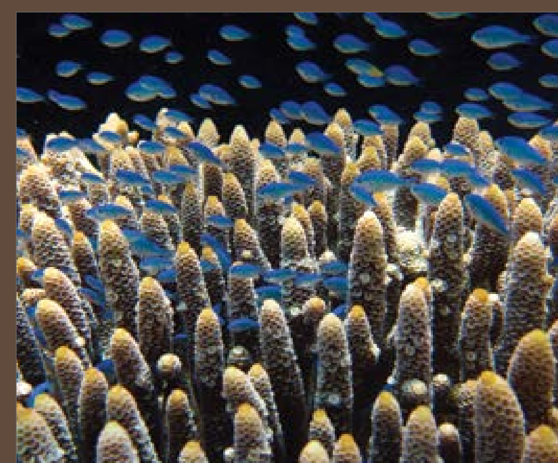
National Aeronautics and Space Administration

Sensing Our Planet









NASA Earth Science Research Features **2016**

Sensing Our Planet

NASA Earth Science Research Features 2016

National Aeronautics and Space Administration

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

www.nasa.gov

Front cover images

Top row, left to right:

Stairs and stripped trees are about all that remain after a tornado hit Lake Martin, Alabama, on April 27, 2011. See the related article, "The power of particles," on page 42. (Courtesy lakemartinvoice/Flickr)

Snow petrels wait along ice edges, ready to snatch krill or fish that come near the ocean surface. See the related article, "In the zone," on page 38. (Courtesy D. Filippi, Institut Polaire Français Paul-Émile Victor/Centre national de la recherche scientifique/Sextant Technology Ltd.)

This photograph shows a large lenticular cloud hovering over part of Torres del Paine National Park, in Chile's Patagonia region. Also called UFO clouds or cap clouds, lenticular clouds make it possible to get a rare glimpse at the crests of gravity waves. When air rushes over mountains and the conditions are right, with cold air and water vapor condensing into droplets, lenticular clouds form at the crest of the waves. See the related article, "The case of the missing waves," on page 16. (Courtesy klausbalzano/Flickr)

Clean drinking water flows out of a fountain at Sforza Castle in Milan, Italy. See the related article, "Soiled soils," on page 20. (Courtesy E. Blaser)

Bottom row, left to right:

Phragmites, a species of common reed, can dominate wetlands. See the related article, "Where the wetlands are," on page 2. (Courtesy E. Banda)

Seen from the shore of Lake Maracaibo, lightning strikes Congo Mirador, a *palafito* or a stilt house village, near the mouth of the Catatumbo River. See the related article, "The Maracaibo beacon," on page 34. (Courtesy H. P. Díaz/Centro de Modelado Científico)

Juvenile blue chromis linger near the branches of an *Acropora millepora* colony off Lizard Island on the Northern Great Barrier Reef. Corals are an important habitat for fish, especially young fish that hide in the reefs to avoid predators. See the related article, "The researcher, the reef, and a storm," on page 30. (Courtesy F. J. Pollock, Pennsylvania State University)

Back cover images

Top row, left to right:

Iceberg B-15A floats in the Ross Sea, Antarctica. Iceberg B-15A is a fragment of the much larger iceberg (B-15) that broke away from the Ross Ice Shelf in March 2000. See the related article, "Tracking the itinerant," on page 46. (Courtesy J. Landis, National Science Foundation)

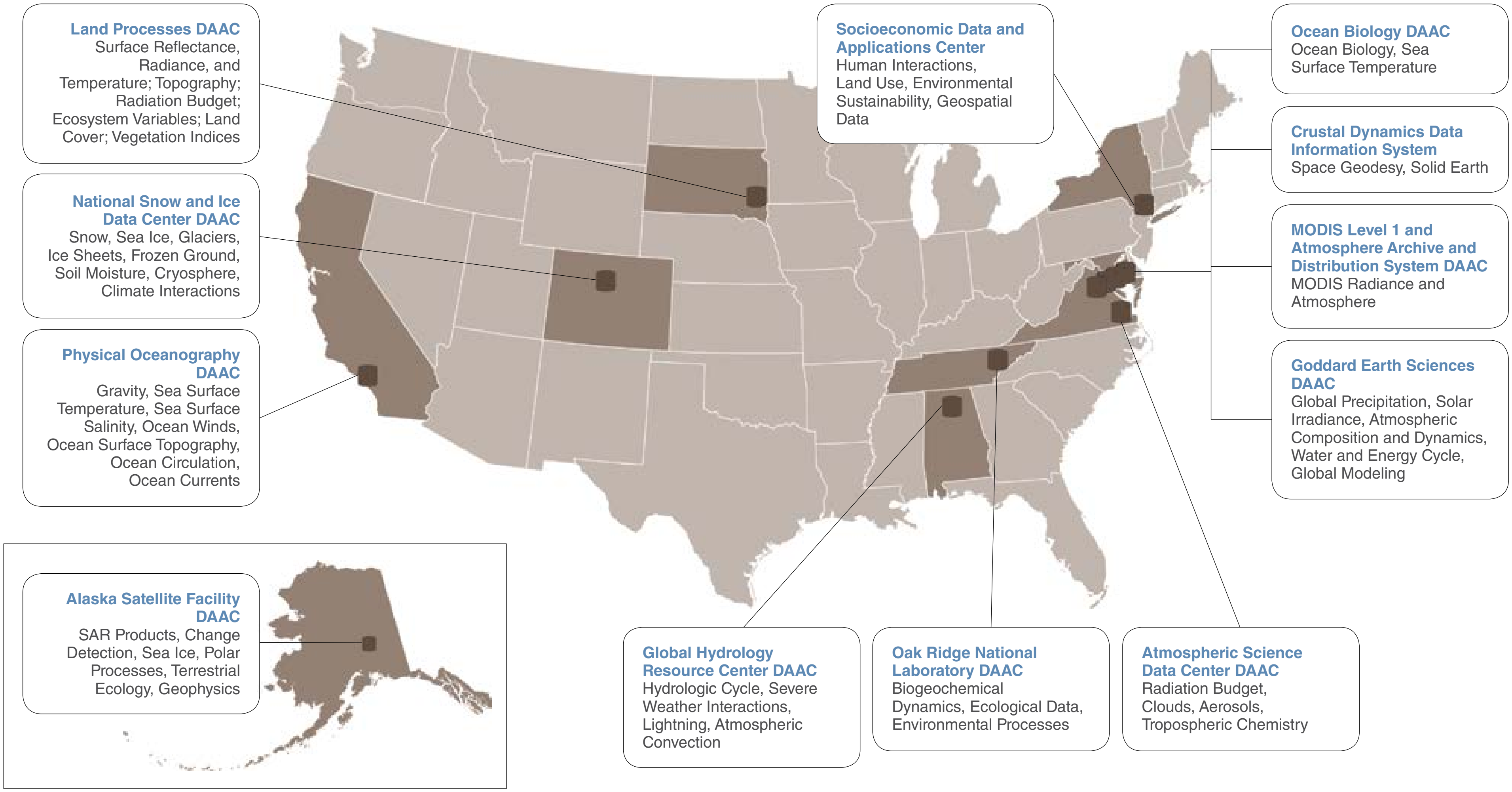
Frost clings to an eddy covariance tower in Barrow, Alaska. The sensors measure methane emissions year round and are equipped with deicers to prevent them from malfunctioning in the Arctic's frigid temperatures. The tower also measures other meteorological variables, including air temperature, humidity, soil temperature, and soil moisture. See the related article, "In the Arctic darkness," on page 12. (Courtesy S. Losacco)

Bottom row, left to right:

A Bedouin shepherd tends his sheep amid a parched landscape in Syria. See the related article, "Crisis in the Crescent," on page 50. (Courtesy J. Werner)

Children play in the fountains at Dilworth Park in Philadelphia. See the related article, "Feeling hot hot hot," on page 8. (Courtesy A. Lewis)

A debris engineer with the U.S. Army Corps of Engineers inspects a house damaged by Hurricane Sandy in Queens, New York. See the related article, "Time and tide," on page 24. (Courtesy B. Beach, U.S. Army Corps of Engineers)



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 9,400 Earth system science data products and associated services to a wide community of users. ESDIS develops and operates EOSDIS, a distributed system of discipline-specific DAACs and science investigator processing systems. EOSDIS processes, archives, and distributes data from Earth observing satellites, field campaigns, airborne sensors, and related Earth science programs. These data enable the study of Earth from space to advance scientific understanding.

For more information

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

About Sensing Our Planet

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

Articles and images from *Sensing Our Planet: NASA Earth Science Research Features 2016* are available online at the NASA Earthdata website (https://earthdata.nasa.gov/sensing-our-planet). Electronic versions of the full publication are available on the site. *Sensing Our Planet* is also available as an iBook from the Apple iBooks Store.

For additional print copies of this publication, please 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 fish. Several stories for 2016 focus on the quality of Earth's groundwater, wetlands, and oceans. Small changes in quality can ripple through ecosystems and affect fish populations, marine food chains and biomes, and human drinking water supplies.

Acknowledgments

This publication was produced at the Snow and Ice Distributed Active Archive Center (DAAC), at the National Snow and Ice Data Center, under NASA GSFC contract No. NNG13HQ03C, awarded to the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder. We thank the EOSDIS DAAC managers and personnel for their direction and reviews, and the scientists who alerted us to recent research that made use of EOSDIS data.

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Sensing Our Planet

NASA Earth Science Research Features 2016

Where the wetlands are

“We’re happy we came up with a nice product for people to use.”

Laura Bourgeau-Chavez
Michigan Tech Research Institute

by Laura Naranjo

Author Henry David Thoreau wrote about wetlands so often he has been called the patron saint of swamps: “I enter a swamp as a sacred place, a *sanctum sanctorum* . . . I seemed to have reached a new world, so wild a place . . . ” He found wetlands enchanting, relishing every experience from the sights and sounds to the texture of the mud. Even the scent was enticing, which he described as the fragrance of Earth itself.

Since Thoreau’s time, much has changed, and many wetlands are no longer such wild places. Wetlands are often drained for human development, replaced by steel mills, shipping ports, and

In wetlands, water saturates the soil to form a shallow, aquatic ecosystem. (Courtesy L. Bourgeau-Chavez) homes. This encroachment drives away wildlife and contaminates the remaining water. Some of the greatest damage has occurred around the Great Lakes region, home to one of the largest expanses of coastal wetlands in the United States. Documenting and protecting wetlands has become crucial to the eight states and two Canadian provinces thronging the lakes. While the lakes themselves have been extensively charted, mapping the surrounding wetlands has proven a slippery task.

Laura Bourgeau-Chavez, a researcher at Michigan Tech Research Institute, was familiar with the problem. She said, "In the past, the United States and Canada have had to patch different maps together." Bourgeau-Chavez uses satellite data to study land cover, and thought she could develop a way to map Great Lakes wetlands. Armed with satellite imagery, hip waders, and a bit of serendipity, she and her team hoped to produce consistent and accurate maps of the entire basin.

Trumpeter swans breed and nest in wetlands, and are found throughout much of the Great Lakes basin. (Courtesy U.S. Fish and Wildlife Service)

Where land meets water

Wetlands are places where land is permanently or seasonally saturated with water, forming a distinct ecosystem that is both aquatic and land-based. Although wetlands may exist wherever water collects, they often border rivers and lakes, creating spongy coastlines astir with fish, birds, and the drone of mosquitoes and dragonflies.

But wetlands are not just scenic retreats. Wetland plants trap sediment, which stabilizes shorelines. They provide a buffer against waves and storm surges. Wetlands also absorb pollutants, preventing toxic elements from flowing downstream or percolating underground. Along parts of Lake Erie, for instance, there are no longer enough wetlands to filter agricultural runoff. Nitrogen and phosphorous now flow into the lake and produce toxic algal blooms that can cover up to 300 square miles.

Across the northern United States, the Great Lakes wetlands cover approximately 35,521 square miles, about the size of Indiana. Yet this is only half their historical area. To protect what remains, the U.S. Environmental Protection Agency funded the Great Lakes Restoration Initiative, which will help clean up toxic areas, control invasive species, and restore habitat. In 2010, the initiative sought something they needed to reach these goals: a map of wetlands across the entire Great Lakes Basin that included both Canadian and U.S. sides.

Although some maps existed, differences in mapping goals and strategies between the two countries and between various interest groups had long prevented efforts to accurately chart wetlands around the entirety of the lakes. For instance, a biologist may study how migrating geese use wetlands while an urban planner might study whether they can build a new

Wetland restoration projects are underway throughout the Great Lakes region. For instance, sawmills lined the shores of Muskegon Lake in the late 1800s. Long after the mills closed, abandoned wood debris contaminated the shoreline and was often visible during low water levels (left). A restoration project dredged the debris out of the area (right) to restore wetland and shore habitats. (Courtesy West Michigan Shoreline Regional Development Commission)

road near that same wetland area. They both collect wetland data, but use different methods, and likely produce results that cannot be easily compared.

Mapping what is wet

Bourgeau-Chavez and her team set out to collect data in the same ways to measure the same criteria. They relied on imagery from two satellites that could identify differences between land and water, as well as different types of vegetation. Surface temperature data from the Landsat satellite helped them distinguish wetlands from uplands, or higher ground. However, Landsat data cannot accurately see wetlands that exist beneath a canopy of shrubs or forest cover. To penetrate vegetation, the researchers added imagery 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).

