm from the Midwest, so it just reminded me of a fall storm." Barnes, however, knew that the gray weather would grow into a cluster of storms more than 6,000 miles across. This armada of tall clouds would move eastward, bringing its fields of wind, humidity, and temperature. "The clouds and storms die out when they get to the dateline," Barnes said. "But in the upper atmosphere, a signal remains and that signal propagates around the globe."

Barnes was witnessing a massive atmospheric disturbance called the Madden-Julian Oscillation (MJO) brewing right above her and her colleagues. The MJO signal, a mélange of intense

A weather radar sits on a shipping container on Addu Atoll in the Indian Ocean where the Madden-Julian Oscillation spawns. Convective clouds form in the background. (Courtesy E. Maloney/Colorado State University) atmospheric convection, air pressure, and wind, is so strong that it can spike rainfall in the South Asian and Australian monsoons and increase the number of violent tornado outbreaks in the United States. It also interacts with other large atmospheric patterns, such as the El Niño Southern Oscillation and the North Atlantic Oscillation. Understanding it could improve long-range weather forecasts and enable scientists to further refine computer models of global climate. But scientists do not know much about the MJO and its signal, especially how and why it spawns every thirty to sixty days over the Indian Ocean. Researchers like Barnes think that important clues can be found in the massive expanse of convective clouds that help power the disturbance across the globe.

The size of Arkansas

Barnes' mentor, Robert A. Houze, Jr., a professor at the University of Washington and an expert in cloud dynamics, was probing expansive groups of extremely tall convective clouds called mesoscale convective systems. "It's when a thunderstorm grows to a very large size, like the size of the state of Arkansas, for example," Houze said. These cloud systems bring heat and moisture from Earth's surface high and deep into the colder upper atmosphere. And because they are so big, they release a lot of precipitation. "All that water that falls out as rain also heats the atmosphere," Houze said. "These huge cloud systems are important elements in atmospheric heat exchange."

In an earlier study, Houze and fellow researcher Jian Yuan found that the cloud systems are associated with 56 percent of rainfall in the tropics. So Houze suspected they played an important role in the MJO. However, both phenomena are so enormous that they are difficult for scientists to measure and observe. "The clouds propagate such a large area," Barnes said. "It's not like a hurricane or a tornado where you can send probes and aircraft, and profile a good portion of the event."

Houze enlisted Yuan to look at satellite data along a swath in the tropics, between the MJO's spawning grounds in the Indian Ocean and where it dissipates just beyond Fiji and Tonga in the Pacific Ocean. "We wanted know more about the population, organization, and structure of deep convective cloud systems in the region, specifically those associated with the MJO," said Yuan, now a professor of atmospheric sciences in Nanjing University. "Satellite remote sensing was perfect for this because it could see what in situ instruments could not."

Seeing superclusters

Yuan used cloud data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Terra and Aqua satellites to pick out cloud tops that exceeded a certain degree of coldness and breadth—the colder the cloud top, the taller the cloud and the deeper the convection. He also pored through precipitation data from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) sensor on the Aqua satellite to tease out the size, intensity, and structure of each cloud system's rainfall pattern.

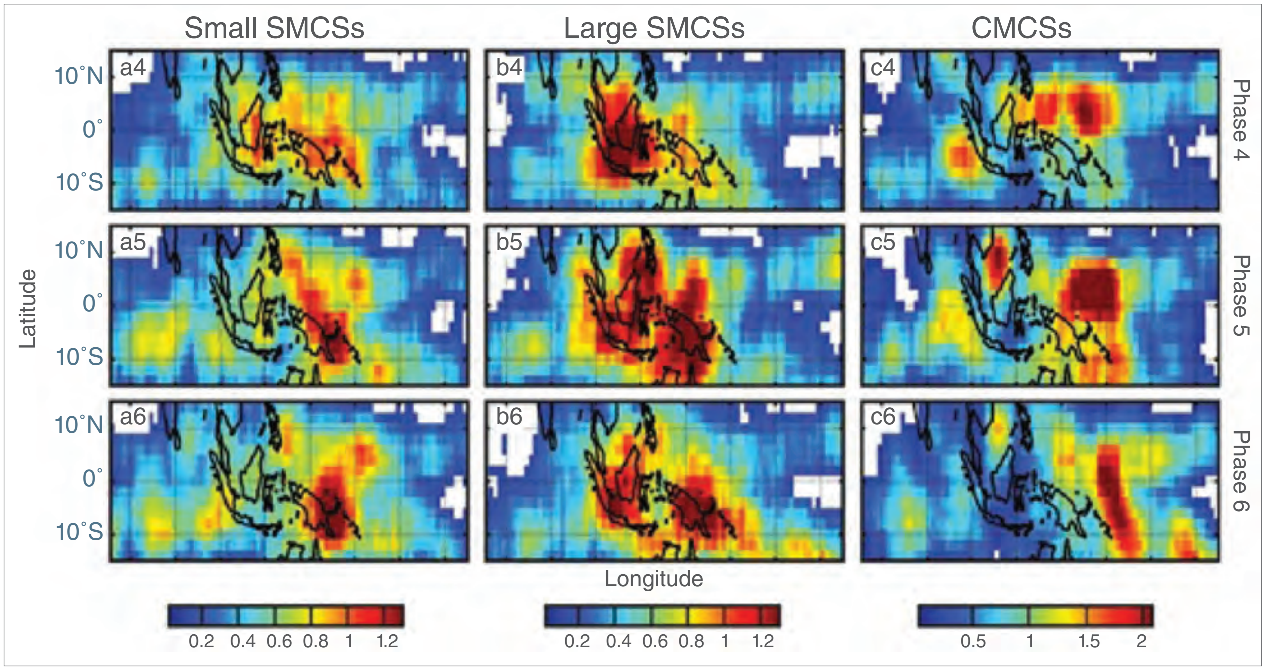
The researchers found that deep, convective cloud systems in the Indo-Pacific region occurred in a pattern consistent with the eastward propagation of the MJO. They also discovered new information about how the clouds behave in the region when the MJO is present. Over continents, they tended to occur in small, separate clusters; over island regions, they occurred as large, separate clusters; and over open ocean, they merged into connected superclusters.

Houze and Yuan's cloud catalogue of sorts was only possible because they had access to remote sensing data. "You would not be able to recognize this just from casual observations in just one place. But with the satellites we have the same measurement tool flying over the whole Earth and we were able to compare these behaviors from one region to another. So from basically knowing nothing, we pretty much got the whole picture now." In the late 1980s, Japanese scientist Tetsuo Nakazawa hypothesized—based on his field observations—that convective cloud systems converged into superclusters. "He talked about superclusters forming over the west Pacific where the ocean is very warm. These clouds were larger than anybody really suspected," Houze said. "We think that those we saw over the western Pacific Ocean are probably the same thing that Nakazawa saw."

The MJO hallmark

The study, however, revealed a limitation in using MODIS data. Although the sensor could tell researchers whether a certain cloud was a deep convective cloud, it could not accurately distinguish between different kinds of convective clouds. For example, it could not separate the tall convective cloud towers from the broad, stratiform clouds within a mesoscale convective system, and this was crucial in finding out if the cloud systems and the MJO were connected.

"The stratiform region is the part of a mesoscale convective system that is extremely broad and wide," Barnes said. "If you think of a squall line



Data from the Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) and CloudSat show how mesoscale convective systems behave in the presence of the Madden-Julian Oscillation (MJO). MCSs tend to occur in small, separate clusters (SMCSs) over continents; over island regions, they occurred as large, separate clusters; and over open ocean, they merged into connected superclusters (CMCSs). (Courtesy J. Yuan and R. A. Houze, Jr., 2013, *Journal of the Atmospheric Sciences*. Copyright American Meteorological Society. Used with permission.)

coming over you, the stratiform clouds are the lighter rain that follows after the heavy precipitation passes." According to Barnes, these stratiform clouds produce a lot of heating in the middle of the atmosphere. "It's that heating that is thought to have a large role in affecting weather far away," Barnes said.

Houze worked with Barnes to replicate Yuan's study, this time using precipitation radar data from the Tropical Rainfall Measuring Mission (TRMM), which could better distinguish cloud types. "The results were very consistent," Houze said. "It was easier to see the difference in the cloud populations in the different parts of the MJO using TRMM, but Jian and Hannah's studies told the same story."

Furthermore, the researchers found that large, stratiform regions changed the most when the MJO was present. Barnes said, "Whether you are looking in the Indian Ocean or the western Pacific, when the MJO passes through you get a lot more of these clouds. What is the hallmark of the MJO? How do you know it's there? It is when you find these large stratiform regions."

Hotter up there

To Houze, this hints that the massive convective cloud systems play an important role in the formation of the MJO. "In these systems, more than 40 percent of the precipitation falls from the stratiform region. As it comes down, it evaporates, and actually cools the lower part of the atmosphere," Houze said. "The upper atmosphere is being heated disproportionately compared to the lower part of the atmosphere," Houze said. "And this affects the nature of the MJO."

Such an unusual heating profile is strong enough to affect larger scale atmospheric circulation. The findings are valuable because scientists do not have a good handle on what sort of atmospheric mechanisms determine the organization and upscaling of deep convection. Their work will help climate modelers better reproduce MJO features in global circulation models.

"This MJO is a very large scale circulation feature which involves multiple scales of motions. You can get the behavior of the MJO incorrect if you assumed that all of the heating was going on in smaller convective clouds and not in the mesoscale convective systems," Houze said. "Getting these heating profiles correct in the tropical atmosphere is a very important problem to solve."

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/baffling-signal-tropics

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

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

Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E)
http://aqua.nasa.gov/about/instrument_amsr.php

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

Tropical Rainfall Measuring Mission (TRMM)
http://trmm.gsfc.nasa.gov

Dynamics of the Madden-Julian Oscillation (DYNAMO)
https://www.eol.ucar.edu/field_projects/dynamo

About the remote sensing data

Satellites	Aqua	Aqua	Tropical Rainfall Measuring Mission (TRMM)
Sensors	Moderate Resolution Imaging Spectroradiometer (MODIS)	Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E)	Precipitation Radar
Data sets	Cloud Product MYD06_L2	Level 2B Global Swath Rain Rate/Type GSFC Profiling Algorithm, Version 2	Orbital 3 Radar Rain Characteristics Orbital 5 Radar Rainfall Rate and Profile
Resolution	1 kilometer and 5 kilometers at nadir	5.4 kilometers	5 kilometers
Parameters	Cloud top	Rain type (convective or stratiform)	Rainfall rate, rainfall profile, rainfall characteristics
Data centers	NASA MODIS Level 1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (MODIS LAADS DAAC)	NASA National Snow and Ice Data Center DAAC (NSIDC DAAC)	NASA Goddard Space Flight Center Earth Sciences DAAC (GES DAAC)

About the scientists

Hannah Barnes is a graduate student in atmospheric sciences at the University of Washington. Her research focuses on the organization and structure of tropical convection. The Department of Energy, the National Science Foundation Dynamics of the Madden-Julian Oscillation (DYNAMO) project, and NASA supported her research. (Photograph courtesy H. Barnes)

Robert A. Houze, Jr. is a professor of atmospheric sciences at the University of Washington. His research focuses on cloud dynamics, cloud microphysics, precipitation processes, tropical meteorology, and radar meteorology. The Department of Energy, the National Science Foundation Dynamics of the Madden-Julian Oscillation (DYNAMO) project, and NASA supported his research. Read more at http://goo.gl/TSahhi. (Photograph courtesy R. A. Houze, Jr.)

Jian Yuan is a professor of atmospheric chemistry at Nanjing University in China. His research focuses on cloud radiative effects, cloud microphysics, the structure and organization of deep convective systems, and satellite meteorology. The Department of Energy, the National Science Foundation Dynamics of the Madden-Julian Oscillation (DYNAMO) project, and NASA supported his research. (Photograph courtesy J. Yuan)

Zebras without borders

"If they arrive before water is available, they're in trouble."

Pieter Beck
Woods Hole Research Center

By Agnieszka Gautier

Hot air lolled with anticipating rain. This was September in Botswana, a time when rising temperatures stack mushroom clouds high into the atmosphere. Hattie Bartlam-Brooks, a field researcher from the University of Bristol in the U.K., stood on top of a jeep, pointing an antenna into the savanna grasslands. She attempted to download Global Positioning System (GPS) data from her collared zebras, tracking their movement within the Okavango Delta. Then the sky

Zebra stripes come in different patterns, unique to each individual. They are social animals that live in harems. Here two stand in the Okavango Delta, Botswana. Unlike horses or donkeys, zebras have never been truly domesticated. (Courtesy M. Munneke) split with a thunderous crack, signaling the first rains of the wet season.

But she couldn't find any of the seven tagged zebras. "They disappeared," she said. "Six months later I found them." Downloaded data reported the zebras had been deep in the Makgadikgadi Pan, 300 kilometers (190 miles) southeast of the delta, partaking in the pan's lush, sweet grasses during the wet season. That year, 2007, brought a huge surprise, and with it great hope for conservationists connecting ancient migratory routes.

Divided they stand

"Everyone thought migration had stopped," Bartlam-Brooks said. In the 1960s, most European colonial powers left Africa carved up by political boundaries, ignoring tribal and natural patterns. Botswana, a flat, landlocked country, protected its cattle industry against wildlife spreading disease with hundreds of miles of fences. With the fences up the zebras stopped migrating. But as the country matured it discovered tourism and removed most northern fences, freeing up large game reserves. Then migration re-established itself, but how? "None of the zebras had been to Makgadikgadi Pan before," said Gil Bohrer, a professor at Ohio State University and a lead for the NASA Movebank project, which links animal tracks to remotely sensed ecological data. "Not only that, migration restarting at all has never been shown before," Bartlam-Brooks said.