Because vegetation can change throughout the growing season, the team collected Landsat and ALOS PALSAR imagery spanning spring, summer, and fall from 2007 through 2011. Images from the two data sets were aligned and mosaicked together to form complete coverage around the lakes. This image fusion allowed the researchers to distinguish wetlands from other types of land cover, and even clarify different types of wetlands, peatlands, and aquatic beds.

Distinguishing various wetland types would make the maps more accurate and permit more specific applications, such as identifying aquatic bird habitat or pinpointing invasive plant species.

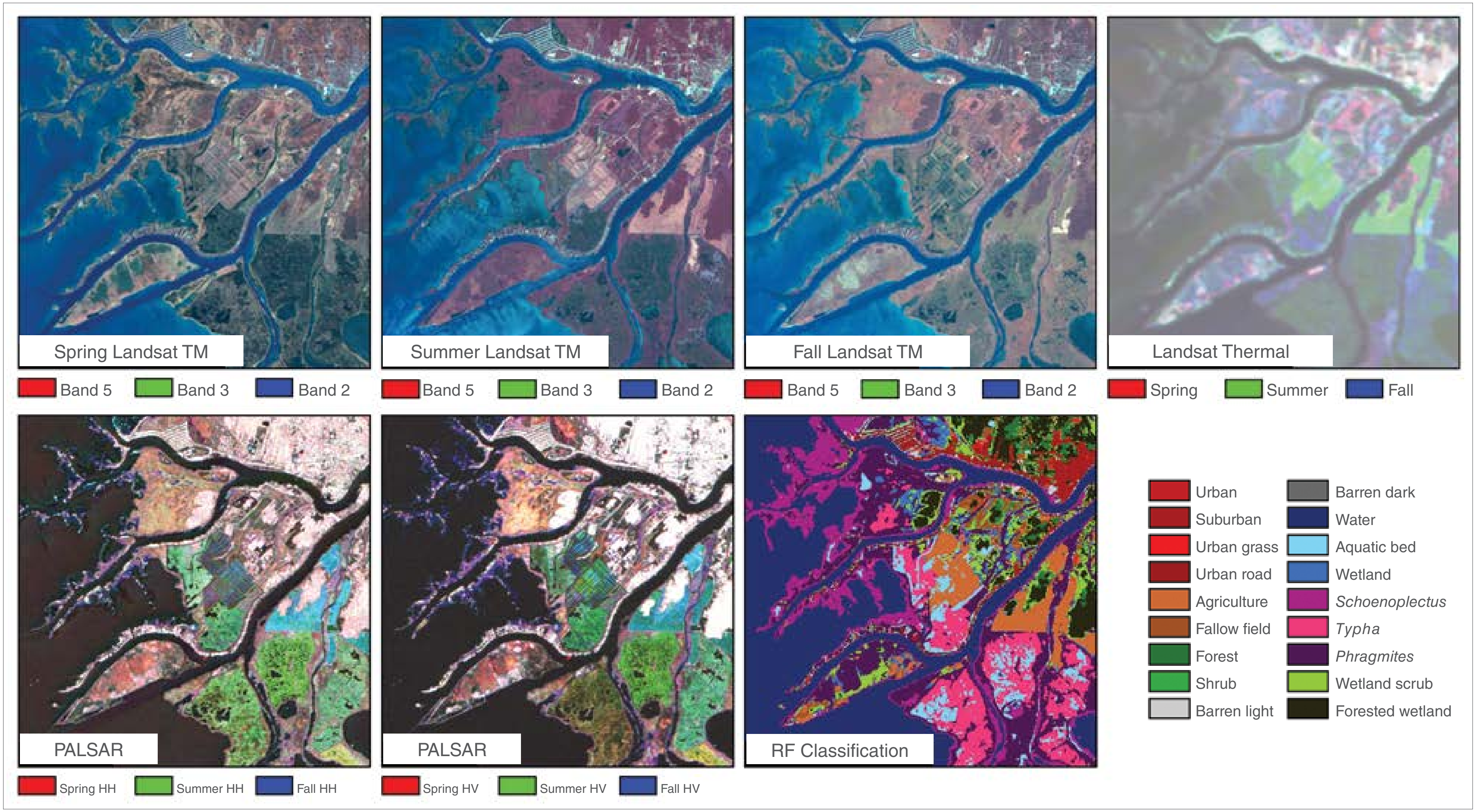
To verify the satellite images, the researchers conducted fieldwork at 1,191 random sites along the Great Lakes coasts. During the summers of 2010 and 2011, teams donned muck boots and waders before sloshing into the wetlands, carrying precise latitude-longitude locations and laminated aerial photos. Geographer Michael Battaglia helped develop the maps, and conducted fieldwork. “We had to navigate to a predetermined point, and once we got there, we would mark where exactly we were within the aerial photo,” Battaglia said. At each site, the teams noted vegetation types as well as growth stage, height, density, and water levels. When necessary, researchers boarded small boats to reach some of the sites. They also took geolocated photographs for further verification.

A subsequent field campaign from 2012 to 2014 brought the total number of sites to 1,751. That total included visits to the Canadian side of the lakes, part of what made this mapping effort successful. At a conference, Bourgeau-Chavez happened to meet a professor from McMaster University in Ontario who not only offered to share her wetland data, but also had a student who could collect field data using the exact same methods. Bourgeau-Chavez said, "We took the student through all the steps of how to create the maps, and field work, and we sent him off with the algorithm and data sets."

Finding the flora

Although the teamwork between two countries was crucial, a similarly important factor was the team's ability to accurately classify various land cover and wetland types. They parsed out twenty-three different types of land cover, including broad classes such as water or forest. The map's more specific classes, such as shrub peatland and forested wetland, illustrate advantages of the team's image fusion approach. Previous Great Lakes wetland maps tended to mischaracterize certain types of vegetation, mistaking heavy forest for swamp or wetland. Battaglia said, "You need those different types of data, which allow us to delineate those types of things more clearly than just using air photo interpretation." The

Phragmites, a species of common reed, can dominate wetlands. (Courtesy E. Banda)



Researchers fused images from two satellites and their sensor bands to map land cover and wetland types during the growth season. Images are from the Landsat Thematic Mapper (TM) and the Phased Array type L-Band Synthetic Aperture Radar (PALSAR) instrument aboard the Advanced Land Observing Satellite (ALOS). HH and HV indicate whether the horizontal or vertical PALSAR microwaves were polarized, respectively. (Courtesy L. Bourgeau-Chavez, et al., 2015, *Remote Sensing*)

team could also distinguish peatlands, which have been difficult to map. Using aerial photos alone, the texture of a peatland may appear more like the texture of a wetland, but the combination of meticulous fieldwork and satellite imagery clarified the distinction.

The maps also classified specific invasive species that have infested many of the wetlands. *Phragmites*, or the common reed, in particular, has been a growing problem along the southern Great Lakes. The thick reeds can grow almost fifteen feet tall. Researcher Sarah Endres often had to bushwhack through stands of *Phragmites*. "Depending on the site, *Phragmites* is so dense it's necessary to break a path just to pass through." *Phragmites* blocks sunlight, forces out native plants, and prevents birds from navigating. Extensive *Phragmites* stands also pose a major problem for people living along the wetlands. Bourgeau-Chavez said, “They’re restricting people’s views of the Great Lakes. Residents can’t get to the water.” Controlling these marauding species is one of the goals of the Great Lakes Restoration Initiative, and with the help of this map, natural resource managers and conservation groups can now locate where invasive species are.

Since the map became available in 2015, conservation agencies and government officials studying the Great Lakes basin have sought it. For instance, the Great Lakes Ecological Forecasting team used the map and field data to create a *Phragmites* risk assessment across the basin, plus a model to forecast the extent of the species by 2020. And the Michigan Department of Transportation requested the map to see exactly where wetlands existed along the state’s coast, so they could avoid building roads into them, and determine where wetlands might impact existing roads. Whether researchers are looking at invasive species or animal habitat, researchers have a consistent set of map data to rely on. “We’re happy we came up with a nice product for people to use,” Bourgeau-Chavez said. The map goes a long way toward protecting what Thoreau called “the wildest and richest gardens that we have.”

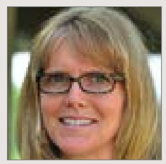
To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/where-the-wetlands-are.

About the remote sensing data

Satellite	Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS)
Sensor	Phased Array type L-Band Synthetic Aperture Radar (PALSAR)
Data set	ALOS PALSAR L1.0
Resolution	Nominal 9 meter ground resolution
Parameter	Terrain
DAAC	NASA Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC)

About the scientists

Michael Battaglia is an assistant research scientist at Michigan Tech Research Institute. He uses geospatial analysis and remote sensing to develop wetland mapping methodologies, conceptual models of environmental phenomena, and K–12 remote sensing education. The U.S. Environmental Protection Agency funded his research. (Photograph courtesy M. Chavez)



Laura Bourgeau-Chavez is a researcher and assistant professor at Michigan Tech Research Institute. She studies landscape ecosystems, focusing on synthetic aperture radar (SAR) and the fusion of SAR and multispectral data for mapping and monitoring wetlands and monitoring soil moisture for fire danger prediction in boreal regions. The U.S. Environmental Protection Agency funded her research. (Photograph courtesy M. Chavez)

Sarah Endres is an assistant research scientist at Michigan Tech Research Institute. She applies geographic information system (GIS) and remote sensing techniques to environmental problems and mapping wetland ecosystems. The U.S. Environmental Protection Agency funded her research. (Photograph courtesy M. Chavez)

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©JAXA/METI ALOS-1 PALSAR L1.0. 2010–2011. Accessed through ASF DAAC, https://www.asf.alaska.edu.

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For more information

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https://www.asf.alaska.edu

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

Feeling hot hot hot

"The lower the socioeconomic status, the more vulnerable the population because they have less access to proper care."

Stephanie Weber
Battelle Memorial Institute

by Agnieszka Gautier

On July 12, 1993, a 61-year-old man with Parkinson's disease was found dead in Philadelphia in his hot, unventilated apartment. A 70-year-old woman was also found dead in her home with no air conditioner, the fan off, and the windows closed. The room was 130 degrees Fahrenheit. Outside it was 96 degrees.

The 1993 Philadelphia heat wave killed 118 people. In the United States, about 620 people die yearly from heat-related causes. Climate scientists predict global temperatures to go up. And cities face the additional challenge of heating up faster and hotter than surrounding non-urban environments. Known as Urban Heat Islands (UHIs), these centers of concrete, high-rises, dark roofs, and car exhaust can add 11 to 14 degrees Fahrenheit to an already hot summer.

Cities like Philadelphia are responding. A group of researchers had an idea: if they could map the most vulnerable sections of a city, where it gets the hottest and where the most sensitive

Children play in the fountains at Dilworth Park in Philadelphia. (Courtesy A. Lewis) populations reside, then outreach and adaptation measures could focus on those neighborhoods. "Those efforts might have the highest bang for the buck," said Natasha Sadoff, a geographer and social scientist at the Battelle Memorial Institute in Ohio.

Planning for cool

The researchers started in the city of brotherly love. "Philadelphia is already very active in climate change adaptation," Sadoff said. After 1993, it became the first city in the country to begin a heat-health watch program. Social services ranged from opening cooling centers, handing out water bottles to the homeless, going door to door to check on people, and switching on the power to late electricity payers. But city adaptation measures take years.

Besides higher downtown temperatures and less nighttime cooling, the UHI extends its warmth beyond the city. Rainwater heats up on dark rooftops, rolls off hot pavement, enters storm drains, and pours several degrees hotter into nearby waterways, causing certain fish populations to plummet. So Philadelphia implemented greening efforts, ripping up unneeded pavements, planting rain gardens to collect stormwater and increasing green roofs, where living vegetation covers the tops of buildings to cool the city and mitigate runoff.

City officials were keen to know how their city adaptations were paying off. How could organizations effectively target their outreach programs? Could small changes on the block level affect a neighborhood's temperature?

Those answers were exactly what Stephanie Weber, the lead scientist on the study, was hoping to find. The study set up an advisory committee consisting of about a dozen people from researchers, city officials, and utility representatives. She said, "We want to show people that data can be incorporated into simple policies for decision makers to use."

But first, Weber needed to know how hot Philadelphia got. She took temperature data from ground-based thermometers, but since they are sparse, she added data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the NASA Aqua satellite, offered through the NASA Land Processes Distributed Active Archive Center. Weber was able to get daily temperatures on a neighborhood scale, between 500 meters and 1 kilometer (0.3 to 0.6 mile) resolution, going back more than ten years.

"Now we had a quantity," Sadoff said. Between 1980 and 2013, the number of heat wave days in urban Philadelphia increased from four to twelve days, while non-urban areas consistently experienced five days per year across the same time period. In addition, they found nighttime temperatures are not dropping like they used to, so people have less respite from heat. Sadoff said, "Having this information allows city officials and organizations to better understand the problem and to seek out funding to address it." Still, which sections of town felt the heat the most? Who was at a higher risk?

Boiling over

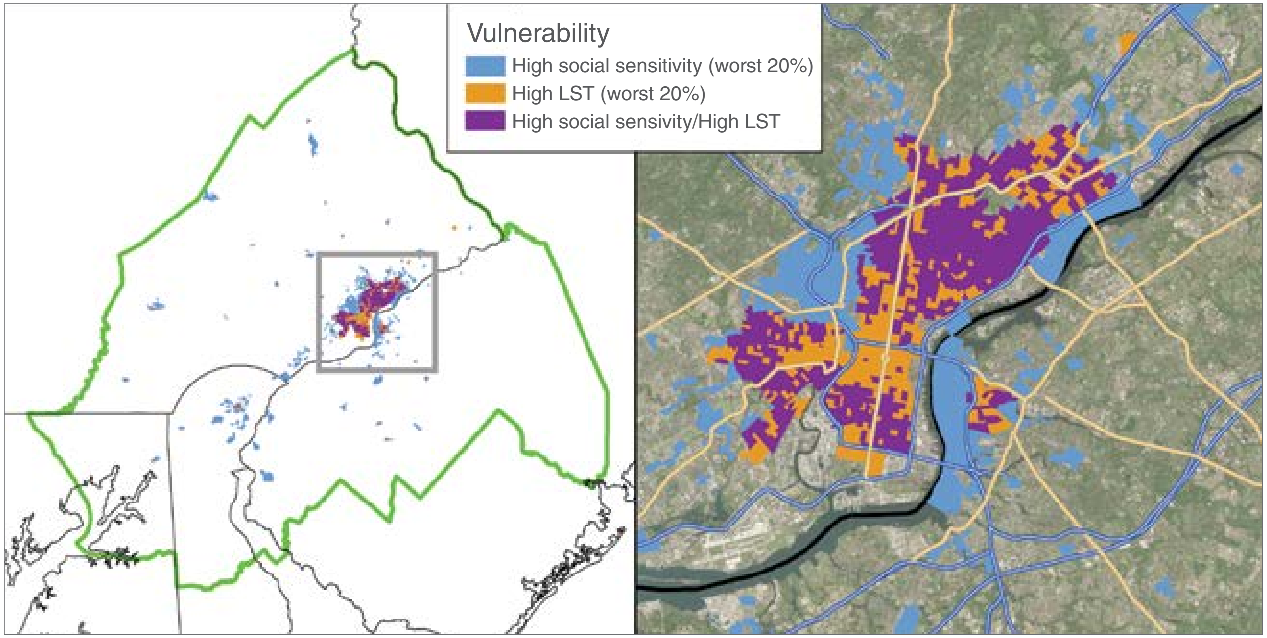
To identify the most sensitive populations, the researchers chose four criteria: the percentage of people living below the poverty line, households with individuals age sixty-five or older living alone, low high school graduation rates, and homes built before 1960. Those buildings

This residential building in Vancouver, Canada is covered in green decks to help mitigate the urban heat island effect. (Courtesy NNECAPA)

typically lack energy efficiency and cooling systems. "The lower the socioeconomic status, the more vulnerable the population because they have less access to proper care. So risk of dehydration and overheating increases," Weber said.

Residents in poorer neighborhoods also suffer the ripple effect of poverty. "With the added risk of living in a high-crime area, people might not open their windows at night to cool off a house," Weber said. They have fewer trees, so less shade and less evapotranspiration—nature's form of air conditioning. "They may also have less access to clean water," Weber said, "and with no filtration system, they may not feel comfortable drinking the tap water."

Hydration boosts sweating. And without sweat, the body cannot cool. Once the body reaches an internal temperature of 104 degrees Fahrenheit,



These maps show where people who are the most vulnerable to extreme heat live in Philadelphia. Researchers used high social sensitivity and high Land Surface Temperature (LST) data to identify the areas. LST data are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS). (Courtesy Battelle Memorial Institute)

heat stroke may occur, even death. In humid climates, sweating becomes ineffective because moisture in the air slows evaporation. The elderly, who make up 40 percent of heat-related deaths in the United States, are less efficient at regulating their temperature. Children up to four years old, people with weak hearts, and those on certain medications are also particularly vulnerable because their bodies have a harder time handling the heat.

Once Weber and her team identified the most sensitive neighborhoods, they overlaid the MODIS map for heat exposure and found that 10 percent of Philadelphia's population lived in the most vulnerable areas. "That's a pretty high number and that's only using four of the social sensitivity measures we chose," Sadoff said.

The number could go up or down depending on selected criteria, but 10 percent of a 1.56 million population is a significant amount: 156,000 people. "It's meaningful to have a map that shows pretty clearly in red that this entire neighborhood or portion of the city is vulnerable," she said.

Cooling the body is the best recovery. Weber said, "The neighborhoods we identified, the city already knew as vulnerable. But being able to identify the most vulnerable within that socioeconomic group was helpful from a policy and programming standpoint." Targeting those populations equates to lives saved. Neighbors helping neighbors and outreach programs—cooling centers, handing out water, and heat exposure education—are the best bet.

On the flip side

To help city officials determine whether their greening efforts have made an impact on temperature, the researchers also looked at MODIS Normalized Difference Vegetation Index (NDVI) data, which measures the degree of green, or vegetation, in an environment. Would the increase in NDVI from greening efforts lead to decreases in Land Surface Temperature (LST)? They found it is still too early to tell because it takes years for trees to grow to maturity. In addition, with a 1 kilometer (0.6 mile) resolution, LST satellite imagery is best suited for neighborhood-level, rather than block-by-block readings. But the team did find a correlation between NDVI and LST, if only in the reverse.

A certain pixel on the map showed an increase in LST and a very large decrease in NDVI. "So I went to Google maps," Weber said, "and a very large building popped up." Looking at imagery from past years revealed the construction of a warehouse. Once the building was constructed, LST went up and NDVI went down. "It's a reverse example of what we were hoping to see. We want to see positive effects," Weber said. Still it is a good demonstration of how small changes can have large temperature implications.

Ultimately, the research team wants to repeat the LST analysis for other cities and turn their analyses into an online tool, so worldwide policy makers could select criteria and see the vulnerability of certain neighborhoods or populations. Urban heating is a global issue. In Europe, there is little to no air conditioning. Recent summers have been some of the warmest since Roman times. In 2003, three months of relentless heat killed 70,000 Europeans, with France being hit the hardest. Afterward, France implemented a

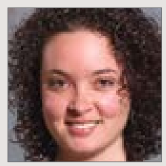
About the remote sensing data

Satellites	Aqua	Aqua	Terra and Aqua
Sensor	Moderate Resolution Imaging Spectroradiometer (MODIS)	MODIS	MODIS
Data sets	Land Surface Temperature and Emissivity 8-Day L3 Global 1km (MYD11A2)	Vegetation Indices 16-Day L3 Global 1km (MYD13A2)	Land Cover Type Yearly L3 Global 500m SIN Grid (MCD12Q1)
Spatial resolution	1 kilometer	1 kilometer	500 meter
Temporal resolution	8 days	16 days	
Parameters	Land surface temperature and emissivity	Vegetation indices	Land cover type
DAAC	NASA Land Processes Distributed Active Archive Center (LP DAAC)	NASA LP DAAC	NASA LP DAAC

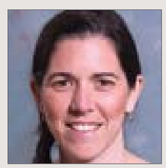
heat wave plan, with one simple strategy of calling at-risk people. Incorporating policy-changing data into practical tools may be the first step in helping cities around the world cool off.

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

About the scientists



Natasha Sadoff is a research scientist at Battelle Memorial Institute in Columbus, Ohio. Her research focuses on the use of data, including Earth observations, to better understand, visualize, and communicate the impacts of climate and environmental change on populations and human health. NASA supported her research. (Photograph courtesy Battelle Memorial Institute)



Stephanie Weber is a principal research scientist in Health and Consumer Science at Battelle Memorial Institute in Columbus, Ohio. Her research focuses on processing and analyzing remote sensing products for a variety of public health applications. NASA supported her research. (Photograph courtesy Battelle Memorial Institute)

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http://modis.gsfc.nasa.gov

In the Arctic darkness

"Everything is freezing. It's cold and it's dark, so people assume not much is going on in the tundra."

Donatella Zona
San Diego State University

by Natasha Vizcarra

Out on the tundra, ecologist Donatella Zona and her colleagues often think of home. "But we can't go home," she said. "We need to make measurements year round." Summer on Alaska's North Slope is quite pleasant. In the winter though, the scientists hunker down at their research site, where average temperatures drop to -18 degrees Fahrenheit.

Most of the time, they futz with wires, calibrate instruments, and check sensor deicers—all to detect faint wisps of methane seeping from the freezing soil. While many researchers study summer methane released by Arctic wetlands

Frost clings to an eddy covariance tower in Barrow, Alaska. The sensors measure methane emissions year round and are equipped with deicers to prevent them from malfunctioning in the Arctic's frigid temperatures. The tower also measures other meteorological variables, including air temperature, humidity, soil temperature, and soil moisture. (Courtesy S. Losacco) to predict future greenhouse gas emissions, Zona and her colleagues suspected cold season emissions are equally important to Earth's changing climate, if not more.

Wet and dry

Methane is an extremely potent greenhouse gas. Over 100 years, each molecule of methane impacts Earth's climate 28 times more than each molecule of carbon dioxide. Human-related sources like livestock farming and fossil fuel production account for 64 percent of Earth's methane emissions. The rest comes from natural sources, mostly from wetlands and in smaller amounts from termites, oceans, and volcanoes.

In the Arctic, methane bubbles up out of lakes, ponds, and swamps. Microbes at the bottom of these environments scarf down decayed matter that have sunk from the surface. In the process, these microbes use up oxygen. Methane-producing microbes love oxygen-poor environments and take over these bodies of water.

Scientists think wetlands are the most dominant oxygen-poor environments in the Arctic and therefore the largest methane sources. So they map these wetlands and use them as a proxy for tallying the Arctic's year-round methane budget. These maps are often based on measurements made in the summer, when wetlands in the Arctic have thawed out.

Zona thinks this reflects a prevailing belief in the scientific community that cold season emissions are not significant. "Everything is freezing. It's cold and it's dark, so people assume not much is going on in the tundra," Zona said. "And there were no data saying otherwise."

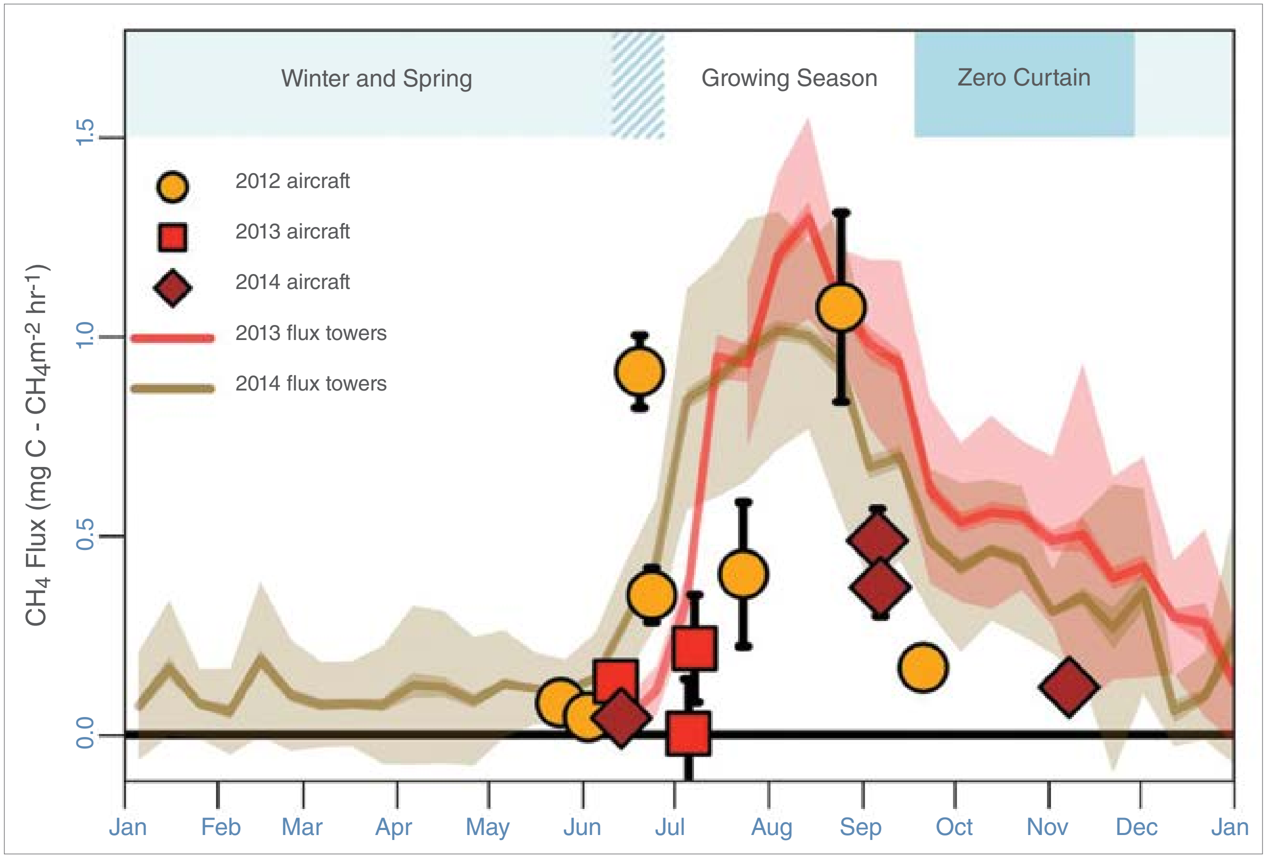
Field assistant Rosie McEwing checks readings from a methane analyzer at Barrow Environmental Observatory in the summer of 2013. (Courtesy P. Murphy)

What little data existed on cold season methane emissions were sparse. That meant that Zona and her colleagues had to collect their own data. "We wanted continuous measurements of methane year round," she said. "And that's not easy because instruments tend to freeze and malfunction in extreme cold."