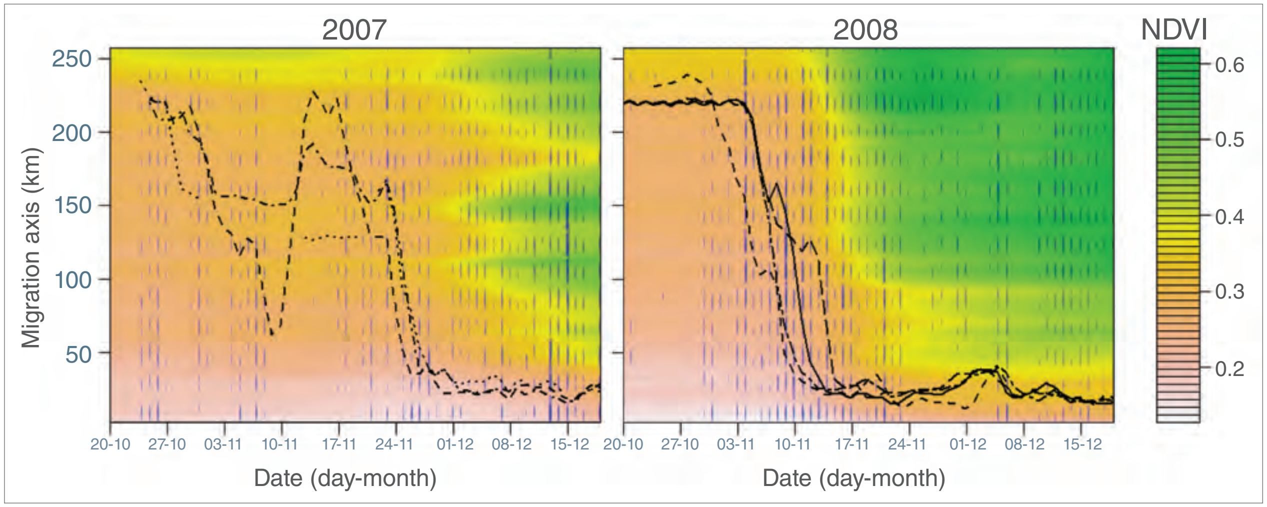
Anecdotal stories told of migration prior to the fence, but in the wild zebras do not live past their teens, and since the fence had been up from 1968 to 2004, there is no way they could have learned the route. "It's not that they followed their mothers as baby zebras and saw the saltpan," Bohrer said. "Three or four generations lived behind the fence."

Baobab trees are scattered on Kubu Island, a dry granite rock island located in the Makgadikgadi Pan. Baobabs store water in the trunk to endure harsh drought conditions. (Courtesy abi.bhattachan/Flickr)

No compelling reason drives the zebra out of the delta. The Okavango River spills into the Kalahari Desert sand, calmly etching its tentacles into a delta that leads to nowhere, no river or ocean, just more sand within reed-lined riverbeds. Verdant year round, it supports herds of elephants, wildebeests, buffalo and hippopotamuses, lone predators like cheetahs and leopards, the barely surviving African wild dog, hundreds of birds, and harems of zebras. It can sustain life year round. And the route from the delta to the Makgadikgadi is desert, no water except for rain-filled waterholes. So why leave?

Basic instinct

"There is somehow, some knowledge within the zebra that sends them there," Bohrer added, referring to the Makgadikgadi. During the dry season, roughly April through May, water pools evaporate, leaving a scorched land. A salt crust gleams in the light, reflecting off the white horizon. Patches of grasslands interrupt the saltpan. And with the arrival of the rains, amidst palm trees, the grass becomes lush and extensive. But there is no permanent water here. Zebras can



The above figures depict zebra migrations from the Okavango Delta to the Makgadikgadi at the onset of the rains in 2007 and 2008. The Okavango Delta is at the top of the graphs and the Makgadikgadi is at the bottom. Different black lines indicate the movements of individual collared animals, three in 2007 and four in 2008. Blue vertical dashes indicate satellite-observed rainfall in the region during the migration. The figure on the left shows the retreat of one collared zebra when greening was not sufficient in 2007. Greening data is shown in yellows and greens, based on Normalized Difference Vegetation Index data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Aqua and Terra satellites. Rainfall data are from the NASA Tropical Rainfall Measuring Mission. (Courtesy H. Bartlam-Brooks et al., 2013, *Journal of Geophysical Research*)

only utilize the high-quality grasses when rains fill the pans and natural waterholes. When they dry up, the zebras return to the delta.

There are false starts to the seasons, however. So how do the zebras know when to go? "It was interesting for us to figure out the cues of migration," Bohrer said. "And with the lack of ground-based data, you go to remote sensing." A unique opportunity for remote sensing had presented itself—for the first time, it could be used to model the initiation of migration and the speed of travel. "Animal movement science has moved forward in leaps and bounds since GPS technology became affordable and widely available," said Pieter Beck, a researcher with the Woods Hole Research Center in Massachusetts. "To all but the smallest land animals, you can strap GPS and get data back." Not only that, NASA instruments have improved, producing images at an ecologically relevant resolution.

People often think the animals migrate when the rainy seasons begin, but what is the exact cue? "Do they sense how much rain accumulated?" Beck asked. "Do they leave with the first big thunderstorm? Do they leave before it? Do they respond actually to the vegetation, which itself responds to the rainfall? And then, how do they pace themselves when on the move?"

On the move

The researchers focused on two environmental variables that remote sensing could easily measure: vegetation and rainfall. They obtained data on the productivity of the grass from Normalized Difference Vegetation Index (NDVI) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Terra and Aqua satellites. They combined NDVI with estimates of precipitation from the Tropical Rainfall Measuring Mission (TRMM) satellite. "Between the precipitation, a direct cue, and the greenness of grass, which is a more sophisticated cue, meaning zebras need to project grass growth and respond to it," Bohrer said, "we can determine the environmental cues that send them on their way."

But could this environmental data actually predict the zebra's movement—the migratory inception, and zebra speed and direction? To answer the question, the researchers created several models of increasing complexity, using data from 2007 and 2008, the years GPS information was available. At the simplest level, the model assumes that zebras start on a fixed date and migrate with a fixed speed. "That's it," Bohrer said, "They don't care about the environment; they just know the date." Timing as a migration trigger is possible considering that the sun is a good indicator of time. The accuracy of predicted zebra location ended up being quite high for such a simple model, 67 percent. "For observations in wild animals that move in complex and unpredictable ways," Bohrer said, "it's actually a crazy high number." Still, do zebras use other cues? The researchers wanted more. "Can we get more accurate?" Bohrer asked.

The next model included cumulative precipitation, using TRMM data that Beck processed between the delta and the Makgadikgadi. The zebras feel enough rain, and then move. The final model added the speed of movement as a function of NDVI and precipitation rate. "So if it's raining strong, they can actually walk slower," Bohrer said. "If it's very green around them, they

Botswana is home to the second largest zebra migration, following the Serengeti. About 25,000 zebra journey the 190 miles between the Okavango Delta and the Makgadikgadi Pan. Zebra perform an important ecological function as grazers, eating the longer strands of grass that then expose shorter growth, allowing wildebeest easier access to their source of food. (Courtesy R. Toller)

Hattie Bartlam-Brooks collars a zebra with Global Positioning System (GPS) to track its location along the re-established migration route from the Okavango Delta to the Makgadikgadi Pan. (Courtesy Botswana Herbivore Research)

walk faster." They want to hurry up and get there because the vegetation is ripe. If it's raining hard, they can pace themselves because the water will linger. "But those are just anthropomorphic interpretations," Bohrer said. "I don't know why they do that, but I know for a fact putting these two variables in the models increases predictive accuracy of zebra location to 92 percent, which is very, very accurate."

So some ancient instinct seems to lure the zebra to the grass, telling them when and how and where to go. They wait until the rain reaches a certain threshold and then walk at a speed that is modified by the greenness and the rain. "Zebras are fascinating," said Bartlam-Brooks, who went to the bush to study the animals on their turf. "I am amazed by their memory of the environment. They can follow highly directed routes to water or new grazing with minimal environmental cues—there are no hills, mountains in Botswana, yet they can orientate themselves in thick woodland or arid shrub over hundreds of kilometers."

Within borders

Understanding the cues that drive such long-distance movements is critical to understanding the fate of migrations with climate change. Climate change models predict the deserts of Southern Africa will be drier more frequently. Migrations may be less successful because the zebras' instincts will be off. "According to models," Bartlam-Brooks said, "unsuccessful migrations will lock out the more susceptible portions of the population, so juvenile recruitment will decrease, the number of youngsters surviving the first year will drop, and that could affect population success." At the same time, zebras adjust.

The desert, like most places on Earth, is governed by microclimates. Just because it started to rain in the Okavango Delta does not necessarily mean the Makgadikgadi pan is green. Beck studied the correlation between the cumulative precipitation in the Okavango Delta and the timing of the greening in the Makgadikgadi pan. "If they arrive before water is available, they're in trouble," Beck said. In most years, the cumulative precipitation in the delta predicts the greening in the Makgadikgadi pan, but there are specific years of drought and intense rain, which are typically El Niño/La Niña years, when those predictions fail. "These years are very hard for them," Bohrer said. “What they think should work, doesn’t.” 2007 proved to be one of those years. Initial rainfall in late October did not sustain into mid-November, delaying greening until early December. That year, zebra returned to the Okavango Delta, proving their resilience.

“Migrations are under threat everywhere, mostly due to habitat loss and conflict,” said Bartlam-Brooks. In Africa, where different countries establish their own wildlife policies, cooperation for their preservation can prove challenging. But this study brings great hope with it. In areas that were once joined and then broken up, many have said there is no point in reconnecting the lands. “Actually it’s not true,” Bartlam-Brooks said. “You can take down a physical barrier that’s been up for decades, and the animals do reconnect to ancient migratory routes successfully.” Wildlife knows nothing about borders, but now inter-system management across Africa may be able to develop conservation corridors and design routes for migration.

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/zebras-without-borders

About the remote sensing data

Satellites	Terra and Aqua	Tropical Rainfall Measuring Mission (TRMM)
Sensors	Moderate Resolution Imaging Spectroradiometer (MODIS)	TRMM Microwave Imager
Data sets	Normalized Difference Vegetation Index (NDVI)	TRMM Daily Rainfall
Temporal coverage	16-day cycle	Daily
Parameters	Normalized Difference Vegetation Index (NDVI)	Precipitation rate
Data centers	NASA Land Processes Distributed Active Archive Center (LP DAAC)	NASA Goddard Space Flight Center Earth Sciences DAAC (GES DAAC)

About the scientists

Hattie Bartlam-Brooks is a research associate for the University of Bristol and lives in Maun, Botswana. She is interested in how resources determine herbivore movement and distribution patterns and how these are affected by anthropogenic factors. The Leverhulme Trust and the Wilderness Trust supported her research. (Photograph courtesy C. Bartlam-Brooks)

Pieter Beck is an ecologist at the Joint Research Centre of the European Commission who specializes in remote sensing and modeling of vegetation. He studies the effects that disturbance and climate have on the phenology, distribution, and carbon dynamics of vegetation as well as the associated land-atmosphere feedbacks. NASA supported his research while at the Woods Hole Research Center (WHRC). (Photograph courtesy WHRC)

Gil Bohrer is an assistant professor for ecological engineering at Ohio State University. His interests involve the development of physical and empirical models to link individual biological organisms to atmospheric processes. NASA and NSF supported his research. Read more at http://goo.gl/k3Qr6s. (Photograph courtesy G. Bohrer)

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NASA Goddard Space Flight Center Earth Sciences DAAC (GES DAAC)
http://daac.gsfc.nasa.gov

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

Tropical Rainfall Measuring Mission (TRMM)
http://trmm.gsfc.nasa.gov

Unexpected ice

"I always thought, and as far as I can tell everyone else thought, that the biggest changes must be in autumn."

Paul Holland
British Antarctic Survey

by Natasha Vizcarra

On the prowl for food, Adelie penguins scan the ice ceiling. They peck at silverfish and hunt for polynyas, gaping holes in the sea ice where shoals of krill and bug-like copepods graze on clouds of algae. When spring comes, the huge plates of sea ice start to melt and later in the brief Antarctic summer all but disappear. Then, algae blooms unfurl: a bacchanalian feast for krill and critters all the way up the Antarctic food chain. Sea ice, sunlight, and food—they all come and go with the seasons in the Southern Ocean.

Paul Holland, a climate modeler with the British Antarctic Survey, has spent the last ten years studying Antarctica's sea ice and the Southern Ocean. Lately, he has been scrutinizing the seasons of Antarctica and how fast the ice comes and goes. Holland thinks these seasons may be a key to a conundrum: If Earth's temperatures are getting warmer and sea ice in the Arctic has been

A pressure ridge forms on the sea ice near Scott Base in Antarctica. These form when separate ice floes collide and pile up on each other. Lenticular clouds are seen above. (Courtesy M. Studinger/NASA) shrinking fast, why then is sea ice in the Antarctic slowly increasing?

Opposite poles

Sea ice is simply frozen seawater. Although found only in the Arctic and the Antarctic, it influences Earth's climate in big ways. Its bright surface reflects sunlight back into space. Icy areas absorb less solar energy and remain relatively cool. When temperatures warm over time and more sea ice melts, fewer bright surfaces reflect sunlight back into space. The ice and exposed seawater absorb more solar energy and this causes more melting and more warming.

Scientists have been watching this feedback loop of warming and melting in the Arctic. To them, Arctic sea ice is a reliable indicator of a changing global climate. They pay the most attention in September when Arctic sea ice shrinks to its smallest extent each year. Measured by satellites since 1979, this minimum extent has been decreasing by as much as 13.7 percent per decade. Antarctic sea ice, on the other hand, has not been considered a climate change indicator. Whereas Arctic sea ice mostly sits in the middle of land-locked ocean—which is more sensitive to sunlight and warming air—Antarctic sea ice surrounds land and is constantly exposed to high winds and waves.

According to climate models, rising global temperatures should cause sea ice in both regions to shrink. But observations show that ice extent in the Arctic has shrunk faster than models predicted, and in the Antarctic it has been growing slightly. Researchers are looking much closer at Antarctica, saying, "Wait, what is going on down there?" Holland is one of those intrigued.

"The Antarctic case is as interesting as the Arctic case," Holland said. "You can't understand one without understanding the other."

Minding the models

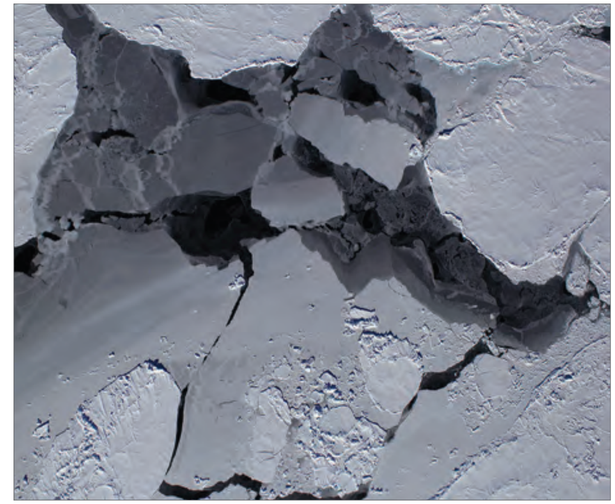
To Holland, the discrepancy calls parts of the climate models into question. Modeling groups from around the world collaborate on the Coupled Model Intercomparison Project Phase 5 (CMIP5), which simulates Earth's climate and predicts how it will change in the near future. World leaders and policy makers rely on it to decide how much countries should limit carbon emissions, known to cause some aspects of climate change.

"Almost all of the CMIP5 models produce a decrease in Antarctic sea ice," Holland said. "There is a problem in the bit that reproduces the last 30 years of sea ice variability." Holland was searching for data to improve and verify his own modeling of trends in Antarctic ice when he noticed that other researchers were finding that the trends varied in strength in the different seasons.

Most studies on Antarctic sea ice trends focus on changes in ice extent. For Holland, it was more important to look at how fast the ice was growing or shrinking from season to season. "Changes in climate forcing directly affect the rate of ice growth," he said, "not the amount of ice." Year to year cooling in autumn, for example, may cause faster ice growth during autumn, but not necessarily an increase in the amount of autumn ice.

Spring surprise

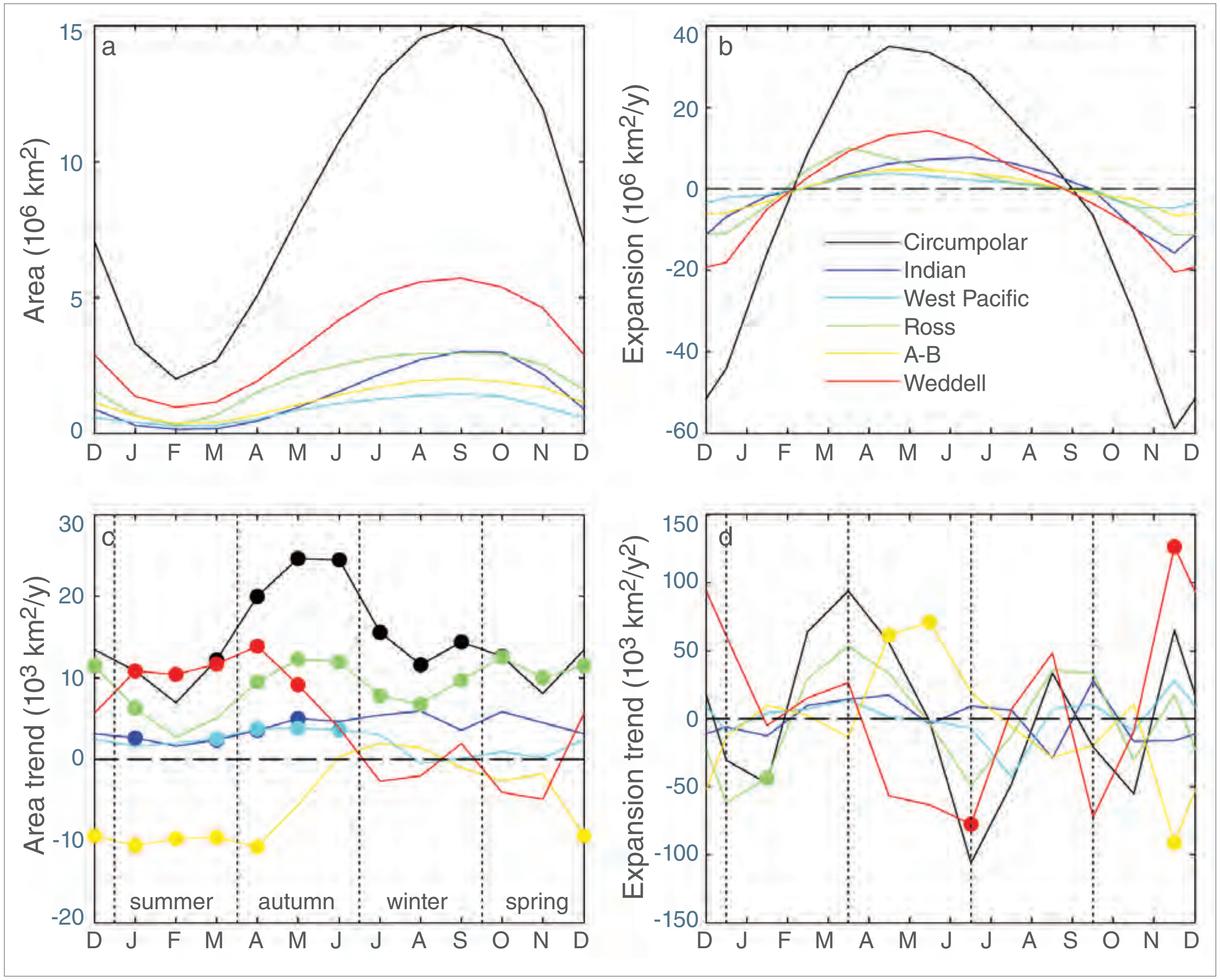
Holland used data from the NASA National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC) to calculate the ice concentration rate of growth for each single



This scene shows a mixture of sea ice types commonly seen in the Southern Ocean. The different thicknesses of sea ice form a spectrum of colors and shapes ranging from dark black open water, a thin grease-like covering called grease ice, and thicker grey ice. Older sea ice has a bright white covering of snow and many chaotic deformation features, visible as ridges and rubble fields and caused by the continuous motion of the ice pack. (Courtesy M. Studinger/ NASA)

day, which he called intensification; and the total ice area rate of growth, which he called expansion. "I did that for all thirty years of data and plotted the trends," he said. Holland's plots showed that the different regions in the Southern Ocean contributed to the overall increase, but they had very diverse trends in sea ice growth. This suggested that geography and different wind patterns played a role. So to gain more insight Holland looked at seasonal wind trends for the different regions.

Holland found that winds were spreading sea ice out in some regions and compressing or keeping it intact in others and that these effects began in the spring. It contradicted a previous study in which, using ice drift data, Holland and Ron Kwok from the NASA Jet Propulsion Laboratory



The panels above show seasonal variations of sea ice quantities for each region and the whole Southern Ocean. The mean monthly total ice expansion (b) peaks in autumn, and mean monthly total ice area (a) peaks in the winter. Interannual trends in monthly total ice area (c) show that for the last thirty years, Antarctic sea ice has tended to expand during the autumn. Interannual trends in monthly total ice expansion (d) show that changes in ice growth in the spring produced the change in the ice the following summer and autumn. (Courtesy P. R. Holland)

found that increasing northward winds during the autumn caused the variations.

"I always thought, and as far as I can tell everyone else thought, that the biggest changes must be in autumn," Holland said. "But the big result for me now is we need to look at spring. The trend is bigger in the autumn, but it seems to be created in spring."

"Paul has created two more sea ice metrics that we can use to assess how Antarctic sea ice is responding," said researcher Sharon Stammerjohn, referring to the measures of intensification and expansion. The new metrics help assess how the system is responding as opposed to simply monitoring the state of the system. "Say your temperature is at 99.2 degrees Fahrenheit," Stammerjohn said. "You don't have any insight to that temperature unless you take it again an hour later and you see that it changed to 101 degrees. Then you can say, okay, my system is responding to something."

Partial explanations

Holland continues to study the Antarctic spring to better understand why Antarctic sea ice is changing. While Holland's work helps researchers begin to see the problem in more detail, scientists continue to develop ideas about why the ice is expanding.

One study paradoxically suggests that ocean warming and enhanced melting of the Antarctic ice sheet is causing the small but statistically significant sea ice expansion in the region. Another study suggests that rain caused by a warmer climate has been causing an influx of fresh water into the Southern Ocean, making it less dense and inhibiting oceanic heat from reaching sea ice in the Antarctic. To date, there is no consensus on the reason for the expansion.

"Partial explanations have been offered, but we don't have the complete picture," said Ted Scambos, a scientist at the NSIDC DAAC. "This may just be a case of 'we don't know yet.'"

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/unexpected-ice

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

About the remote sensing data

Satellites	Nimbus 7 and Defense Meteorological Satellite Program (DMSP) F8, F11, F13, F17
Sensors	Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), Special Sensor Microwave Imager/Sounder (SSMIS)
Data set	Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data
Resolution	25 kilometers
Parameters	Sea ice concentration
Data center	NASA National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC)

About the scientists

Paul R. Holland is an ocean modeler at the British Antarctic Survey in Cambridge, United Kingdom. His research focuses on ocean-ice shelf interaction, polar oceanography, sea ice, ice shelf glaciology, gravity currents, and lake hydrodynamics. NASA and the British Antarctic Survey supported his research. Read more at http://goo.gl/nAUwFQ. (Photograph courtesy P. R. Holland)

Ted Scambos is the lead scientist at the National Snow and Ice Data Center. His research focuses on glaciology, remote sensing of the poles, climate change effects on the cryosphere, Antarctic history, geochemistry, and planetary science. NASA supported his research. Read more at http://goo.gl/NZygTB. (Photograph courtesy P. Gibbons)

Sharon Stammerjohn is a senior research associate at the Institute of Arctic and Alpine Research at the Universtiy of Colorado Boulder and assistant adjunct professor at the University of California Santa Cruz. Her research focuses on polar oceanography and climate, and ecosystem response to climate variability. The National Oceanic and Atmospheric Administration supported her research. Read more at http://goo.gl/TxtnqI. (Photograph courtesy S. Stammerjohn)

Shake, rattle, and sink

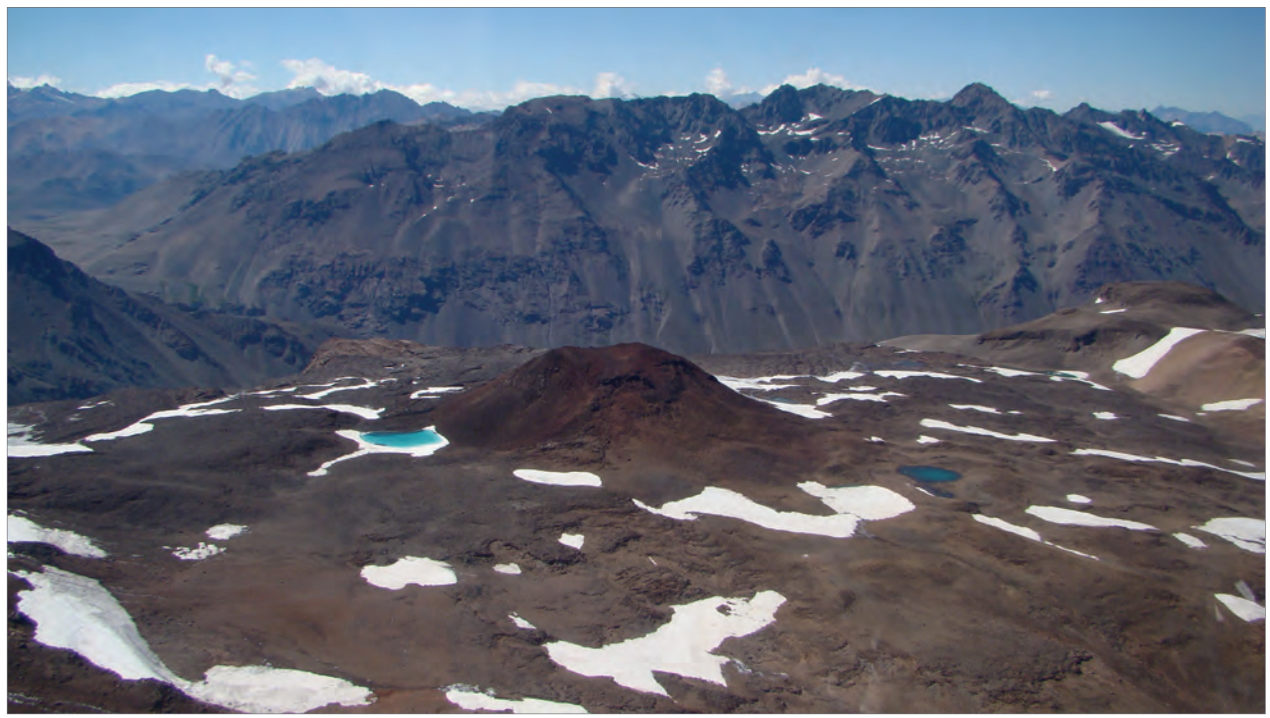
"Personally, I think it's just flat-out cool that there's stuff happening on the Earth that's still being discovered."