High and low

From June 2013 to January 2015, the scientists took turns spending months at the Barrow Environmental Observatory, a cluster of labs at Alaska's northernmost point and about 1,300 miles south of the North Pole. The observatory lies a few miles from Barrow (population 4,300), which is accessible only by plane. In the evenings, the scientists bunked in sparsely furnished Quonset huts. In the daytime, they watched over five instrument towers equipped with methane-sniffing sensors. Sometimes they had to traverse boardwalks built over the tundra to check on instruments; other times they took planes to get to the towers which are spread out along a 186-mile transect line.

In the summers, the researchers swatted mosquitos and trudged on tundra as mushy as porridge. Summer also brought that singular tundra smell, faintly reminiscent of lavender flowers. In the autumn, winter, and spring, what the researchers consider the cold season, they gingerly walked on tundra alternately soft, crusty, or frozen stiff. The tundra's top layer, called the active layer, thaws in the summer and freezes in winter,



This graph shows high methane emissions from Arctic tundra, even after summer or the growing season. Data are from five eddy covariance flux towers over a 186-mile transect across the North Slope of Alaska (shaded bands). The red line indicates the 2013 mean and the brown line indicates the 2014 mean. Light red and brown shades indicate the standard deviation and the darker shade the 95 percent confidence intervals. Yellow circles show the regional emissions of methane calculated from the NASA Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) aircraft data for the North Slope of Alaska for 2012, red squares for 2013, and brown diamonds for 2014. The mean dates for the onset of winter, the growing season, and the zero curtain period are indicated in the band on top. (Courtesy D. Zona, et al., 2016, *PNAS*)

unlike the permafrost underneath that stays frozen all year.

While Zona's team only saw flat or hilly landscapes with squat vegetation, their colleagues in the NASA Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) viewed the tundra's unique features from the sky. On a C-23 Sherpa aircraft, the CARVE researchers gazed at a landscape pockmarked by elongated thaw lakes and polygon shapes patterned by wedges of ice, typical of land underlain by permafrost.

As the tundra cycled twice through summer, fall, winter, and spring, the aircraft flew over the transect fifteen times, measuring methane with a payload of sensors similar to those that Zona's team tended to on the ground. Was there methane out on the freezing tundra? Could methane-producing microbes even survive the frigid Arctic winter?

After collecting data for two years, instruments on the ground and in the air agreed: methane emissions during the cold season accounted for more than 50 percent of the total annual methane emissions. This contradicts what computer models assume, that the Arctic's largest methane emissions come from wetlands, and only happen in the summer.

The findings could call for big changes in the way scientists collect data on methane emissions. "We need to consider the cold period to arrive at an accurate budget of Arctic methane emissions during the entire year," Zona said. Indeed, methane rises from the tundra in the winter, and the researchers traced it to unexpected stirrings within the active layer.

Activity in the active layer

Zona first saw the first hints in the tower and aircraft data. Most of the cold season methane emissions happened during what scientists call the zero curtain period, when soil temperatures in the active layer lingered near freezing. This happens when the active layer's middle section remains thawed, favoring the activity of methane-producing microbes. Cold, winter air may freeze the active layer's surface. Permafrost may cool the bottom. However, the middle could remain thawed well into the winter. To test this idea, Zona and her colleagues drove metal rods through the frozen tundra surfaces. The rods pierced the active layer without resistance, but stopped at the layer of hard permafrost.

Curiously, soil temperature remains stable during the zero curtain period, keeping methane-producing microbes active. In some sites, the researchers found that the zero curtain period stretched longer than summer, implying an extended period of methane emissions. "We were surprised to see how long it takes for the soil to freeze completely, and how the persistence of this unfrozen soil maintained substantial methane emissions well into the winter," Zona said.

In some instances, thick snow cover insulated the active layer, extending the zero curtain period and enhancing emissions. The finding has huge implications for the Arctic's methane budget. Recent studies forecast that continued warming will bring deeper snow to the Arctic, and already, regions north of the Arctic Circle are warming twice as fast as the rest of the Northern Hemisphere.

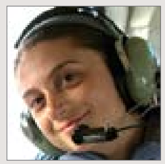
Zona's findings also suggest that Arctic methane emissions could be more sensitive to climate change than scientists previously thought, as winter is warming faster than summer, potentially delaying the freezing of the tundra. The Intergovernmental Panel on Climate Change projections do not even include greenhouse gas emissions from summer wetlands and from thawing Arctic permafrost. And Zona's findings highlight the relevance of Arctic methane emissions. More years of data on cold season emissions would solidify these findings.

Back at Barrow, the researchers prepare for another season on the Alaskan tundra. The two years of observations have led to other questions and a stronger conviction that cold season emissions matter.

About the data

Platforms	Eddy covariance towers, NASA Sherpa C-23 aircraft
Sensors	Gas analyzers
Data set	CARVE-ARCSS: Methane Loss From Arctic-Fluxes From the Alaskan North Slope, 2012–2014
Spatial resolution	Point location
Parameter	Methane flux
DAAC	NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC)

About the scientist



Donatella Zona is an associate professor at San Diego State University and a research fellow at the University of Sheffield in the United Kingdom. Her research interests include the impact of climate change on biodiversity, ecosystem functioning, and greenhouse gas emissions in the Arctic. NASA, the National Science Foundation and the U.S. Department of Energy supported her research. Read more at https://goo.gl/THa81t. (Photograph courtesy D. Zona)

"The next step for us is to understand what's going on during this cold period," Zona said. "What controls the emissions? How does it change from year to year? How does it relate to the Arctic's short growing season?"

Zona's students are observing Arctic plants that seem to act like chimneys, drawing methane from the not quite frozen active layer and ushering the gas out into the atmosphere. It means more missed holidays and racing to get work done between long and dark polar nights. It also means the shimmery treat of seeing the occasional aurora borealis. "There are so many open questions," Zona said, not without a hint of excitement.

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

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For more information

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https://daac.ornl.gov

NASA Carbon in Arctic Reservoirs Vulnerability Experiment
http://science.nasa.gov/missions/carve

The case of the missing waves

"It's like a movie, 'Come see gravity waves. Now in 3D.'"

Neil Hindley
University of Bath

by Karla LeFevre

Decked out in a white spacesuit, Alan Eustace, a space diver and former Google executive, jumped from a perfectly good balloon in 2014, setting a record free fall speed of 1,321 kilometers per hour (821 miles per hour). The balloon had carried him more than 25 miles above Earth into the stratosphere, where commercial jets fly and the air is too thin to breathe.

Yet amazing things happen in the stratosphere every day—things we cannot see, like massive, invisible waves. These atmospheric phenomena, called gravity waves, have piqued the interest of Corwin Wright, a researcher at the University

This photograph shows a large lenticular cloud hovering over part of Torres del Paine National Park, in Chile's Patagonia region. Also called UFO clouds or cap clouds, lenticular clouds make it possible to get a rare glimpse at the crests of gravity waves. When air rushes over mountains and the conditions are right, with cold air and water vapor condensing into droplets, lenticular clouds form at the crest of the waves. (Courtesy klausbalzano/Flickr) of Bath. Like ocean waves, gravity waves can travel for thousands of miles, building tremendous momentum and power along the way. Wright wanted to better understand them and their behavior to improve the models that predict weather and climate. But those models have not been able to fully see them, until now.

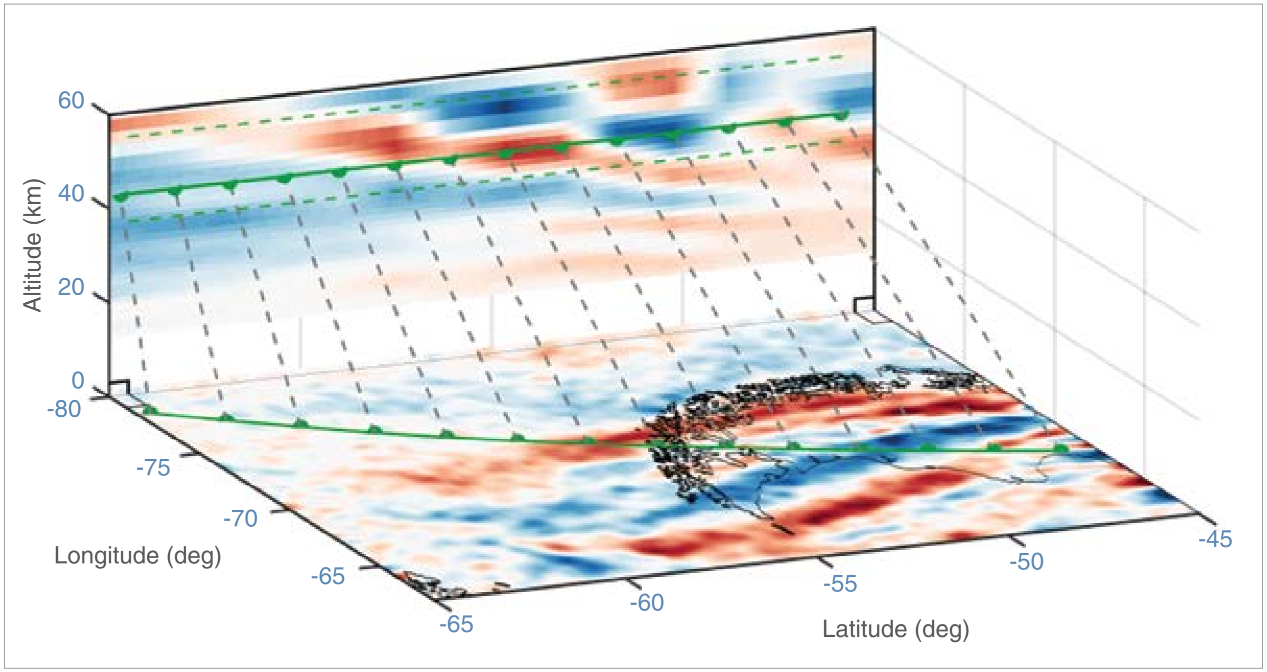
Serious air waves

Neil Hindley, Wright's colleague, said, "If we could see them, we'd see the atmosphere as a large undulating mass of all kinds of waves going in all sorts of different directions, mostly from the bottom up." Like the surface of the ocean, the atmosphere is never still, driving weather and climate.

But unlike the ocean, the atmosphere has no lid, so gravity waves tend to propagate up and up. When they finally break, as ocean waves breaking on a shore, these waves of air crash and release their energy into the upper atmosphere. That can force winds to blow in different directions and amp up circulation in the atmosphere.

Hindley went on to describe the reasoning behind their name. Not to be confused with gravitational waves, which are phenomena that occur in space, gravity waves are of this world. "If I imagine myself as a pebble in a stream, the water has to flow up and over me and then down the other side," he said. "When the water goes over the other side, it falls back down under gravity." On the surface, water moves up and down, oscillating under gravity and creating a lasting rippling effect. This happens in the atmosphere, too, but instead of water flowing over a pebble, air flows over mountains.

Most notably, strong westerly winds flow over the mountains of the southern Andes and the



This figure shows combined temperature measurements from the Atmospheric Infrared Sounder (AIRS) and Microwave Limb Sounder (MLS) instruments for May 6, 2008. Gravity waves reveal themselves in the cooler temperatures (dark blue) and their forms correspond with both sets of data; dark blue indicates temperatures at -20 degrees Kelvin and dark red at 20 degrees Kelvin. White indicates a temperature of 0 degrees Kelvin. MLS readings are shown on the vertical plane (top) and AIRS on the horizontal plane (bottom). Green semicircles show identical points in both planes, with MLS atmospheric measurement locations at an altitude of 42 kilometers (26 miles). The data have been interpolated (a process of taking two known measurements and estimating the value between them) and scaled for visual clarity. (Courtesy C. Wright, et al., 2016, *Geophysical Research Letters*)

Antarctic Peninsula, and are ideal conditions for generating gravity waves. Violent thunderstorms over the Southern Ocean or fluctuations in the jet stream can also create them. Wright said, "There's a massive peak of gravity waves over the Andes that is often ten times bigger than the rest of the world."

Nick Mitchell, also at the University of Bath, said, "Say you have a thunderstorm over the horizon. Ocean waves will flow away from the thunderstorm and break on the beach thousands and thousands of miles away from where the storm was. These do the same thing. They take energy and momentum from the lower atmosphere to the edge of space and, in so doing, influence the circulation of the atmosphere."

Cloak of invisibility

If those waves are not accounted for in a model, it can skew a prediction. "They're a pain," Hindley said. "We don't really know where they are or what they're doing."

Knowing more about the waves would have practical implications, too. "It might not tell us

This photograph shows the Space Shuttle Endeavour as it appears to travel between two different layers of the atmosphere: the mesosphere (blue section) and the stratosphere (ivory middle section). The orange band is the troposphere, the layer of the atmosphere where our planet's clouds and weather occur. The photograph was taken from the International Space Station as the Endeavour orbits approximately 321 kilometers (200 miles) above the Earth, far higher than the boundary between the mesosphere and troposphere, at approximately 50 to 60 kilometers (31 to 37 miles). (Courtesy NASA)

whether it will rain at your auntie's barbeque tomorrow," he said, "but it is essential if you want to predict record hot summers or freezing cold winters in the coming months and years." And for climate change predictions ten to twenty years down the line, these stratospheric waves can have a big impact.