Matthew Pritchard
Cornell University

by Karla LeFevre

Scientists know that an earthquake can stir up volcanic activity far from its epicenter. On February 20, 1835, a major earthquake in Concepción, Chile woke naturalist Charles Darwin from his nap in Valdivia some 269 miles away. "I happened to be on the shore and was lying down in the wood to rest myself," he wrote. "There was no difficulty in standing upright, but the motion made me almost giddy. It [felt] something like the movement of a vessel in a little cross-ripple." In the days following the Concepción earthquake, he counted hundreds of small tremblings, as he called them, and witnessed multiple volcanoes erupting. This pattern of a major earthquake followed by frequent volcanic eruptions repeated itself in the area in 1906 and 1960.

So when an 8.8 magnitude earthquake struck north of Concepción in Maule, Chile on February 27, 2010, nearly two hundred years after Darwin visited the area, scientists were poised to monitor the volcanic stirrings with sophisticated satellite imagery. Yet nothing seemed to be happening. Lead scientist Matthew Pritchard from



Tinguiririca is one of five volcanoes that subsided during the 8.8 magnitude earthquake in Maule, Chile in 2010. (Courtesy M. Pritchard and L. Lara)

Cornell University said, "So we were scratching our heads and thinking: Why was this earthquake so different?"

Radar love

Pritchard instinctively turned to InSAR, or Interferometric Synthetic Aperture Radar. Scientists are fond of this particular remote sensing technique because they are able to comb vast swaths of the Earth—entire volcanic chains, for example—quickly and safely, no matter how remote or dangerous the terrain. InSAR can also detect extremely subtle shifts in the Earth's surface like rising or sinking, down to millimeters. Such fine detail of displacement above ground can reveal movement underground, such as groundwater flowing beneath cities or magma flowing under volcanoes. Researchers can even detect activity at so-called "zombie volcanoes," volcanoes believed to have been dead for several million years.

InSAR starts with SAR, which can provide a detailed look at the Earth's surface. Synthetic aperture radar instruments are surprisingly large, at least figuratively speaking. Standard radar uses an antenna to volley high-frequency electromagnetic pulses toward the landscape. How quickly the pulses return to the antenna sketches out a picture of the topography. The larger the antenna, the more detailed the picture, but enormous antennas are a drag on spacecraft. Rather than hauling mile-long revolving antennas to space, SAR relies on the forward movement of the satellite along its flight path to effectively mimic an extremely long antenna scan.

Once the data are gathered, interferometry comes into play. Two SAR scenes from different days are overlaid to create a picture of wave

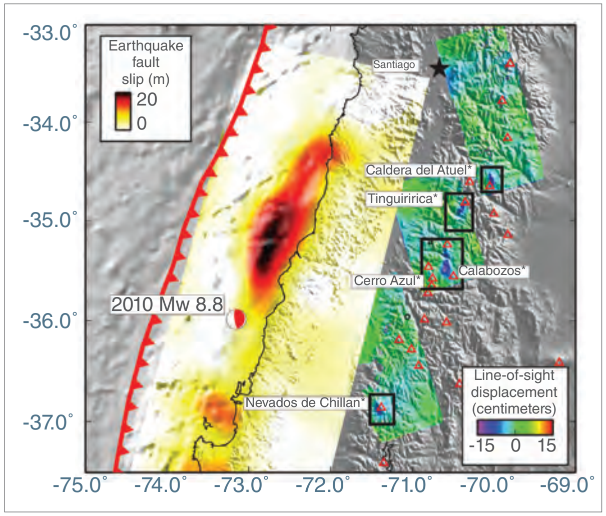
Researchers Matthew Pritchard and Gabriel Gonzalez examine a large crack caused by an earthquake in the Atacama Desert of northern Chile. A major earthquake can cause volcanic unrest hundreds of miles from its epicenter. (Courtesy M. Pritchard and R. Allmendinger)

interference. The resulting images, called interferograms, are striking maps that show ground displacement through whorled, concentric rings called fringes. To the uninitiated, colored interferograms tend to look more like 1970s psychedelic art than something retrieved by a satellite. But to researchers studying how the Earth's surface changes, they speak volumes. Pritchard said, "What you end up with is this beautiful picture that you can look at to see whether there is ground deformation or not."

That sinking feeling

After the Maule, Chile earthquake, Pritchard and his colleagues were expecting to see the land deformed by a flurry of volcanic eruptions. They developed InSAR images of the area using data from the Phased Array type L-band Synthetic Aperture Radar (PALSAR) instrument, on the Japan Aerospace Exploration Agency and Ministry of Economy, Trade and Industry (JAXA/METI) Advanced Land Observing Satellite (ALOS). The ALOS PALSAR data, although copyrighted by JAXA/METI, are made available through the NASA Alaska Satellite Facility Distributed Active Archive Center to NASA scientists due to the strong partnership developed between JAXA and NASA.

They thought they would see the ground surface of the volcanoes in the region lifting up, and shallow underground chambers filling with magma. Cornell team member Jennifer Jay said, "That whole overriding plate should have uplifted." Instead of uplifting, the volcanoes sank. "What we found was the exact opposite," Pritchard said. "We found that five volcanoes responded, but they all subsided, so that was a big mystery to us."



This interferometric map of southern Chile marks where the fault slip occurred after the 8.8 magnitude earthquake near Maule in 2010. The slip is indicated by black and red in the center of the map. The five volcanoes indicated sank several centimeters during the earthquake. Data are from the Phased Array type L-band Synthetic Aperture Radar (PALSAR) instrument on the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS). (Courtesy M. Pritchard et al., 2013, *Nature Geoscience*)

Adding to the mystery, all five volcanoes showed similar changes. All had sunk approximately 5 to 15 centimeters (2 to 6 inches) in elliptical shaped areas that were approximately 10 to 15 kilometers wide by 20 kilometers long (6 to 9 miles by 13 miles). And all five elliptical areas were oriented in a north-south direction. Stymied, the team began running through different scenarios that might explain the odd characteristics.

In the meantime, a 9.0 magnitude earthquake rocked Tohoku-Oki, Japan on March 11, 2011. Though they did not know it at the time, scientists in Japan studying the aftermath found striking similarities to what Pritchard and his team had found in Chile. "It was eerie how similar our results were to theirs," Pritchard said. Using InSAR data, Youichiro Takada and Yo Fukushima of Kyoto University also found that five volcanoes had subsided. In addition, the size of the sunken areas was comparable. Even their elliptical shape and north to south orientation were similar. "Pritchard's study is valuable," Takada said. "With two independent cases, we may say that this is a ubiquitous phenomenon."

This led to several theories about what might explain the phenomenon. Perhaps the ground shaking allowed volcanic gases to escape, for example. To test this, the Cornell team pored over thermal infrared images from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Moderate Resolution Imaging Spectroradiometer (MODIS). But the images revealed no change in surface temperature around the five Chilean volcanoes during the sinking. With no sign of hot gases leaking from underground chambers, the Cornell researchers considered other possibilities.

If it holds water

Water, not gas, might be the answer. Streams and rivers flow more vigorously after major earthquakes. Scientists partially attribute this to the ground shaking, which drains ground water reserves through fractures into streams.

Stream flow increased again after the 2010 Maule earthquake; Pritchard and his team feel this is key to understanding the ground sinking. "In volcanic areas, there are a lot of hot springs," he said. "If you visualize Yellowstone, there are pockets of hot fluids coming through and those fluids have minerals in them, which eventually partially clog up the pathways. So our best explanation right now is, when an earthquake shakes them up, the fluids suddenly break through any blockages and are released." It is possible, then, that this release of fluids somehow made eruptions less likely. And it could explain why the ground around these volcanoes suddenly deflated.

In the case of Japan, magma flow might be key. Takada and Fukushima theorize that the sudden sinking of the five volcanoes near Tohoku-Oki was due to magma flowing out of volcanic chambers. "We think hot and weak plutonic bodies exist in the crust beneath the subsided volcanoes," Takada said. Unlike the pressure that builds to cause a volcanic eruption, weak rocks called plutons that softened when heated likely allowed the magma to flow out of chambers. What is clear is that both teams independently discovered that volcanoes can sink when shaken.

Jay said, "Because this volcanic subsidence hadn't been seen before, we did a lot of analysis to make sure this was definitely a real physical phenomenon." Whether the water and magma theories are proven or disproved remains to be seen, but there is plenty more to learn as InSAR data increasingly become available, particularly with more frequent satellite overpasses. "Since the [InSAR] technique is relatively new, we don't have a lot of examples," Jay said. "And we only get acquisitions every few months, so we really just need more data."

For both teams there is also still the question of why these underground hydrothermal and magmatic systems have large elliptical shapes. It also remains unclear why they are oriented in a similar north-south direction. One theory is that these features may have something to do with the volcanic arc. Volcano chains that form above a subduction zone and next to a boundary where plates are converging, as both chains had, form a long arc. Identifying future cases of earthquakes triggering volcanic subsidence will help the researchers unravel the mysteries of these processes. Until then, both teams will keep honing their theories. Pritchard said, "Future research will tell us which team is right, or maybe neither of us are. Personally, I think it's just flat-out cool that there's stuff happening on the Earth that's still being discovered."

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/shake-rattle-and-sink

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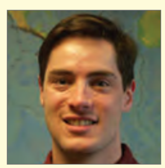
About the remote sensing data

Satellites	Japan Aerospace Exploration Agency Advanced Land Observing Satellite (ALOS)	Terra	Terra and Aqua
Sensors	Phased Array type L-band Synthetic Aperture Radar (PALSAR)	Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)	Moderate Resolution Imaging Spectroradiometer (MODIS)
Data sets	L1 SAR Data	On-Demand L2 Surface Kinetic Temperature	Nighttime Calibrated Radiances 5-Min L1B Swath 1 km V005
Resolution	20 meters	90 meters	1 kilometer
Parameters	Radar backscatter	Surface kinetic temperature	Surface kinetic temperature
Data centers	NASA Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC)	NASA Land Processes DAAC (LP DAAC)	NASA MODIS Level 1 and Atmosphere Archive and Distribution System DAAC (MODIS LAADS DAAC)

About the scientists

Jennifer Jay is a postdoctoral fellow in the Global Volcanism Program at the Smithsonian Institution. Her research focuses on volcano deformation and magma movement in the Central and Southern Andes using remote sensing techniques and field studies. NASA supported her research. Read more at http://goo.gl/0Xyqsw. (Photograph courtesy J. Jay)



Matthew Pritchard is an associate professor in the Earth and Atmospheric Sciences Department at Cornell University. His research focuses on measuring changes in the shape of the Earth and modelling the processes that cause such changes, including earthquakes, volcanoes, groundwater, landslides, and glaciers. NASA supported his research. Read more at http://goo.gl/rDmtyQ. (Photograph courtesy M. Pritchard/Cornell University)

For more information

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https://www.asf.alaska.edu

NASA Land Processes DAAC (LP DAAC)
https://lpdaac.usgs.gov

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

Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS)
http://www.eorc.jaxa.jp/ALOS/en/index.htm

JAXA Phased Array type L-band Synthetic Aperture Radar (PALSAR)
http://www.eorc.jaxa.jp/ALOS/en/about/palsar.htm

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

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

Salt of the sea

"The reality is we know very little about salinity in the oceans and how it changes."

Jorge Vazquez-Cuervo
NASA Jet Propulsion Laboratory

by Agnieszka Gautier

In *The Day After Tomorrow*, a doom and gloom Hollywood film, buoys signal plunging temperatures in the North Atlantic Ocean, a symptom of a major current collapsing. Catastrophic storms ensue. Sea levels rise with the force of a bursting dam. A climatologist's model proves true: the stalled current triggers an ice age. New York City plunges into a polar, subarctic freeze, and the Statue of Liberty disappears beneath hundreds of feet of snow, leaving only her torch of icicles visible.

Though the science in the film is flawed and the events exaggerated, scientists acknowledge that if enough freshwater dumps into the North Atlantic Ocean, the large-scale Atlantic Meridional Overturning Circulation that transports heat from the tropics to the North Atlantic could slow down and potentially lead to colder climate in Europe. The actual mechanisms behind the

In Naruto, Japan, a boundary between different water masses appears as a sliver of still water beyond turbulent waters. The stratification of disparate densities creates varying momentums within the ocean waters. (Courtesy ume-y/Flickr) trigger are complex. To fully understand the intricacies of ocean circulation, researchers need to add a missing piece—salinity, or the saltiness of the ocean surface.

Ocean motion

"This is one of the untapped areas, looking at salinity across the globe," said Michelle Gierach, a research scientist at the NASA Jet Propulsion Laboratory (JPL) in California. To measure sea surface salinity (SSS) from space with an accuracy equivalent to one-eighth teaspoon of salt per gallon of water, NASA and the Argentina Comisión Nacional de Actividades Espaciales (CONAE) launched the Aquarius/Satélite de Aplicaciones Científicas (SAC)-D mission in June 2011.

Salt affects buoyancy. Saltier, denser water sinks and fresher, less dense water floats, causing vertical and horizontal currents within the oceans. Winds move upper-ocean currents, but the real engine behind deep-water currents is density, and that is driven by temperature and salinity differences of water masses. Density shifts might speed up or slow down currents and cause water masses to sink within the water column, providing information about water column stratification.

While 3.5 percent of Earth's ocean is salt, freshwater added to the ocean dilutes salinity values. For example, strong rains across the equatorial Pacific from South American to Indonesia form a band of low salinity water. But warm areas with much evaporation and little precipitation increase salinity. So the atmosphere and ocean respire as one giant organism, exchanging breaths between seasons, even days. Within each breath is a redistribution of heat and salt.

With Aquarius launched, scientists hope to better monitor ocean currents and the global water cycle. "Understanding how water moves on this planet is really important," said Jorge Vazquez-Cuervo, another JPL scientist on the study. Gierach added, "We've always had these views of what it should look like, but to now observe it and monitor it, that's what's really interesting to me."

But Aquarius had limitations. No one expected it to pick up a salinity signal in marginal seas, seas partially enclosed by islands, archipelagos, or peninsulas, like the Mediterranean or the Gulf of Mexico. "We did not have high expectations for the quality of the signal near land because of land contamination and radio frequency interference," Gierach said. The brightness of nearby land compared to the dark ocean would swamp the satellite signal, and given the waveband of Aquarius instruments, radio frequencies could interfere with satellite readings.

An added bonus

Still, Gierach wanted to try. More than half of the freshwater input in the Gulf of Mexico comes from the Mississippi River. If Aquarius could see this freshwater signal, scientists could better monitor how freshwater plumes affect these smaller seas. Gierach said, "We need to see how this discharge affects the regional system. Then we can see potential global implications." In May 2011, the Mississippi flooded, becoming one of the largest and most damaging inundations in U.S. history. To save Baton Rouge and New Orleans, a spillway opened and drowned 4,000 square miles of rural Louisiana. Gierach combed the Aquarius data on the chance it had seen this surge of freshwater off the Louisiana coast.

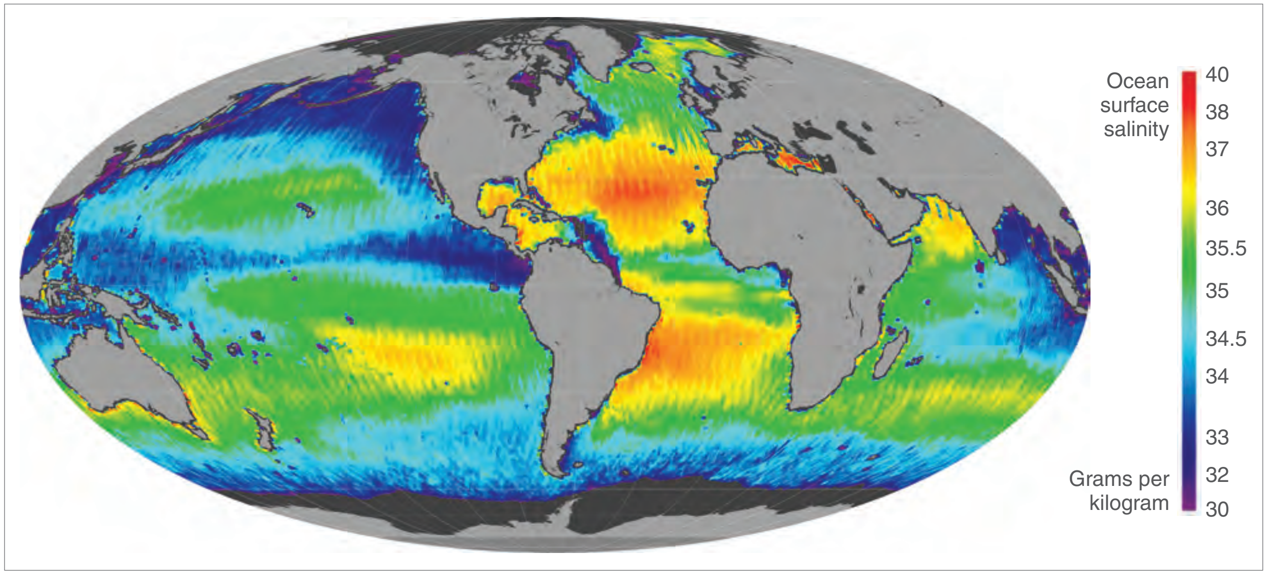
"Aquarius picked up the signal, so that was a pleasant surprise," Gierach said. But there was something else, the extent. "This wasn't just

The NASA IceBridge mission continues to survey the Barnes Ice Cap on Baffin Island. This remnant of the Laurentide ice sheet belies its once massive size, when it covered all of Canada and parts of the northern U.S. Sudden shifts in deep ocean currents may have initiated past ice ages. (Courtesy M. Studinger/NASA)

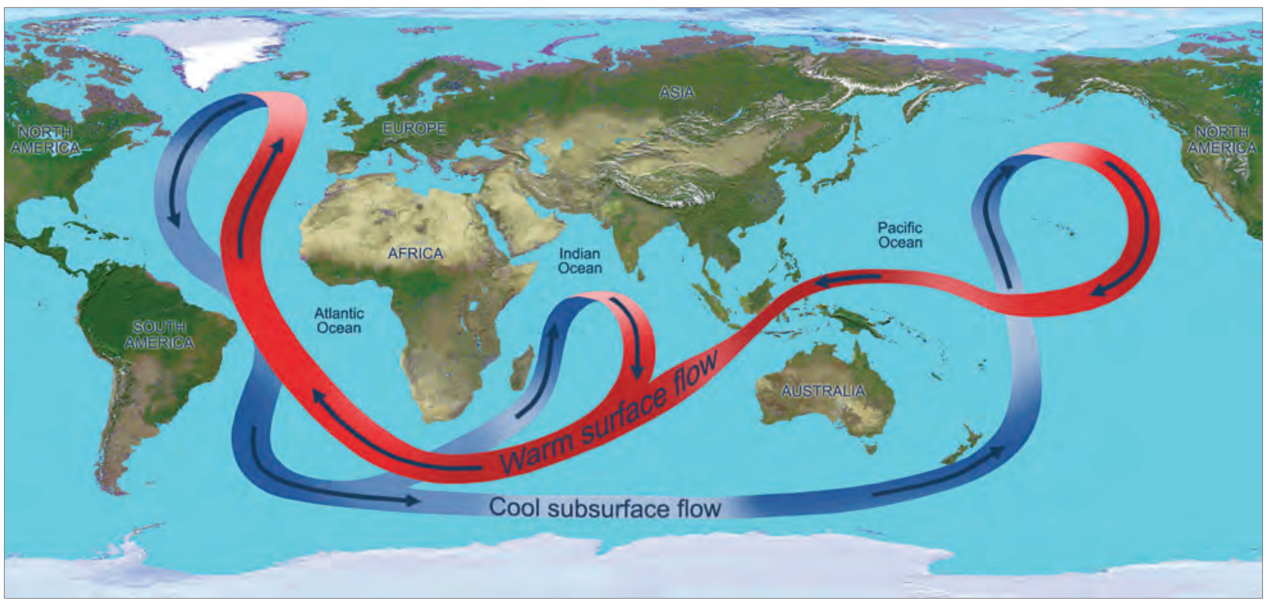
something you saw one kilometer outside of New Orleans," Vazquez-Cuervo said. "The effect traveled a thousand miles and hugged the Mississippi coast, down Florida, and almost the entire eastern part of the Gulf of Mexico. So that was surprising."

But was the freshwater signal real? To check, Gierach turned to the European Space Agency's Soil Moisture Ocean Salinity Mission (SMOS), which also measures SSS, and the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Aqua satellite, from which biological activity at the sea surface can be inferred. Since river discharge carries higher concentrations of nutrients, it enhances biological activity. So MODIS served as a passive tracer of the freshwater plume. Both SMOS and MODIS validated Aquarius. What Gierach was seeing was real.

Gierach does not expect the Mississippi River discharge alone to have a significant global



This image of Aquarius sea surface salinity (SSS) measurements averaged for 2012 shows a global color scale of salinity intensity. Warm colors mark stronger salinity values. Values are shown in a range between 30 grams per kilogram (purple) and 40 grams per kilogram (red). (Courtesy N. Kuring/NASA)



Thermohaline circulation describes deep-water currents that are found below 400 meters and that make up about 90 percent of the ocean. Global density gradients drive the formation of deep-water masses in the North Atlantic and the Southern Ocean. (Courtesy NASA JPL)

impact, but because Aquarius can read signals within marginal seas, scientists can look to other seas, then to other freshwater discharge events like floods, monsoons, and glacial and ice sheet melt. Reading these freshwater plumes may tell stories about what changing climate means for critical ocean circulation patterns. "That's sort of unknown and very interesting, scientifically and societally. But it's going to take a bit of time. Right now we only have approximately three years of data," Gierach said.

The climate pendulum

Sea surface salinity values are saying something else about the ocean. "Currents have a different salinity structure than the surrounding environment, a gradient right at the current boundary that the satellite picks up," Vazquez-Cuervo said. Shifts in salinity can disrupt these barriers, altering ocean circulation. "This seems basic but the reality is we know very little about salinity in the oceans and how it changes."

Temperature and salinity govern seawater density, or its buoyancy. Density differences then drive deep-water currents, or thermohaline circulation, into a submarine river of warm and cold waters churning through the ocean. Ocean currents move heat poleward where heat is released into the atmosphere to maintain and regulate higher-latitude climate. As seawater freezes, it rejects salt, rendering the remaining seawater cold and salty, and thus, heavier and denser. But freshwater dumps, either from a change in rain patterns, glacial melt, or increased river runoff, would make the cold water less salty, thus less dense. This, in turn, could rattle the salinity component of thermohaline circulation, slowing down the sinking of dense water and the associated thermohaline circulation.

So to be able to finally capture salinity means scientists can monitor aspects of the thermohaline circulation. One set of combinations may swing the pendulum into a period of freeze, while another may trigger a melt. Though the exact formula is not fully understood, it is clear ocean circulation is a critical component. Aquarius adds the missing link, even if only on the surface because surface salinity measurements can still provide insight to what might happen at depth.

Take for instance the Gulf Stream, which hugs the U.S. East Coast and then branches off into the Northwest Atlantic. As it goes north, the waters cool and density increases. Further north, sea ice forms, pinching salt out of the ice and into surrounding waters. It consolidates. This more salt-laden, cold water sinks. Known as deep-water formation in the Northwest Atlantic, it moves around the globe, and then comes up in different places. But if over time temperatures warm and less sea ice sets, less sinking will occur, further affecting the global climate.

Salinity may not get the same news buzz as sea level rise. The impact of salinity is much more indirect. Gierach said, "If you change the overall ocean circulation, for example, slow down the thermohaline circulation, you're not bringing as much warm water north or cold water south, so you're changing temperature regimes, atmospheric regimes, weather patterns, but also the biology which adapts to certain environmental conditions." Everything would be impacted. Ice may not encase the Statue of Liberty, but density shifts will alter climate as we currently know it.

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/salt-sea

About the remote sensing data

Satellites	Aquarius	Aqua
Sensors	Aquarius SAC_D	Moderate Resolution Imaging Spectroradiometer (MODIS)
Data sets	Level 3 Sea Surface Salinity	Level 3 Chlorophyll a
Resolution	1.0 degree	9 kilometer
Parameters	Sea surface salinity	Chlorophyll a
Data centers	NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)	NASA Ocean Biology Processing Group DAAC (OBPG DAAC)

About the scientists

Michelle Gierach is a research scientist at the NASA Jet Propulsion Laboratory in Pasadena, California. Her research interests include the application of satellite observations, in situ data, and model simulations to study biophysical interactions and ecosystem dynamics of the ocean, and the ocean's relation to climate variability. NASA supported her research. Read more at http://goo.gl/KgcHHA. (Photograph courtesy M. Gierach)

Jorge Vazquez-Cuervo is a research scientist at the NASA Jet Propulsion Laboratory in Pasadena, California. His research interests include the application of sea surface temperature data to coastal areas and the use of sea surface salinity data in marginal seas. NASA supported his research. Read more at http://goo.gl/AyhwwM. (Photograph courtesy J. Vazquez-Cuervo)

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

Strange bedfellows

“Fires are very old in our ecosystems.”

Juli Pausas
Desertification Research Centre

by Natasha Vizcarra

The humble shrub *Banksia media* can be an unsettling sight. After a bushfire, its flowers look like burnt corncobs that have sprouted clams with orange tongues sticking out. These protrusions are actually seedpods that had cracked open in the heat of the fire, an adaptation that took thousands of years to develop and allowed the shrub to thrive in the fire-prone West Australian bush.

Humans tend to think that plants and fires do not mix. But they are old friends, said Juli Pausas, a plant ecologist at the Desertification Research Centre in Spain. “Some plants flower only after a fire, and some develop thicker barks to survive,” he said. “Evolution has shaped plants with traits that allow them to reproduce despite fires. This is why we know that fires are very old in our ecosystems.”

“Yet, in some places you have more fires than is natural,” Pausas said. “And when you depart from natural fire regimes, that’s when problems begin.”

Scientists are piecing together a global portrait of how fire behaves around the globe, in antici-

A prescribed fire is applied to a *Pinus nigra* stand in Portugal. (Courtesy P. Fernandes) pation of a much larger change in natural fire rhythms. If small disruptions can cause problems, how will larger, more widespread trends like higher global temperatures affect these delicate fire cycles?

A fragmented view

Plants and flames make fascinating, albeit counterintuitive, bedfellows. Caroline Lehmann, a lecturer in biogeography in the University of Edinburgh, remembers the bushfires near her childhood home in Sydney, Australia. "I remember walking through the bush three months after an incredibly intense fire," she said. "The bush was green, none of the trees had died, and I was like, 'What's going on here?'"

This is why many who study the behavior of fire also study the plants that these fires burn. Fire and plant ecologists read tree rings, collect plant specimens, and map plant species and wildfire zones. They observe how different plants and trees react to fires. "In the past, research on fire has been ecosystem-specific and as a consequence, regionally fragmented," Lehmann said. "For instance, some people studied the Ponderosa pine systems of the western United States, or they might specialize in the eucalyptus savannas of northern Australia. Historically, researchers have developed their ideas of fire from working in different regions quite independently."