Though usually invisible to the naked eye, it is possible to see small sections of gravity waves. When conditions are just right, with the right mix of cold air and water vapor, lenticular clouds can form at the crest of the waves as they rush over mountains. These clouds are often called "cap clouds" or "UFO clouds" because they appear to cap or hover over mountain peaks.

Gravity waves are a real challenge because they are largely invisible to climate and weather models. The crux of the problem is the way satellites see them. Satellite instruments sweep the atmosphere in either a vertical or horizontal plane, so their measurements are either one- or two-dimensional. That is helpful, but does not reveal critical clues, such as the direction the waves are moving, or how fast.

As a result, satellites only capture one side of a wave. This is like trying to measure a sheet of paper by looking at its edge. For a few measurements, this simply gives a one- or two-dimensional glimpse of the waves. For the millions of measurements needed in a model, that limited view skips many waves altogether. Mitchell said, "We are missing waves and we know it's because the models aren't representing gravity waves properly." Models of winter over the Antarctic and Southern Ocean, for instance, show far fewer waves than they think must be present in the real atmosphere.

The researchers were stumped. Satellites offer a much-needed global view, but how could they harness them to fully capture gravity waves?

Cracking the case

Then Wright thought: Why not combine the vertical and horizontal data? For that to work, he would need to find a pair of satellite instruments orbiting one another closely so their measurements would line up. Without this, there would be more errors than meaningful data.

He found such a pair in the Microwave Limb Sounder (MLS) and the Atmospheric Infrared Sounder (AIRS). These instruments are mounted on satellites in the A-Train, a series of NASA satellites that follow each other in the same orbit and, in this case, just over a minute apart. With MLS looking vertically and AIRS horizontally, the two instruments thoroughly scan the atmosphere for variations in temperature. The team combed through the new data, tweaking their process along the way. They knew they were onto something.

"It's like a movie," Hindley said. "'Come see gravity waves. Now in 3D.'" By combining the data, they found the more complete view of the waves that had been lacking. And with that, they can more accurately estimate the speed and force of gravity waves. That information is key. It allows them to track the direction the waves are traveling, which in turn helps them determine if gravity waves are forcing winds to speed up or slow down, and where.

"We can now use that information to piece together the story of the waves," Wright said. That means that, for the first time, they will also be able to work out the overall effect that gravity waves have on the atmosphere, which will help improve the task of predicting weather and climate. Their only worry now is that the data will run dry. Mitchell said, "I lie awake worrying about the satellites failing. Many of them are quite old." If that were to happen, perhaps Mitchell and his colleagues would need to consider donning spacesuits and collecting the data themselves.

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/the-case-of-the-missing-waves.

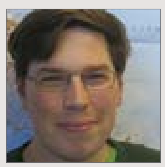
About the remote sensing data

Satellites	Aqua	Aura
Sensors	Atmospheric Infrared Sounder (AIRS)	Microwave Limb Sounder (MLS)
Data sets	AIRS/Aqua L1B Infrared (IR) Geolocated and Calibrated Radiances V005 (AIRIBRAD.005)	MLS/Aura Level 2 Temperature (ML2T.003)
Resolutions	13.5 kilometer	1.5 to 6 kilometer
Parameters	Brightness temperatures	Brightness temperatures
DAACs	NASA Goddard Earth Sciences Distributed Active Archive Center (GES DAAC)	NASA GES DAAC

About the scientists

Neil Hindley is a postdoctoral scientist at the University of Bath. His research interests include satellite occultation and stratospheric dynamics. The University of Bath supported his research. (Photograph courtesy N. Hindley)

Nicholas Mitchell is a professor at the University of Bath. His research addresses the role that gravity waves, tides, and planetary waves play in the dynamics of Earth's atmosphere. The University of Bath supported his research. Read more at https://goo.gl/GkMBZH. (Photograph courtesy N. Mitchell)



Corwin Wright is a postdoctoral scientist at the University of Bath. His research addresses the role that gravity waves, tides, and planetary waves play in the dynamics of Earth's atmosphere. The University of Bath supported his research. Read more at https://goo.gl/Y69UnV. (Photograph courtesy C. Wright)

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http://daac.gsfc.nasa.gov

Soiled soils

“If we had stuck with the census data, we might have represented the wrong trend.”

Son V. Nghiem
NASA Jet Propulsion Laboratory

by Natasha Vizcarra

In Milan, 135 spires and pinnacles of the medieval Duomo di Milano pierce the sky. So do numerous skyscrapers that have sprouted around the cathedral in the last fifty years. Wealth from this financial and industrial powerhouse has expanded the city upwards and outwards, sprouting satellite towns in the surrounding Po Valley in northern Italy.

But where there are buildings, there are people. And where there are people, there is sewage. Waste from Milan’s 1.3 million population is shunted beneath cobblestone streets, through underground pipes, and into treatment plants. The pipes can leak and contaminate aquifers—underground layers of rock or soil that hold groundwater and supply drinking water to millions of people.

Marco Masetti, a professor of geology at the University of Milan, has been studying Italy’s groundwater quality over the last twenty years. “Groundwater supplies as much as 60 percent of Po Valley’s drinking water,” Masetti said. “And our groundwater quality has been bad.”

The UniCredit Tower in downtown Milan towers at 758 feet and is Italy’s tallest building. (Courtesy S. V. Nghiem)

Masetti and his colleagues are trying to find where the contaminants come from. Do these come from burgeoning cities like Milan? Or do these come from the Po Valley countryside, where manure and fertilizer can seep into groundwater?

"Past studies suggest nitrate presence in groundwater is strongly related to urban sources," said Stefania Stevenazzi, Masetti's student and the lead researcher on the study. "We want to confirm that, but we also want to know what the trend is," she said. "How have nitrate concentrations in Po Valley's groundwater increased or decreased over time?"

Permeating the Po Valley

Nitrate is a chemical compound found in decomposing organic material like manure, plants, and human feces. Natural nitrate levels in aquifers are generally low, but human activities cause them to rise. Farmers could raise levels, for example, when they cultivate in areas where the soil layer is thin or when they over fertilize their crops. City dwellers also raise nitrate levels just by living and working where they are. So nitrate groundwater pollution can happen anywhere in Po Valley, a 18,000-square mile stretch of land in northern Italy that is home to a third of the country's population and is among the most heavily cultivated lands in Europe. But how to track something you cannot even see?

First, Stevenazzi and her colleagues needed to know what kind of rock and soil layers the nitrate would be moving through underneath Po Valley. They looked at core data from well drillings along extensive transects from a few miles north of Milan to just south of the Po River. With these, they reconstructed the valley's geological layers, which revealed how quickly or slowly nitrate could soak down into aquifers. It also told them where the aquifers were shallow or deep, and protected or unprotected. The researchers used the data to find out where nitrate contamination likely happens and where future contamination could occur.

Next, they had to find how much nitrate was already present in different parts of the valley. The researchers found nitrate concentration data from the region's environmental agency, which samples water from 221 wells uniformly distributed in the shallow aquifer of the study area. The well water, sampled every six months from 2001 to 2011, showed an increasing trend in nitrate groundwater contamination in the northern half of the valley, where the sprawling city of Milan is located, and a decreasing trend in the southern half, which was more rural.

Although they now had an idea where nitrate was showing up and evidence that concentrations were increasing, they still could not truly point to a source. They needed to find a connection between the changes in the nitrate concentrations underground and changes happening aboveground. "It's not possible to identify exactly where the nitrate source is located because it's underground and invisible," Stevenazzi said. "So we considered population density as a proxy for the urban nitrate sources."

The researchers looked into using population data from the Italian government. However, the national census is taken only every ten years, which was not enough data for the study. Next, they looked into using high-resolution aerial photographs of Po Valley. It was more frequent than the census data, but had its own problems.

Clean drinking water flows out of a fountain at Sforza Castle in Milan, Italy. (Courtesy E. Blaser)

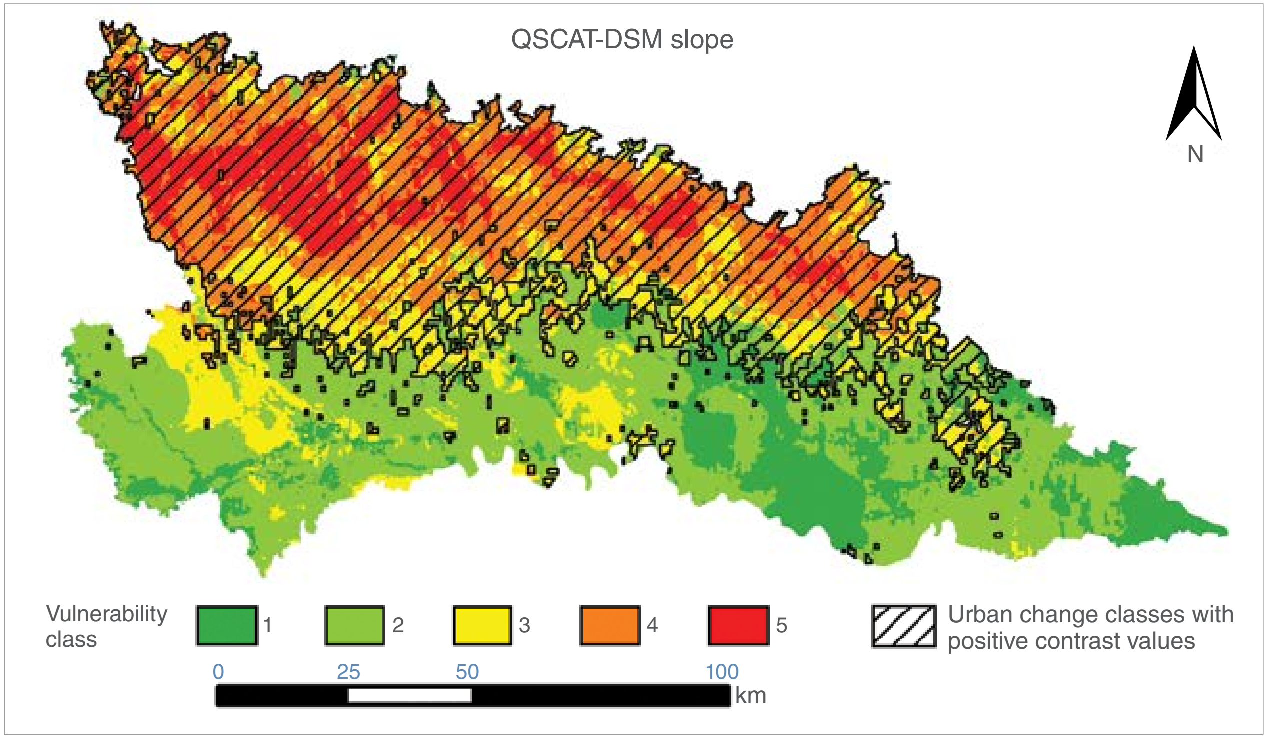
"The number of years between the surveys were inconsistent and some areas were excluded from the surveys," Stevenazzi said. "We needed data that had continuous coverage both in time and in space."

Scanning for skyscrapers

For this, they turned to NASA scientist Son V. Nghiem. Nghiem had developed a novel method to use data from the SeaWinds scatterometer, flying on the NASA QuikSCAT satellite, as a proxy for changes in urban landscapes.

Scientists mostly use SeaWinds to measure ocean wind speed and direction. The sensor transmits microwave pulses to Earth's surface, then measures the power reflected back to the instrument. This backscattered power indicates the ocean surface's roughness, which in turn relates to near-surface wind speed and direction.

Nghiem's QuikSCAT-Dense Sampling Method (DSM) would allow Masetti and Stevenazzi to



This map shows groundwater vulnerability to nitrate contamination in Italy's Po Valley region using QuikSCAT Dense Sampling Method (DSM) data. Colored areas signify vulnerability classes. Green shades represent very low vulnerability; light green is low; yellow is medium; orange is high; and red is very high. The hatched areas show places that have experienced urban changes of more than 6 percent per decade. (Courtesy S. Stevenazzi, et al., 2015, *Hydrogeology Journal*)

train SeaWinds on land instead. The method detects various urban changes—skyscrapers sprouting, suburbs expanding, factories being torn down and malls built in their stead—even in areas where urban growth occurred at a relatively low rate.

Nghiem compares the SeaWinds sensor to radar instruments on aircraft. "When there is one aircraft near you, you see a dot on the radar. For a bigger aircraft, you see a bigger dot, and more dots for more aircraft," Nghiem said. QuikSCAT sees buildings the same way as it flies over them. "Over one building, it sees one signature, but when it flies over a bigger, taller building, it would see a bigger signature," Nghiem said. "And when you have a hundred of these bigger, taller buildings, then the backscatter of the signature becomes stronger."

Population paradox

When Masetti and Stevenazzi applied DSM to SeaWinds data over Po Valley for the years 2000 to 2009, the results showed that most of the urban changes clustered around the north and northwest where cities and industries are concentrated. They found few changes in the southern area, which consisted mostly of agricultural fields. When they compared the DSM data to the well data they had earlier acquired, they saw a clear, direct relationship between urban changes and nitrate contamination trends.

The researchers went a step further and used the DSM data and the geological data they had collected earlier to generate a groundwater vulnerability map. The map shows areas in the Po Valley that are vulnerable to groundwater nitrate contamination. The degree of vulnerability depends on natural factors like groundwater depth and groundwater velocity, and man-made factors like the growth of urban areas. Urban areas that grow quickly, for example, are vulnerable. Regions that have deep groundwater are also vulnerable, because nitrate tends to not degrade when it flows through sediments above a deep water table.