Savannas, for example, love fire. "They are dominated by a contiguous layer of grass and a discontinuous overstory of trees," Lehmann said. This means savannas are always bathed in sunlight. The climate is hot and the grasses cure and ignite easily. "Savanna grasses grow rapidly and can sustain fire often, perhaps every year to every five years," she said. Tropical forests are the opposite. Dense tree canopies keep the understory dark. The climate is humid, which also keeps the understory moist. "It is difficult to light a fire in that environment," Lehmann said. "The fuel—in terms of what will sustain a fire—is simply too wet."

But there has been a growing need to look at fire patterns in larger geographic areas, across biomes and ecosystems, because of potential changes in climate patterns. Just as climate shapes vegetation and fire shapes vegetation, a changing climate will eventually alter patterns of fire. Researchers have tried to get a bigger view of fire by using aerial photography to examine historical fire scars. Now they are turning to images and data from Earth observing satellites. "It's mind blowing that now we can talk about these relationships at a global scale," Lehman said. "Coming to grips with a global picture of fire can't be undervalued."

The flammable middle ground

Like Lehmann, Pausas is one of those pursuing a global theory of fire. In a 2007 study, Pausas and colleague Ross Bradstock of the University of Wollongong found that fires in southeast Australia frequent a sort of middle ground in the productivity spectrum. On one end are unproductive ecosystems like arid deserts and tundra, and on the opposite end are highly productive systems like tropical rainforests. They found that fire favors ecosystems in the middle of this spectrum, where it is wet enough for some vegetation to grow but dry enough to accommodate fires. Now, he wants to know if satellites can see this pattern all over the globe.

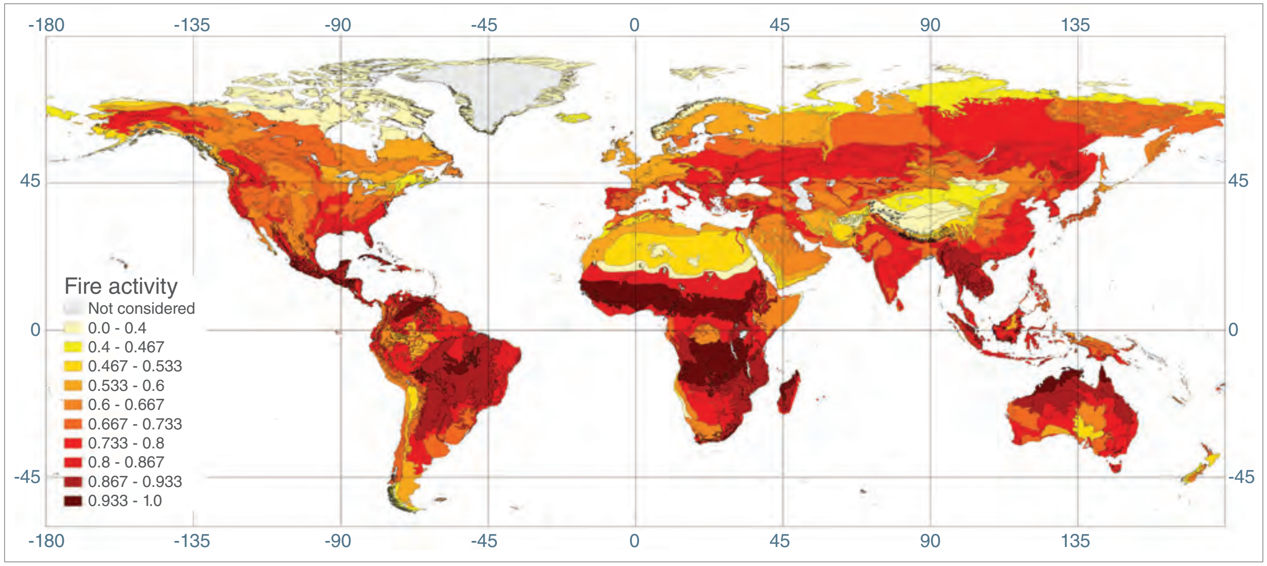
"We want to understand how productivity in ecosystems influence fire activity on a global scale," Pausas said. The lushness or scarcity of plants in an area affects how often wildfires occur and how intensely they burn. More importantly, it tells scientists how sensitive an ecosystem might be to droughts or unusually hot summers.

This photograph shows *Banksia media* before and after a fire. (Courtesy B. Miller, left, and S. Walsh, right)

Researchers have used remote sensing data to look at Earth's fire and vegetation balance, some dividing Earth into grids with squares a few kilometers wide and some partitioning the globe into its major biomes. The problem with the first approach, Pausas said, is that the grid is a very artificial system. "You can't see biological boundaries between grid squares," he said. A single square could contain two areas similar in fire activity, but totally different plant types and plant coverage. "It limits understanding of the patterns we might find," Pausas said. Biomes, like deserts, forests, grasslands, and tundra, are also too big. "Each biome contains lots of variability," Pausas said. "They are very large and span different continents."

A new fire map

Pausas turned to a smaller scale. He divided Earth into ecoregions, which contain roughly



The image above shows a new ecologically-based global fire map derived from fire activity data, Net Primary Productivity (NPP) data, and Normalized Difference Vegetation Index (NDVI) data. The color intensity in each ecoregion represents an ecoregion's fire activity index (from 0 to 1, unitless). The NPP data set was developed by Marc Imhoff, former Terra project scientist at the NASA Goddard Space Flight Center, and colleagues. (Courtesy J. G. Pausas and E. Ribeiro, 2013, *Global Ecology and Biogeography*)

the same kind of vegetation, climate, and fire rhythm, and excluded areas like Antarctica that lacked burnable vegetation. "It's an easier and statistically powerful way to study patterns," Pausas said.

Using this scale, he plotted how many fires burned in each ecoregion by using fire activity data from the NASA Fire Information for Resource Management System. Pegging each ecoregion's productivity level was trickier. To find out the lushness or scarcity of vegetation for each ecoregion, Pausas used Net Primary Productivity (NPP) data from the NASA Socioeconomic Data and Applications Center. NPP data map an area's net solar energy, converted to plant organic matter through photosynthesis. Pausas then double-checked productivity levels by comparing the NPP data with Normalized Difference Vegetation Index (NDVI) data, a measure of Earth's greenness from space. And to tease out the relative role of fuel and climate on fire activity, Pausas sought aboveground biomass data and climatic data from other sources.

The result is "a new, ecologically-based global fire map," Pausas said. It shows that fires occur in nearly all of the world's ecoregions. Fire activity peaks in tropical grasslands and savannas, and significantly decreases in arid deserts and moist tropical rainforests, confirming his hypothesis. Curiously, the highest rate of fire activity did not register right smack in the middle of the productivity scale as he expected. These would have been areas like the sprawling savannas of Africa and Australia and the dry tropical forests in southern Mexico, central India, Madagascar, and South America. Instead, many fires happened closer to the high productivity end, where one might find denser savannas or thinning tropical forests.

Oil and water

Pausas has a few theories. First, fire suppression practices in temperate coniferous forests, like those in the United States, may have contributed to the skewed pattern. Not enough fires are happening in areas that are historically adapted to more frequent fires. Pausas also thinks that deforestation has increased fire activity in tropical rainforests. Lehmann said, "At this stage, humans are driving the change in the instances of fire in the tropical region." Deforestation allows more flammable grasses and woody plants to invade cleared areas while human activity provides an ignition source. "Historically, tropical forest systems burned very, very infrequently," Lehmann said.

Overall, the map suggests that in addition to human-caused fires, a scenario of higher global temperatures will make lush subtropical forests and temperate forests even more vulnerable to an increase in wildfires. "It's much easier to increase fire in a wet ecoregion with lush vegetation than in a dry region," Pausas said. "That the sensitivity of fire to high temperatures is much stronger in high-productivity areas implies that small changes in temperature have a much higher effect on fire activity in high-productivity areas."

A warmer Earth also means more droughts. In wet tropical forests, a change in temperature can influence how moisture evaporates from the land, which in turn influences rainfall patterns. "We may find that we have an increasing frequency of droughts in those systems," Lehmann said.

"Drought in this closed canopy system causes trees to die and fall over; this will allow the vegetation to dry out and create spots where fire can ignite and spread."

Pausas' map shows that fire has already begun to spread from fire-friendly biomes like savannas to tropical forests. Whether tropical forests can adapt quickly enough to become fire-friendly regions is the million-dollar question. "Tropical forests and tropical savannas are essentially like oil and water," Lehmann said. "Forests and savannas are systems that can't mix because the properties that are fundamental to each vegetation type are just so different. Plants in each ecosystem have adapted to their climate and fire conditions over tens of thousands of years. We are changing that very quickly."

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/strange-bedfellows

About the data

Satellite	Terra	
Sensor	Moderate Resolution Imaging Spectroradiometer (MODIS)	
Data sets	Global Active Fire Data	Global Patterns in Net Primary Productivity
Resolution	0.5 degrees	0.25 degrees
Parameters	Global fire activity	Net primary productivity
Data centers	Fire Information for Resource Management System (FIRMS)	NASA Socioeconomic Data and Applications Center (SEDAC)

About the scientists

Caroline Lehmann is a lecturer in biogeography in the School of GeoSciences at the University of Edinburgh. Her research focuses on the ecology and evolution of tropical ecosystems and plant-fire coevolution. Australia's Macquarie University supported her research. (Photograph courtesy C. Lehmann)

Juli G. Pausas is a plant ecologist at the Centro de Investigaciones sobre Desertificación (Desertification Research Centre) in Spain's National Research Council (CIDE-CSIC). His research focuses on the ecology and evolution of Mediterranean vegetation, specifically on understanding the role of fire in shaping plant species, populations, communities, and landscapes. The Spanish government supported his research. Read more at http://www.uv.es/jgpausas. (Photograph courtesy J. Belliure)

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NASA Fire Information for Resource Management System (FIRMS)
http://earthdata.nasa.gov/firms

Global Patterns in Net Primary Productivity
http://sedac.ciesin.columbia.edu/data/set/hanpp-net-primary-productivity

Profiles in intensity

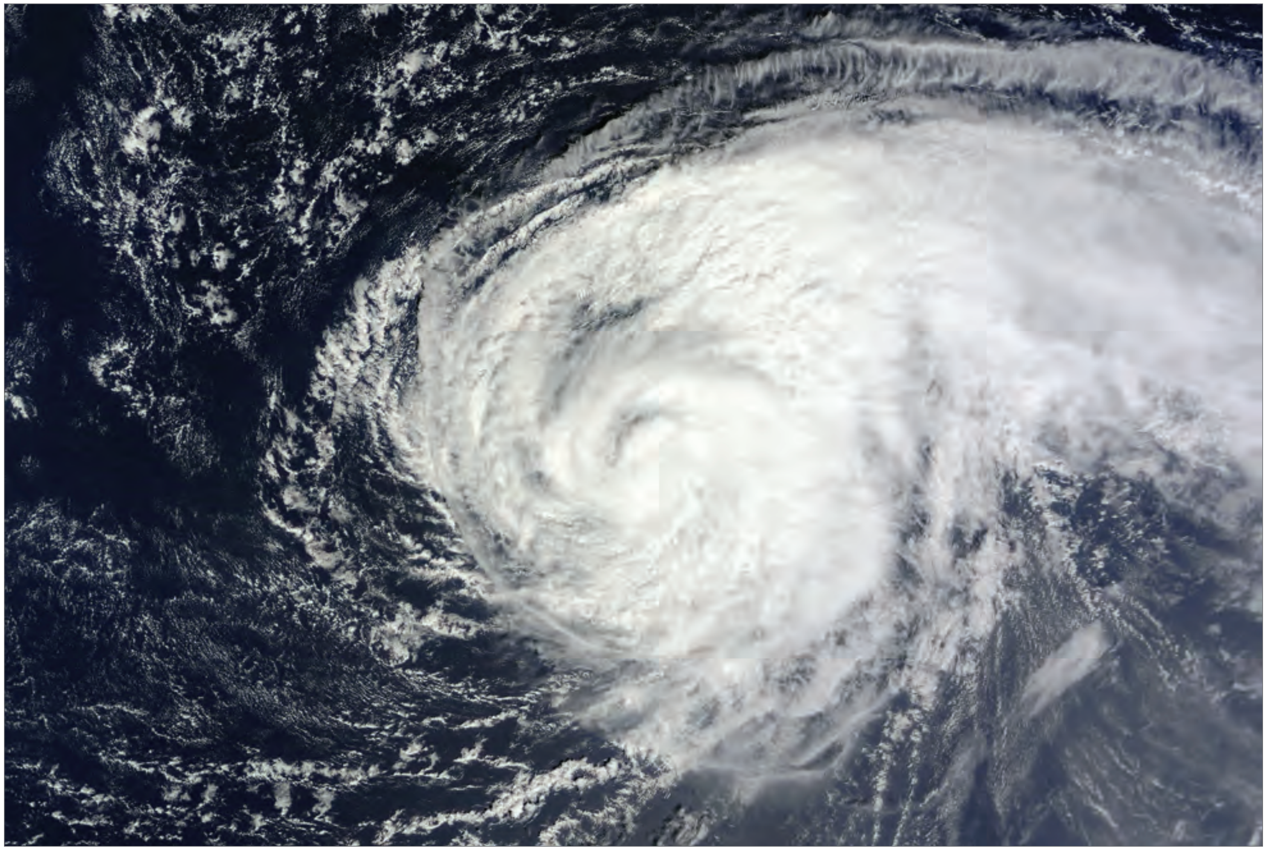
"Reliably predicting a tropical cyclone's intensity has turned out to be one of the hardest problems in atmospheric sciences."

Jim Doyle
U.S. Naval Research Laboratory

by Agnieszka Gautier

In less than twenty-four hours, Tropical Storm Wilma mushroomed into a Category 5 hurricane. "How the storm was able to do that is still a bit of a mystery," said Scott Braun, a NASA research meteorologist. "A lot of storms have favorable environments and never undergo that intensification rate. So we're not quite sure why that storm was so special." Having one of the fastest intensifications on record, it hit Mexico's tourism industry, drowned Havana, Cuba, and left six million Floridians without power. The 2005 hurricane became the most intense on record for the Atlantic Basin.

Predicting the track of a storm has improved, but rapid intensification continues to challenge



The NASA Terra satellite captured this true-color image of Hurricane Nadine in the Atlantic Ocean on September 16, 2012. (Courtesy Land Atmosphere Near-Real Time Capability for EOS [LANCE] System, NASA GSFC) scientists. “Reliably predicting a tropical cyclone’s intensity has become one of the hardest problems in atmospheric sciences,” said Jim Doyle, a scientist at the U.S. Naval Research Laboratory (NRL). He is part of the five-year NASA Hurricane and Severe Storm Sentinel (HS3) mission, using airborne observations to study a storm’s inner-core processes and its surrounding environment—in particular, the Saharan Air Layer (SAL), a very hot, dry, and dusty air mass in the Atlantic Basin.

“We’re interested in how the SAL suppresses or favors storm intensification,” Braun said. Early findings suggest some past explanations of the SAL’s significance have been oversimplified. In addition, information gathered while soaring above 55,000 feet has brought the tops of hurricanes into focus, a side benefit of the mission and one that may shed light on hurricane intensification.

The dust within

A sea of sand, the Sahara Desert alternates between barren plateaus and steep, shifting dunes. Strong winds loft dust from the dunes skyward, and then sweep it across the Atlantic basin. Researchers have been studying the Saharan dust for decades, trying to understand its influence in hurricane formation and intensification. “But there’s some debate as to how big of an influence it really is,” Braun said.

Earlier studies argued for and against its influence in hurricane formation. Some suggested it hinders storm development when hot, dry air, like the SAL, funnels into the core. A storm’s ability to intensify relies on cloud formation within the inner core, and clouds need humid air to form. By directly entering the circulation, the SAL evaporates clouds, stopping or slowing formation.

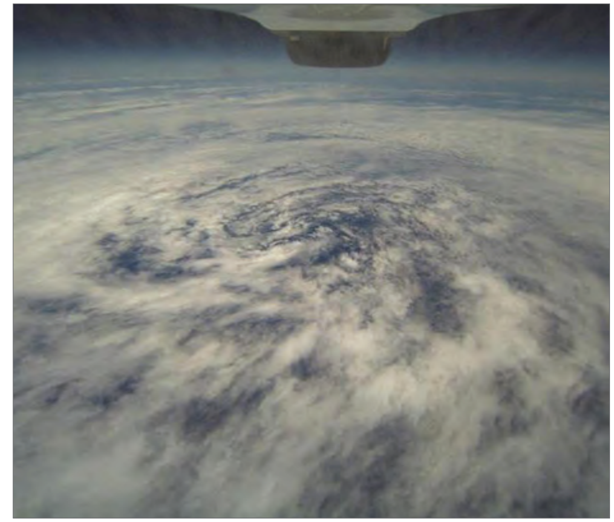
But HS3 studies of Hurricane Nadine in 2012 did not quite see that. “Right now our observations don’t support a direct influence in this case, but the SAL suggests an indirect influence, weakening the storm,” Braun said. “It’s sort of able to do it from a distance.” The dust layer absorbs solar radiation, which may cause temperature gradients and shifting wind speeds near and within the storm, impacting its development.

HS3 makes one thing clear: the effect of the SAL is not cut and dried. “We’ve often looked for the easy explanations,” Braun said, “I think we’re getting a better sense at what stage in the lifecycle of a storm the SAL can play a role.” Early on in a storm’s development, the SAL may be more consequential, before the tempest fully forms and is able to protect its inner core with impassable, well-organized walls of wind and rain.

Getting the spins

Hurricanes are monstrous energy machines, converting heat energy garnered from a warm ocean to mechanical energy through convection, or heat transfer. Hurricanes spin two ways. Primary circulation moves in a horizontal direction, while secondary circulation cycles air vertically: in, up, and out. Warming air flows in at the bottom, up through the rain bands and eye wall, and then fans out at the top. As a storm gets more organized, inflow toward the center near the surface increases.

The hope with HS3 is to connect the structure of convection, the upward section in secondary circulation, to the evolving low-level and upper-level wind fields. Much like ice skaters can spin faster

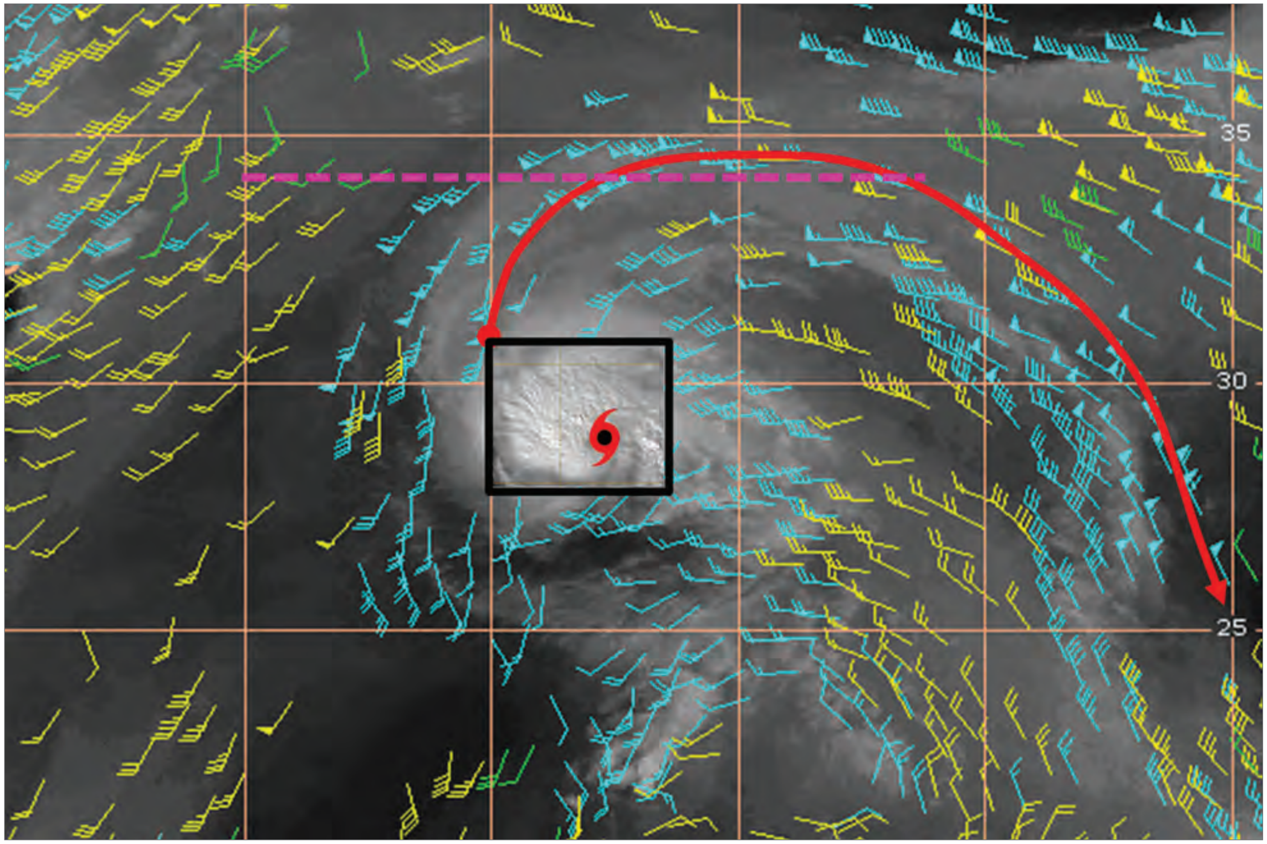


A camera on the underside of the Global Hawk aircraft took this photograph of Tropical Storm Frank from an altitude of 60,000 feet on August 28, 2010. (Courtesy NASA/NOAA)

by pulling their arms in, winds speeds increase as the low-level air moves toward the center. But air cannot speed up unless clouds pump low-level air out at the top.

That is why Peter Black at NRL approaches intensification from a different angle. “The outflow essentially acts like a vacuum cleaner,” Black said. Forcing air away, the suction drops the storm’s central pressure, and then warm air fills the vacuum. As long as warming air rises up and out faster than new air spirals in, the central pressure in a developing hurricane will fall. And falling pressure is an indicator of hurricane intensity. “Though still a matter of debate,” Braun said, “HS3 provides the best opportunity to date to examine the role of the outflow layer in hurricane intensification.”

Satellites have been mapping hurricanes since the 1970s, but their images of the outflow layer



Motion vectors are superimposed on a satellite image of Hurricane Nadine in 2012. A red hurricane symbol marks the center. Strong convection to the northwest gives rise to an outflow jet (solid red curve) that spirals clockwise away from the storm center toward the equator (blue wind vectors), suggesting a dynamic connection between the inner core of the storm and the environment. The dashed magenta line indicates the approximate flight path of the Global Hawk aircraft from the Hurricane and Severe Storm Sentinel mission. Satellite data are from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the NASA Aqua satellite. (Courtesy P. Black/NRL)

lacked the nitty-gritty details. Getting a sense of the structure of the inner core may be key. Black said, "From our perspective, the HS3 mission is sort of a breakthrough." Outflow is a side benefit of the mission. Braun, HS3's principal investigator said, "It never was part of the original proposal, but later we realized the mission could play a significant role in looking at the outflow structure because of the Global Hawk capabilities and its payloads."

The mission's unmanned NASA Global Hawk aircraft operate at extreme altitudes up to 63,000 feet, climbing into the stratosphere above a storm. Getting that high is not easy. Most airplanes struggle to burn jet fuel with the low oxygen at that altitude. Flying for up to twenty-six hours and decked with profiling sensors, lasers, cameras and other instruments, the Global Hawks can now see the full extent of the top layer of hurricanes, where outflow happens.

An unexpected profile

For the mission, two Global Hawks soar. One probes the inner core or eyewall region of the storm where the most intense surface winds and rainfall occur. The other Hawk samples the outflow layer by deploying as many as 88 dropsondes, instrumented packages that parachute down through the storm. The result is an image of outflow structure unlike what scientists had imagined.

"Many of us were a bit surprised by the wind profiles we saw in the outflow layer," Braun said. Dropsondes showed that outflow winds peak at the very top of the layer rather than somewhere within. These winds experience sharp transitions as opposed to more gradual transitions. And overall, the shape of the full outflow layer is much more concentrated, much thinner than satellite data or models had estimated.

Then there are the outflow jets—roaring channels of humid, high-speed air that surround the top of a hurricane. Sometimes a hurricane only has one channel. Other times, two or more form in different quadrants of the storm. Through these channels most of the air is being evacuated from the storm, but, as the dropsondes show, it is not a uniform process. "Not everything is going out equally in all directions," Black said. "Something in the environment around the storm focuses the air into high-speed channels."

Black said, "We had noticed that whenever the tropical storm developed two of these outflow jets, one directed at the equator, one directed towards the pole, it seemed to correspond to a period of rapid intensification." To help link these events with causes and effects, scientists turned to storm models to reproduce the outflow structure.

Waiting for the big one

Doyle's team of research meteorologists specializes in tropical cyclone observations and prediction, a vital component of the HS3 mission. In 2012, with Hurricane Nadine, scientists got their first chance to assimilate dropsonde outflow data into their prediction model. HS3 had three successful flights in ten days, each deploying 60 to 75 dropsondes. Doyle's team ran the prediction model with and without the dropsonde data. "We found the dropsondes were able to help the forecast quite a bit," Doyle said. "And most importantly, the forecasting model improved substantially."

But not all storm forecasts respond well to dropsonde data. "So we're trying to tease out where this impact is coming from," Doyle said. For now, they have to wait for more storms and more measurements. Meanwhile, the NASA Global Hydrology Resource Center Distributed Active Archive Center is building an archive of data from HS3 for further study.

Still, the mission is not without its challenges. If weather is too harsh at the airfield, the Global Hawks cannot take off. And, of course, hurricanes have to form. The mission missed Hurricane Sandy by a week, and no major hurricanes developed in 2013. "I'm sure people were glad not to deal with hurricanes then, but when you're doing a field campaign that's not quite what you want," Braun said. "We could use some additional cases." For now, scientists are equipped with the right set of questions. Getting the details right may improve warning systems. And since studies show most people base their evacuation decisions—if and when to leave—on intensity forecasts, answering these questions could better prepare communities for the next big whirlwind.

About the remote sensing data

Platform	NASA Global Hawk aircraft
Sensors	Various airborne sensors and instruments
Data set	Hurricane and Severe Storm Sentinel (HS3) data
Parameters	Total vertical velocity, convected vertical velocity
Data center	NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC)

About the scientists

Peter Black is a senior scientist at the Naval Research Laboratory (NRL) in Monterey, California. His interests include investigating tropical cyclone intensity changes related to hurricane boundary layer structure, ocean response, hurricane air-sea interaction, remote sensing of surface winds, and hurricane outflow channels. The Office of Naval Research (ONR), NRL and NASA supported his research. (Photograph courtesy M. Burnges, NRL)

Scott Braun is a research meteorologist at the NASA Goddard Space Flight Center in Greenbelt, Maryland. He studies hurricanes from the inside out using satellite and aircraft data to investigate how hurricanes interact with their environment. He is the principal investigator for the NASA Hurricane and Severe Storm Sentinel (HS3) mission. NASA supported his research. (Photograph courtesy NASA)

James Doyle leads the mesoscale modeling section at the Naval Research Laboratory (NRL) in Monterey, California. He is one of the primary developers of the Navy's prediction system, and leads efforts for improving prediction and physical understanding of mesoscale phenomena: tropical cyclones, gravity waves, and marine boundary layer circulations. The Office of Naval Research (ONR) and NASA supported his research. (Photograph courtesy J. Doyle)

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http://www.nasa.gov/mission_pages/hurricanes/missions/hs3

Rooting out rainfall

"We've discovered in the last ten years or so that even the high latitudes have big impact on tropical rainfall."