To Nghiem, the map challenges the use of population data to represent urbanization. "The old idea is that population is where you register your home and where you sleep," Nghiem said. Indeed, census data showed that growing cities experience decreasing population density, while the surrounding small towns experience increasing population density. "People may work in Milan but they live in the outskirts where homes are less expensive and there is less pollution," Nghiem said. However, the well data and DSM data showed that nitrate contamination increases in areas of rapid urban development. That would be in the Milan urban center, and not in the suburbs where people live. "If we had stuck with the census data, we might have represented the wrong trend," Nghiem said.

A vulnerable valley

Regional officials have been communicating with Masetti's team and have been anticipating such a map. It could guide land use planners when deciding whether or not to transform rural land to industrial or commercial land. For example, if the map marks an area as extremely vulnerable, then the cost to the community's groundwater quality might outweigh projected economic benefits. It can also tell water resource managers which aquifers need more or less protection.

"If you force people to clean the water where water is already clean, you waste your money, while an insufficient restriction may not work where the groundwater contamination is severe," Nghiem said. "Because of the map, a more effective policy can be implemented."

What the team accomplished extends beyond Po Valley. The map will help Italy comply with a European Union directive that requires member countries to identify areas where groundwater is showing increasing trends of contamination. Other countries can benefit as well. Masetti said, "With DSM, existing and future satellite scatterometer data can be used to make and update maps of groundwater vulnerability as urbanization accelerates across the world."

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

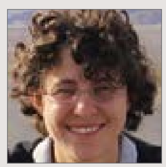
About the remote sensing data

Satellite	QuikSCAT
Sensor	SeaWinds scatterometer
Data set	SeaWinds on QuikSCAT Level 2A Surface Flagged Sigma0 and Attenuations in 25Km Swath Grid Version 2
Resolution	25 kilometer
Parameter	Radar backscatter
DAAC	NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)

About the scientists

Marco Masetti is an associate professor in engineering geology at the University of Milan. His research uses spatial statistical methods to evaluate the time and space dependent vulnerability of aquifers to non-point sources of contamination and the characterization and monitoring of groundwater flow and transport in unsaturated soils. The Italian Ministry of Education, Universities and Research, and regional environmental agencies supported his research. (Photograph courtesy M. Masetti)

Son V. Nghiem is a senior research scientist at the NASA Jet Propulsion Laboratory. His research focuses on active and passive remote sensing, and its scientific research and applications in land, ice/snow, water, ocean, and atmosphere processes. NASA supported his research. Read more at https://goo.gl/LYF5d8. (Photograph courtesy NASA)



Stefania Stevenazzi is a postdoctoral researcher at the University of Milan. Her research interests include how groundwater quality is affected by anthropogenic activities, in particular the urban sprawl phenomenon. The Italian Ministry of Education, Universities and Research and regional environmental agencies supported her research. (Photograph courtesy S. Stevenazzi)

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For more information

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

QuikSCAT
https://podaac.jpl.nasa.gov/QuikSCAT

POPLEX Experiment Field Campaign
http://urban.jpl.nasa.gov/poplex/description.html

Time and tide

"We are living in areas that over time have dramatically changed, and will continue to change."

Kytt MacManus
CIESIN

by Jane Beitler

Oceanographer and engineer Stefan Talke had become a kind of historian. In the U.S. National Archives and at other archives around the world, he searched out forgotten tide gauge records of the Pacific Ocean and North America. The records date as far back as the mid-1800s. Some had been digitized; others were still sitting in boxes. He photographed old paper graphs and logbooks, and his students at Portland State University helped tabulate the records.

The tide level measurements strung from ports in Florida and up the U.S. East Coast into Canada, then from Alaska down the U.S. West Coast and along the Pacific Rim from Japan to New Zealand. The data would help reconstruct a history of sea levels, and extreme storms that pushed tide levels up. Like other researchers, Talke wanted to

A debris engineer with the U.S. Army Corps of Engineers inspects a house damaged by Hurricane Sandy in Queens, New York. (Courtesy B. Beach, U.S. Army Corps of Engineers) be able to measure how tide levels had changed, and how much of the change might be caused by a warming climate or by how people have modified estuaries—the places where fresh and salt water meet—to better suit their uses. When he ran into oceanographer Philip Orton at a conference in 2012, he was headed to the New York City branch of the National Archives to hunt for more tide records, and agreed to look for storm records for Orton too.

The data would help them sooner than they thought, and in unexpected ways. Two months later, Hurricane Sandy drowned the New York and New Jersey coasts in a catastrophic storm surge. Orton, who lives and works in the area, immediately shifted his focus to how he as a scientist could help. "Before Sandy we were saying storm risks will get worse in the future," Orton said. "Suddenly my job went from talking about what might happen in the future, to helping people see how they could ameliorate it." And during this time Orton and Talke began to see the past as part of a future solution.

The future is now

Even before Sandy, Orton, a physical oceanographer at the Stevens Institute of Technology in New Jersey, saw how the rescued data could help his work improving storm surge forecasts. He was especially interested in a big storm that had hit New York City in its early days.

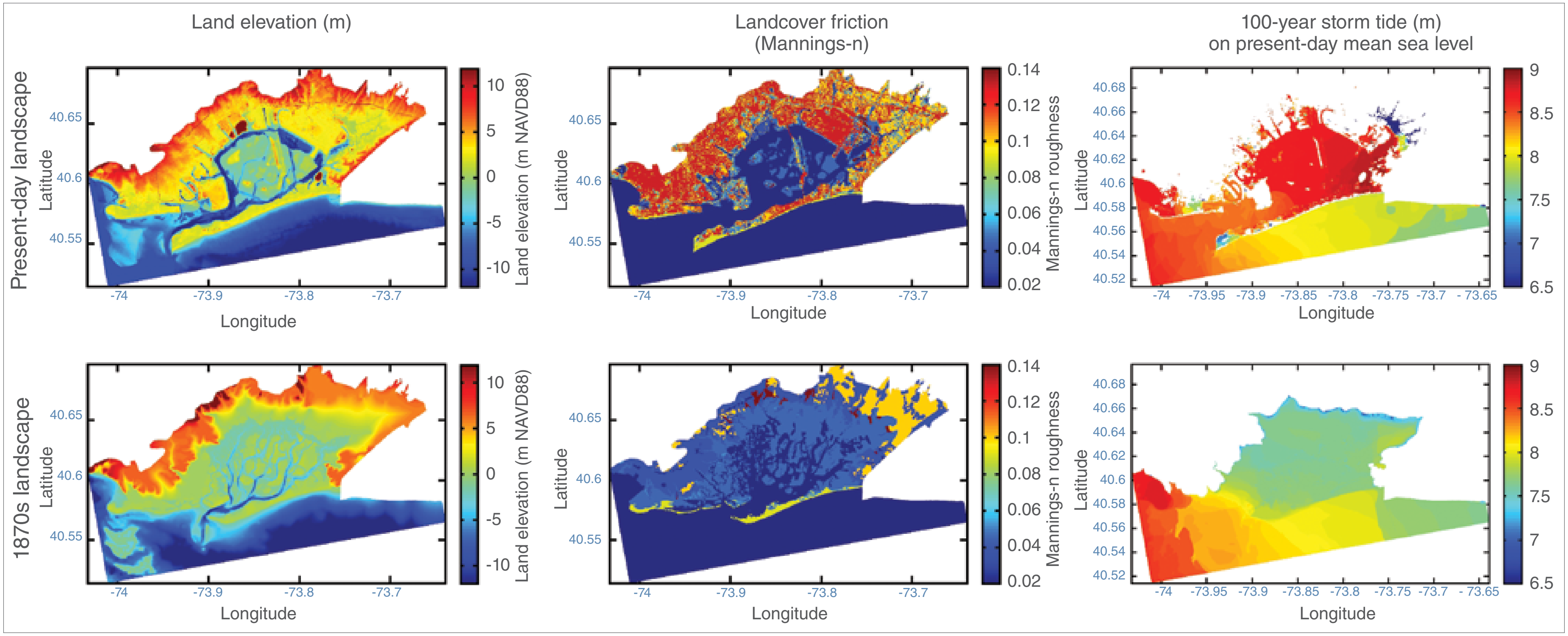
So at the archives in New York City, Talke labored through boxes of tide gauge records from the nineteenth and twentieth centuries and old newspaper accounts of storms. He searched for information about what was then the only hurricane to make a direct hit on New York. The storm, named the Norfolk and Long Island

Volunteers bail out the Museum of Reclaimed Urban Space in East Village, New York City, following Hurricane Sandy. (Courtesy B. Cavanaugh)

Hurricane, bashed the Caribbean and skipped along the East Coast, destroying houses in North Carolina and whipping Virginia with its strongest winds. It made landfall at New York City in the evening of September 3, 1821. Manhattan Island was completely flooded to Canal Street. The storm surge reached 13 feet at Battery Park, a record only broken by Sandy 191 years later. Floods and winds tore apart houses, ripped wharves from their foundations, and blew ships ashore. Few deaths were reported, though a house on Broadway collapsed and killed ten cows.

Small and fast-moving, the 1821 storm hit New York like a freight train. Water levels surged in an hour and left almost as quickly. In contrast, Sandy was the largest storm ever measured in the Atlantic. Nearly a thousand miles wide, it parked its wrath over the coast for three days then arrived onshore, piling up the ocean on the land and lashing cities and towns with winds and rain.

Sandy fit the mold of future storms that worry scientists. As the Earth warms, climate models forecast storms to be intensified by warmer ocean waters and disrupted climate patterns. And as glaciers and ice caps melt and sea level increases, existing defenses from storm surge can be overwhelmed. Hurricane winds are dangerous, but storm surge can be more devastating. A large storm surge brings floods and ushers in waves that pound structures with a power of 1,700 pounds per cubic yard. Sandy's peak winds had



These maps of Jamaica Bay show how long-term changes to the landscape have affected storm tides. The left column shows the land elevation for the present day and for the 1870s, before the bay was altered for human purposes. The center column shows the relative friction of the land cover for the present landscape and for the 1870s, measured with the variable "Mannings-n roughness." The third column shows modeled storm tide levels on the present-day and 1870s landscapes, based on present-day mean sea level. (Courtesy P. Orton)

dropped from 115 to 80 miles per hour by the time it made landfall. It was mainly the storm surge and flooding that killed 49 people and caused $42 billion in damage in New York alone, and shut down the entire city for days.

Tale of two or three cities

In the days following Sandy, talk turned to a $20 billion plan to protect New York City. Planners looked to solutions used in other low-lying regions in the world. After Hurricane Katrina, New Orleans and the U.S. Army Corps of Engineers built 133 miles of levees, flood gates, and seawalls, some up to 54 feet high, around the city. The Netherlands, where half the country lies less than one meter above sea level, spends around $1.3 billion a year on water control. Known for their dikes, the Dutch have been turning to nature for help. Recently, the country dumped 706 million cubic feet of sand off the coast north of Rotterdam to promote the formation of protective sandbars.

After a multi-million dollar design competition, plans include hardening the city's utilities and transportation systems, as well as protecting the coastlines from flooding. In New York City, Lower Manhattan would be surrounded by flood walls and levees, and raised earthen berms that would also serve as a park. "New York City and the Corps of Engineers want natural solutions, but they don't see any options," Orton said. Skeptical that engineered solutions are the only or best defenses, Orton wanted to bring science to the discussion. As a hydrodynamic modeler, he knew how water moves, and what slows and stops it in nature.

But Orton and Talke turned their thoughts to something odd in the historical tide and storm data. "Storm surge has been increasing in the last 100 years, increasing much faster than sea level rise," Talke said. "Why is this happening?" They suspected that storm surge has outpaced sea level rise because of how humans have changed the environment. Wetlands that used to absorb storm surges were filled to build homes, airports, parks, and businesses. Port builders dredged deep channels for shipping, giving waters a fast track to the cities that burgeoned around them. Could undoing some of these changes protect cities from storm surges?

Wetlands are known to slow and absorb storm surge, and limited restoration of some wetlands is in progress. But Orton knew the limits of this measure. "The rule of thumb is one foot of flood reduction from every 2.7 miles of wetlands that the storm has to pass over," he said. That would translate to 27 miles of wetlands to stop a ten-foot surge. While this might work along the swampy coasts of Louisiana, it may not work for people who live right up to the shores in New York and New Jersey.

A man slogs through flooded streets as residents clean out their homes in Midland Beach, Staten Island, New York following Hurricane Sandy. (Courtesy N. Dvir, Polaris)

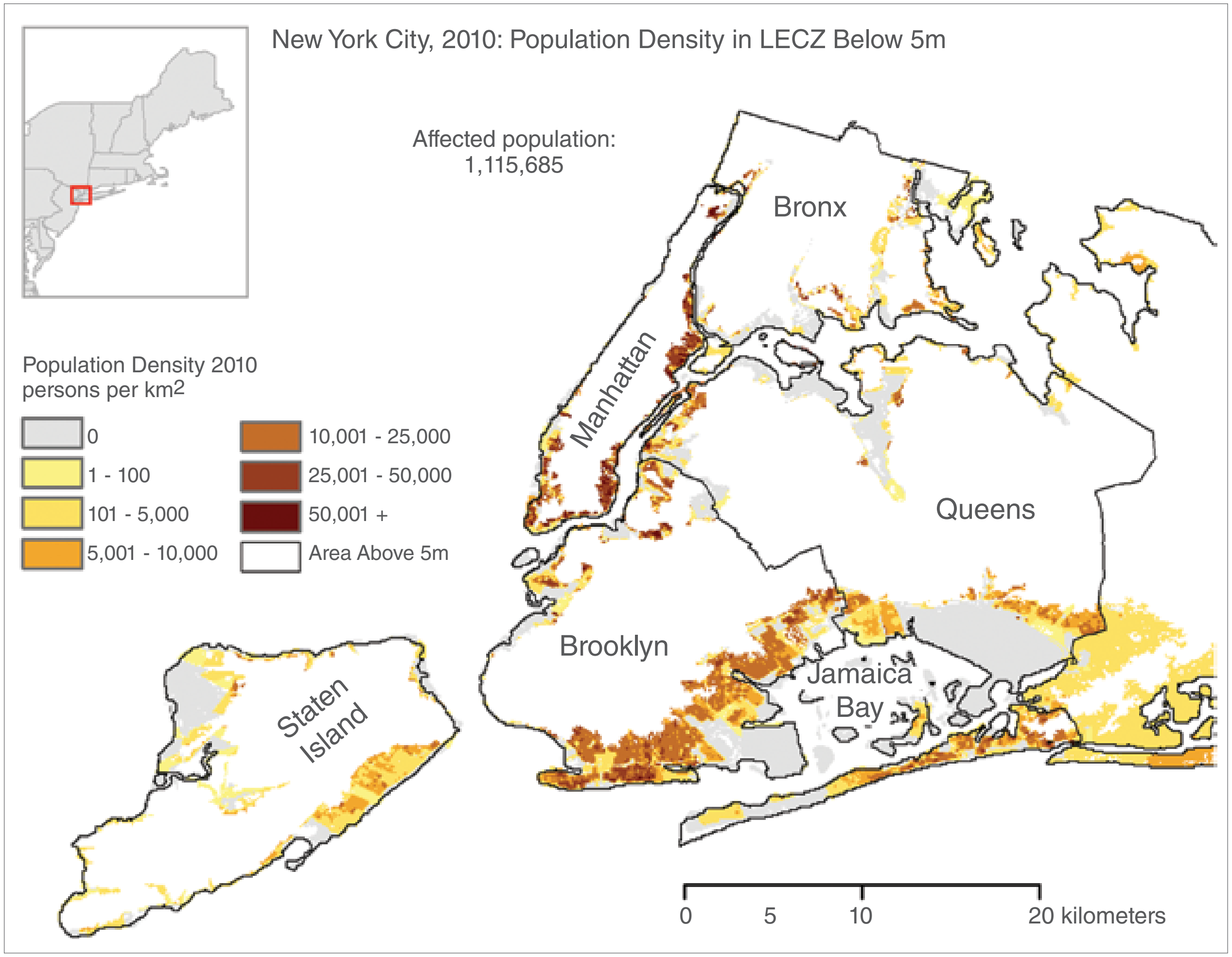
Experimenting with nature

Amidst this talk of reversing history to prepare for the future, it occurred to the researchers that the deep shipping channels could be part of the answer. What if they were shallowed? "Jamaica Bay right away struck me as one place in the New York City area that would be good to study," Orton said. In 1821, southern Long Island was swampier, and Jamaica Bay, at its southwest end, was shallower. Since then, more than 12,000 acres or 75 percent of the original wetlands have been lost, and the bay dredged for three shipping channels. Like wetlands, shallow waters add friction, and friction slows water movement and helps keep water from entering the bay.

With a small grant from the National Oceanic and Atmospheric Administration, Orton fired up his hydrodynamic models to test these ideas. He ran a scenario in which Jamaica Bay's wetlands were restored to their 1879 footprint and depths, and another in which the inlet was shallowed to no more than two meters at low tide. A third scenario simulated what would happen if only the narrowest inlet was made shallower. All three scenarios were run against simulations of both Sandy and the 1821 hurricane.

The results were encouraging. The wetland scenario by itself provided little relief from either storm. Shallowing the entire bay reduced water levels by 15 percent for Sandy, but 46 percent for the fast-pulse 1821 storm. Shallowing only the narrowest inlet was more effective than wetland restoration for a slow-moving storm like Sandy, and provided a 30 percent reduction for the 1821 storm.

Orton admits that there would be practical issues to shallowing the bay. Although Jamaica Bay's deep shipping channels are used less for commercial shipping and more for tasks like moving sewage sludge out of the city, still there would be some economic impact if the channels



This map of the New York City boroughs and the western edge of Nassau County (right edge of the map) shows the population density in contiguous low-elevation coastal zones below 5 meters above mean sea level. The population density data are based on 100-meter resolution 2010 population data. Lidar elevation data at 1-meter resolution are used to filter for elevation; the map only shows population density data where more than 50 percent of a cell area is below 5 meters in elevation. (Courtesy K. MacManus)

were shallowed. Bringing in large amounts of sand to fill the channels requires a massive source of sand, and it is not certain that the sand will stay put.

Or the channels could be decommissioned and allowed to fill naturally over decades. Orton thinks there might be time for that. Sea level rise helps hurricane storm surge get up on the shore, and model forecasts say sea level will be about two to six feet higher in New York by the year 2100. Shallowing could provide some relief for several decades as scientists and engineers continue to ponder ways to protect coastal areas.

Shallowing may also have fewer unwanted side effects than other measures, according to the simulations. "When you use these approaches to reduce flooding, they don't cause flooding to happen somewhere else," Orton said. "If you do it right, if you don't choke the inlet too much, these approaches have a capacity for absorbing and not reflecting the surge."

People and place

In 1821, Manhattan had a population of about 123,000. Today, 20 million people live in the greater New York City area. Orton and Talke's study included a population map showing the risks in the Jamaica Bay area. More than 1.1 million people in New York City boroughs and Nassau County live in low-elevation coastal zones, below five meters (16 feet) above mean sea level.

"The NASA low elevation population data were valuable," Orton said. "It shows that there's just as much of a population around the bay as in Manhattan."

"The sheer number of people in that situation is challenging to manage," said Kytt MacManus from the Center for International Earth Science Information Network at Columbia University, who developed the localized maps from a NASA Socioeconomic Data and Applications Center (SEDAC) data set. Evacuation would push millions of people over gridlocked roads and through choked bridges and tunnels. "And many people are unwilling to evacuate," MacManus said, alluding to research showing about half of people ordered to evacuate refuse to or are reluctant to leave, or face barriers to leaving such as age, illness, or poverty. "Without making policymakers aware of elevation issues, and making the connection to the number of people impacted, it is hard to get their attention. The data broaden the community that registers on their radar," MacManus said.

MacManus thinks the study's historical and scientific approach helps residents, too. "It builds a context for people to understand the place that is their home," he said. "The bay is a dynamic place. We are living in areas that over time have dramatically changed, and will continue to change."

People figure in Orton's research in other ways. "A lot of work is design first and public input later. This study was built with the public and decision makers involved," Orton said. "It's important to interact with real people. There's a lot of fear of big change." He is now also studying narrowing as well as shallowing. "We're working hard for scientists to be heard in the conversation," he said. "There are options for flood protection other than walling ourselves in."

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/time-and-tide.

About the data

Data set	Low Elevation Coastal Zone (LECZ) Urban-Rural Population and Land Area Estimates
Resolution	3 arc seconds, 30 arc seconds
Parameter	Population
DAAC	NASA Socioeconomic Data and Applications Center (SEDAC)

About the scientists

Kytt MacManus is a geographic information system (GIS) programmer for the Center for International Earth Science Information Network (CIESIN) at Columbia University. His research interests include the development of data-driven web applications for decision support and the integration of global population and housing censuses. The National Oceanic and Atmospheric Administration and NASA supported his research. (Photograph courtesy K. MacManus)

Philip Orton is a research assistant professor at the Stevens Institute of Technology in Hoboken, New Jersey. His research interests include air-sea interaction, flood risk assessment, ensemble forecasting, sediment transport, and coastal and urban meteorology. The National Science Foundation and the National Oceanic and Atmospheric Administration supported his research. Read more at https://goo.gl/xZEHvR. (Photograph courtesy P. Orton)

Stefan A. Talke is an assistant professor at Portland State University. His research focuses on tidal processes, storm surge, mixing and sediment transport in estuaries, rivers, and the ocean. He uses both satellite images or infrared video and archival tide data to better understand how estuaries, rivers, and coastal regions function and change. The National Science Foundation and Portland State University supported his research. Read more at https://goo.gl/dfJ7G8. (Photograph courtesy S. Talke)

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http://sedac.ciesin.columbia.edu

AdaptMap - Flood, sea level rise, and adaptation mapper for Jamaica Bay, New York City
http://adaptmap.info

The researcher, the reef, and a storm

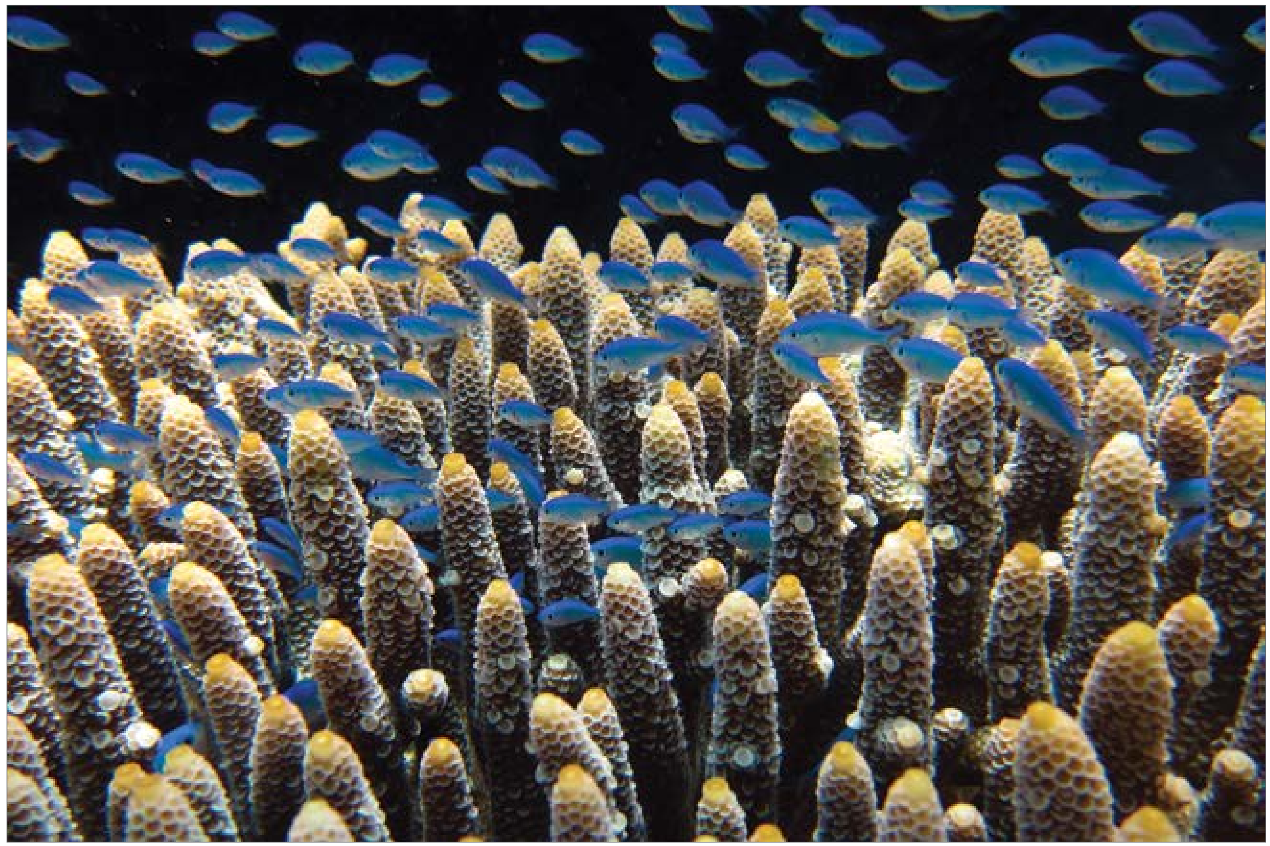
“Just like us, corals are animals that can become injured or wounded.”

Joleah Lamb
Cornell University

by Natasha Vizcarra

It was just her luck. Marine ecologist Joleah Lamb was organizing a coral reef survey in Australia’s Great Barrier Reef when a cyclone plowed through her study sites. Cyclone Yasi had crept in from the east, near the Fiji Islands, as a tropical depression. By the time it crossed the Coral Sea and landed over touristy Mission Beach it was a Category 5 behemoth.

But the tenacious PhD student carried on. Two weeks after the storm, she picked her way over roads littered with branches and sand, passing houses with roofs ripped off and boats washed ashore. She and her colleagues pulled on their



Juvenile blue chromis linger near the branches of an *Acropora millepora* colony off Lizard Island on the Northern Great Barrier Reef. Corals are an important habitat for fish, especially young fish that hide in the reefs to avoid predators. (Courtesy F. J. Pollock, Pennsylvania State University) wetsuits, got on boats, and headed to the reefs. "This happens a lot in ecological studies and we just roll with it," she said. "Data is data!"