Dargan Frierson
University of Washington

by Laura Naranjo

When viewed from space, the tropics are often obscured by a loosely swirling band of clouds meandering around the equator. The recipe that forms this band is fairly simple: Hot tropical air rises, water vapor in the heated air forms clouds, and the water often precipitates out as rain. But rain does not fall evenly across the tropics. "It's clear from any map of precipitation that it rains more in the Northern Hemisphere than in the Southern Hemisphere," said Dargan Frierson, a professor at the University of Washington.

Because heat drives rainfall, Frierson was perplexed: Where was this hemispheric heat

Many locations north of the equator, such as Guyana, tend to receive more rain than locations in the southern tropics. (Courtesy T. Rampersad) imbalance coming from? And will climate change push that rain even further north, bypassing some of the globe's critical rice and tea croplands?

Atmosphere or ocean heating?

This swath of rain forms along the equator where the trade winds converge and steer tropical storms. It tends to govern the tropical climate, creating wet and dry seasons rather than cold winter and hot summer seasons. Frierson became curious about what heat source could pull those rain bands north on such a large scale. Some scientists speculated that the northwest-to-southeast tilt of the ocean basins in the tropics draws heat and rain north. They also thought the fact that there is more land in the Northern Hemisphere than the Southern Hemisphere might be responsible. To test this, Frierson created computer models simulating an Earth without landmasses, called aquaplanet models. On an ocean-covered Earth, with no landmasses to interfere with oceanic or atmospheric circulation, one might think that precipitation would be more uniformly distributed. But that was not the case. "We found that in the aquaplanet model, heating is still plenty strong enough to move the rain band into the Northern Hemisphere," Frierson said.

This meant neither landmass asymmetry nor tilting ocean basins was the culprit. Some other process must heat the Northern Hemisphere on a large enough scale to tug tropical rainfall north. "It really matters which hemisphere is heated more," he said. When he delved into the dilemma, he had two suspects: heating at the top of the atmosphere from radiation, or heat in the oceans.

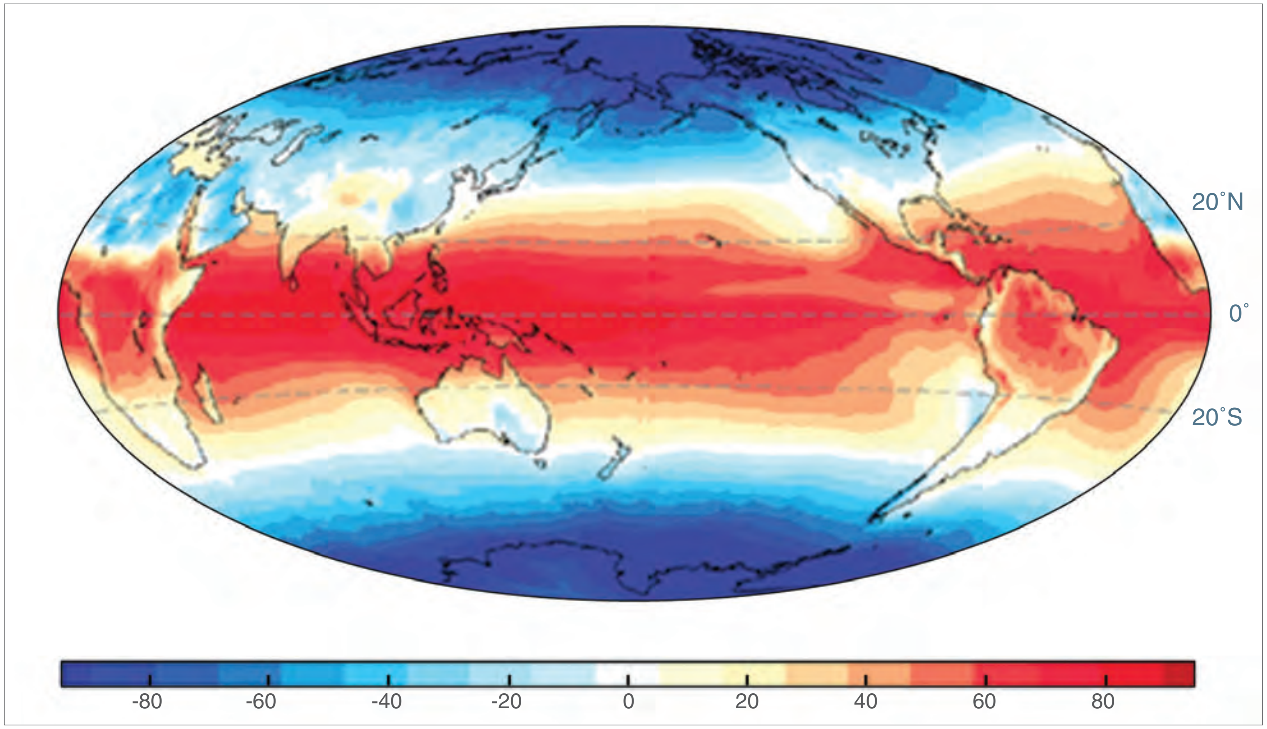
First, he and his colleagues looked at energy from radiation. The Earth is heated by the sun, and is cooled by outgoing longwave radiation.

Much of the world's rice is produced in Southeast Asia, which lies in the northern tropics. Shifts in rainfall could devastate the industry. (Courtesy P. Chandran)

Data from two NASA Clouds and the Earth's Radiant Energy System (CERES) instruments, flying on the NASA Aqua and Terra satellites, along with data from the NASA Solar Radiation and Climate Experiment (SORCE) satellite and other sources, allowed the researchers to calculate incoming solar radiation, while subtracting longwave radiation, as well as radiation reflected out by geographical features like ice and deserts. This gave them the total radiation for each hemisphere.

It turns out both hemispheres receive the same amount of solar radiation. So for top-of-atmosphere heating to be the culprit, then the Northern Hemisphere would have to retain more of the incoming solar radiation or emit less longwave radiation. Yet that was not the case. "We were really surprised," Frierson said. "The Sahara and Arabian deserts in the Northern Hemisphere reflect away a lot of solar radiation. This ultimately leads to the Southern Hemisphere retaining more radiation."

The results buoyed their theory that if radiation was not pulling tropical rain bands north, heat in the oceans was the likely source. "The CERES data was really the key piece of the puzzle," Frierson said. "Honestly, it was one of the coolest times of my scientific career: downloading that data, doing that calculation, and seeing that



At the top of the atmosphere (TOA), incoming and outgoing radiation determine Earth's average temperature. This data image shows averaged net downward TOA radiation from the Clouds and Earth's Radiant Energy System (CERES) instrument from 2001 to 2010. The Southern Hemisphere receives more net radiation than the Northern Hemisphere. (Courtesy D. Frierson et al., 2013, *Nature Geoscience*)

answer. It helped us confirm that radiation was not the driver, so we had more confidence that it must be the ocean."

Salty, sinking water

But how do oceans influence rainfall patterns? Oceans store and transport heat through currents that work much like giant conveyor belts. Global temperature differences help stimulate this circulation. Solar radiation is most intense along the equator, and gradually decreases at higher latitudes. "The fact that higher latitudes get less sunlight than lower latitudes is the fundamental driver of oceanic and atmospheric circulations," said Yen-Ting Hwang, who studies ocean heating and circulation.

Another key factor in ocean circulation is salt. Salt water is denser than fresh water, and therefore sinks. Cold water is denser than warm water, and likewise sinks. Consequently, fresh, warm water remains near the surface and salty, cold water sinks into the deep ocean. This produces the continual churning and movement that form a large set of the world's ocean currents, called the Meridional Overturning Circulation.

Frierson and his colleagues focused on a giant, continuous loop in the Atlantic that transports warm water from the tropics to the poles, traveling all the way from Antarctica to Greenland. At the poles, sea ice squeezes salt out of water as it freezes, leaving even saltier water. "Salty and cold water sinks in North Atlantic high latitudes. The dense water travels in the deep ocean and most of it upwells in the Southern Ocean," Hwang said. "The overturning circulation in Atlantic constantly brings warmer water from Southern Hemisphere to the Northern Hemisphere and brings colder, denser water away from the Northern Hemisphere." While landmasses may not directly contribute to hemispheric warming, they do affect ocean circulation. Hwang said, "The way that the continents are set up makes the Atlantic saltier than the Pacific, which is a key driver of the Meridional Overturning Circulation."

When the researchers modeled ocean heating, they confirmed that temperature overturning was creating a warmer North Atlantic. "Water sinks near Greenland because it's really cold and salty," Frierson said. But they also found this warming helped drag the rain bands slightly north of the equator. "The sinking cold water near Greenland just flushes out all the really cold stuff from the North Atlantic," Frierson said. "So you're left with warmer water there, and it sort of tugs all the warmth toward that, too." The ocean releases some of that heat into the atmosphere, which in turn fuels atmospheric heat circulation and pulls more warm air to the north of the equator. That pool of warmer air creates the tug, shifting tropical precipitation slightly north.

Tail wagging the dog

Scientists long thought that the tropics control global climate and weather patterns. But they have since realized that extratropical regions, further from the equator, also influence far-reaching patterns. "We've discovered in the last ten years or so that even the high latitudes have big impact on tropical rainfall," said Frierson. "It was kind of like the tail wagging the dog." This means that changes in polar climate or sea ice formation could influence where rain falls. "The Meridional Overturning Circulation is very slow—it takes hundreds of years to recirculate," he said. "But it is something that we expect to change with global warming."

If the oceanic overturning process that transports heat slows down or changes, more cold water can pool in the North Atlantic, coaxing tropical rain bands south. "We actually started this research with the goal of understanding how the tropical rain belt would change with climate change," Hwang said. "The tropics are one of the most vulnerable places to climate change. At the boundaries of tropical rain belt, people depend on rainy seasons to grow crops. An anomalous variation in the location of the tropical rain belt results in tremendous changes to local rainfall and affects millions of people." Most of the world's rice paddies are located across Southeast Asia, in the northern tropics. Likewise, much of the world's tea and coffee are produced in countries that lie in the north tropics, such as India and Colombia.

Other changes, such as increasing fresh river runoff from Siberian rivers coupled with decreasing sea ice could create fresher, warmer Arctic waters less likely to fuel overturning in the oceans. Frierson said, "So instead of that cold water being flushed down into the deep ocean, it's going to instead stay up there." This would help offset the tendency for tropical rainfall to shift northward with climate change.

About the remote sensing data

Satellites	Terra and Aqua
Sensor	Clouds and Earth's Radiant Energy System (CERES)
Data set	CERES Energy Balance and Filled Top of the Atmosphere (EBAF-TOA) Ed2.8
Resolution	1 degree latitude, zonally gridded
Parameter	Radiant energy flux
Data center	Atmospheric Science Data Center Distributed Active Archive Center (ASDC DAAC)

About the scientists

Dargan Frierson is a professor in the Department of Atmospheric Sciences at University of Washington. His research focuses on large-scale climate dynamics, with particular interest in using a hierarchy of climate models to study how major climate features will change with global warming. The National Science Foundation and the University of Washington supported his research. Read more at http://goo.gl/us19y0. (Courtesy D. Frierson)

Yen-Ting Hwang is an assistant professor in the Department of Atmospheric Sciences at National Taiwan University. Her research involves understanding global atmospheric dynamics and its interactions with clouds, aerosols, and ocean. The National Science Foundation and the University of Washington supported her research. Read more at http://goo.gl/CXVKMc. (Courtesy K. Rasmussen)

"We hear all the time about how the tropics can affect the rest of the world, with El Niño and La Niña, but the extratropics can also affect the tropics," Frierson said. "I think any kind of study that contributes to how rainfall there is determined and how it might change in the future is really important."

To access this article online, please visit http://earthdata.nasa.gov/sensing-our-planet/rooting-out-rainfall

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For more information

Atmospheric Science Data Center Distributed Active Archive Center (ASDC DAAC)
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Clouds and Earth's Radiant Energy System (CERES)
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MODIS Level 1 and Atmosphere Archive and Distribution System DAAC

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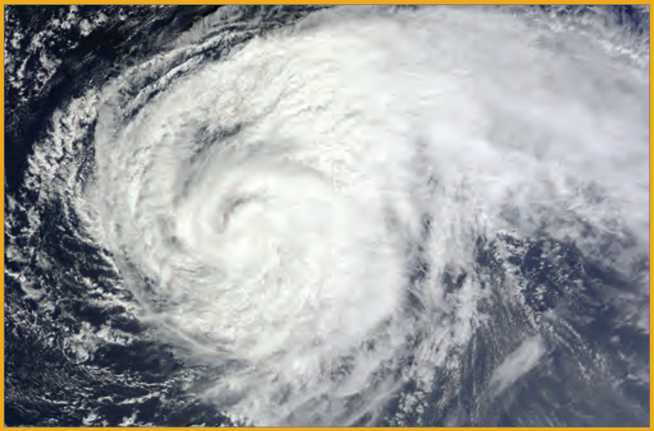



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