When they reached Cairns, the damage was breathtaking. "We observed many reefs with immense levels of damage, such as broken and exposed coral skeletons and overturned coral colonies the size of cars," Lamb said.

She noticed something else. "There was a lot of disease where the cyclone hit," Lamb said. She tweaked her research plan and collected storm damage data as well. In a follow up survey six months later, she saw the same. Were the diseases somehow intensified by storm damage?

Underwater epidemics

Lamb was in Australia to investigate whether marine reserves like the Great Barrier Reef Marine Park protect coral reefs from marine diseases. Beginning in the 1950s, various countries established marine reserves to protect reefs from increasing overfishing and other human activities. It is unclear to scientists whether reserves can also shield reefs from diseases.

Lesions, bleaching, black bands, and white spots: Lamb studies these ghoulish markings and other signs of disease on corals worldwide. "Just like us, corals are animals that can become injured or wounded," Lamb said. And just like humans, injured corals are less able to fight off diseases.

While they look like underwater plants, corals are animals and are closely related to jellyfish. Each coral is made up of thousands of tiny animals, called polyps. The polyps feed on plankton, but also rely on algae that live in their tissues to provide energy.

Millions of marine species begin their lives on coral reefs. On a night dive, life and death dramas unfold under the divers' bright lights. Billions of coral polyps emerge, snatching plankton with their stinging tentacles. Tiny wrasses nibble parasites off larger fish that would otherwise eat them. Among rocky coral, feisty damselfish farm algae. Under the reefs, shrimp hide with baby fish, eaten by bigger fish, and then larger fish.

Everything changes when the corals get sick. "Once a pathogen infects a coral, the tissue loss typically continues to spread across the coral and is unstoppable," Lamb said. That could mean death for the whole colony and the marine creatures that depend on it for food and shelter.

Zoom in, zoom out

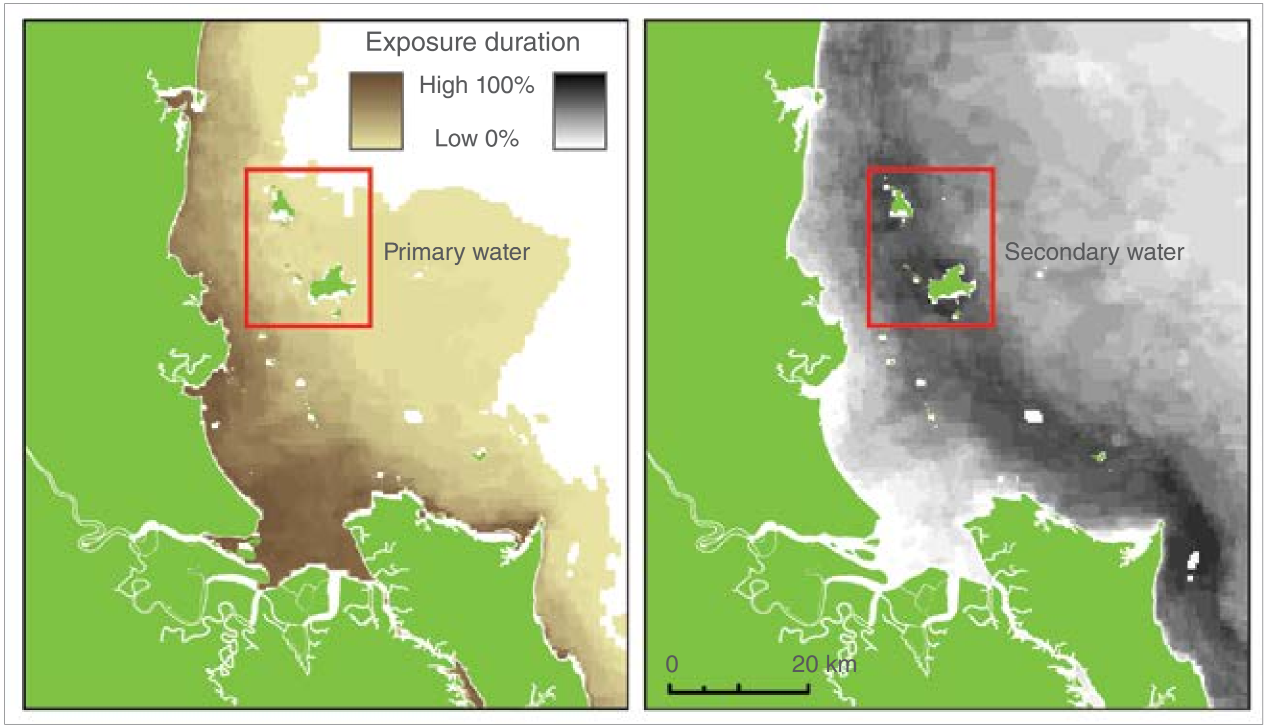
Lamb planned to compare the rates of disease inside and outside the reserves. After recording signs of disease affecting colonies off the Whitsunday Islands and the coastal towns of Port Douglas and Cairns, she surveyed for two more summers around the Palm Island group that was hit the hardest by Cyclone Yasi, and further south around the Keppel Island group where yearly floods dump silt on the reefs. She also noted evidence of recent injuries, like broken corals and open wounds from entangled fishing line.

Months later, when Lamb compared the average number of diseases inside and outside the reserves, she found that marine reserves can, to a degree, protect coral reefs from disease, despite damage from storms. Coral disease levels in the Palm Islands were seven times lower inside marine reserves compared to outside reserves a year after Cyclone Yasi. Reefs outside reserves did not fare well: Coral diseases were more prevalent, particularly where reefs had high levels of injured corals and discarded fishing line.

Marine ecologist Joleah Lamb hovers near table coral as she examines the reef for signs of disease and damage. (Courtesy J. Rumney)

"Corals have an immune system to fight pathogens, but if they are stressed in any other way, they are less likely to be able to fight off the infection," Lamb said. "Fishing line not only causes coral tissue injury and skeleton damage; it also provides additional surfaces for potential pathogens to colonize, increasing their capacity to infect wounds caused by entangled fishing line."

However, she found no clear pattern for this in regions affected by flooding. "Maybe there are



These images compare how frequently coral reefs around the Keppel Islands (red box) were exposed to primary water, or runoff from floods containing large sediment (left); and secondary water, or runoff containing fine sediment (right). Shading intensity indicates the duration of exposure. Data are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Aqua satellite. (Courtesy J. B. Lamb, et al., 2016, *Philosophical Transactions of the Royal Society B*)

other drivers for why this is happening," she said. "I thought, we need to look at the long-term history of these sites."

So Lamb worked with Amelia Wenger, then a researcher at the ARC Centre of Excellence for Coral Reef Studies at James Cook University, to find water quality data for her study sites. "We were fortunate to have a long-term data set that combined in situ water quality and remote sensing data," Wenger said.

The data set uses true color satellite imagery from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS). Wenger used this to map water quality and flood plumes at their study sites. When they combined this with their field data and ran these through statistical models, clear patterns emerged.

A caveat

Here was the catch: Marine reserves can protect coral reefs from disease only if the water quality is good. In the Keppel Islands, coral reefs were repeatedly exposed to higher than average levels of fine sediments and nutrients. In these sites, disease levels inside the marine reserves were the same as outside the reserves.

"It was a huge surprise," Lamb said. She had assumed that large sediment from the yearly floods draining into the sites would smother coral and cause diseases. Instead the diseases were related to finer sediment and chlorophyll-rich waters.

"When a flood takes everything off land, you have sediment, you have nutrient from fertilizers, you have pesticides from farms," Wenger said. "It's obvious in the satellite image, because you see this murky brown plume sitting in otherwise bluish sea water."

Large sediments float in the plume for a few days. When they sink, smaller sediments remain. Sunlight breaks into the plume, allowing nutrient-fed algae to bloom, which causes oxygen levels in the water to drop. "Chronic hypoxia or exposure to algal blooms could be equally detrimental in the development of disease," Lamb said.

Lamb and her colleagues urge marine reserve managers to improve water quality and limit human activities that injure corals. "I hope this sends a clear message to other regions in the world about the benefits that reserves can have on reef health and the importance of incorporating land management into the reserve planning process," she said.

"This study looks at things from multiple scales and does a great job of connecting the dots," said Kevin Lafferty, a marine ecologist at the U.S. Geological Survey who was not part of the study. "Oftentimes we look at marine diseases or other environmental problems and get stuck at 'we have a problem.' This study shows us, 'here's what drives the problem and here are specific solutions.'"

Watching the reefs

In hindsight, Lamb should not have been worried about Cyclone Yasi interfering with her research plans. “If the cyclone hadn’t hit some of my sites I would not have thought of collecting the data,” she said. “It came by accident really, and led me down this whole path of research.”

“About 275 million people live within 30 kilometers of coral reefs and rely on them for food, coastal protection, income, and cultural value,” Lamb said. “However, disease outbreaks have caused significant declines in coral cover, with losses of up to 95 percent in some reef regions.”

Reefs are increasingly threatened by coral bleaching, caused by higher water temperatures or extreme weather events. With Earth’s temperature projected to rise, marine ecologists like Lamb will have their hands full and will need to connect more dots double time.

“You do it for the love, that’s for sure,” Lamb said. It’s the same love that keeps divers and snorkelers returning to the reefs.

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/the-researcher-the-reef-and-a-storm.

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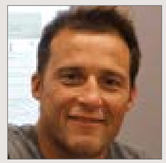
About the remote sensing data

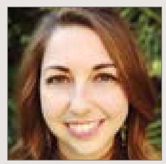
Satellite	Aqua
Sensor	Moderate Resolution Imaging Spectroradiometer (MODIS)
Data set	Daily MODIS Level 0 Data
DAAC	NASA Ocean Biology Distributed Active Archive Center (OB.DAAC)

The Level 0 data were converted into true color images with a spatial resolution of 500 by 500 meters, using the OB.DAAC NASA SeaWiFS Data Analysis System (SeaDAS).

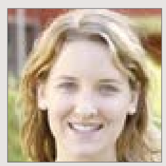
About the scientists



Kevin Lafferty is a research ecologist at the U.S. Geological Survey at the University of California Santa Barbara. His research focuses on invasive species ecology, the conservation of marine resources, assessing the effects of marine reserves, and investigating strategies for protecting endangered shorebirds, fish, and abalone. Read more at https://goo.gl/TR2SO3. (Photograph courtesy S. Fernandez)



Joleah Lamb is a NatureNet postdoctoral fellow at Cornell University in Ithaca, New York and The Nature Conservancy. Her research focuses on identifying and managing the influence of reef and coastal-based industries on coral health and disease. The Australian Government National Environmental Research Program and The Nature Conservancy supported her research. Read more at https://goo.gl/u0RwxD. (Photograph courtesy S. Beveridge)



Amelia Wenger is a postdoctoral research fellow at University of Queensland, in Australia. Her research focuses on connecting ecological and spatial data to assess responses of coastal and marine systems to threats. The Australian Research Council, the Australian National Environmental Research Program, and James Cook University’s Marine Monitoring Program supported her research. Read more at https://goo.gl/tJiVs5. (Photograph courtesy I. McLeod)

For more information

NASA Ocean Biology Distributed Active Archive Center (OB.DAAC)
http://oceancolor.gsfc.nasa.gov

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

NASA SeaWiFS Data Analysis Sytem (SeaDAS)
http://seadas.gsfc.nasa.gov

The Maracaibo beacon

"The winds are key. It has to do with how the winds are dancing."

Ángel Muñoz
Princeton University

by Agnieszka Gautier

A lightning bolt fractures the night sky. Wings of phosphorescent pink unfold to illuminate Lake Maracaibo, a brackish bay that opens north to the Caribbean Sea. A quarter of Venezuela's population lives in the highest concentration of lightning on Earth, 250 flashes per square kilometer (0.4 square miles) per year. "A lot of people die each year," said Ángel G. Muñoz, a physicist and researcher at the National Oceanic and Atmospheric Administration. The lightning is so consistent—occurring 300 days a year at the same time and in the same area, where the Catatumbo River meets Lake Maracaibo—it has earned its own proper name, Catatumbo Lightning.

Around the world, lightning is forecast only a few hours, and at best, days in advance. Muñoz and his team wanted to do better. He said, "We're talking about three months in advance. That is huge." Catatumbo Lightning is consistent on a daily scale, but its behavior shifts along the year and between years. If the team could capture

Seen from the shore of Lake Maracaibo, lightning strikes Congo Mirador, a *palafito* or a stilt house village, near the mouth of the Catatumbo River. (Courtesy H. P. Díaz/Centro de Modelado Científico) its physical mechanisms, they could be the first to predict lightning on a seasonal scale.

River of fire

Shortly after dusk, lightning strikes Lake Maracaibo about twenty-eight times a minute for up to nine hours. “The lightning can be so continuous that you see everything around you,” Muñoz said. Suspended over the mouth of the Catatumbo River, which locals call the “river of fire,” this strobe light brightens night into day. “You should be afraid, but it is so impressive that your fear gets overwhelmed. You actually don’t feel fear,” said Joaquín Díaz-Lobatón, a physicist and researcher at the Centro de Modelado Científico at Universidad del Zulia in Venezuela.

Sailors have embraced this phenomenon for centuries, using the Maracaibo lightning as a beacon. When Italian navigator Amerigo Vespucci sailed into Lake Maracaibo in 1499, he encountered a city of huts built on stilts. He called the floating city Venezuela, or “Little Venice,” or so one story goes. Today, the lake supports 20,000 fishermen, and many live in *palafitos*, one-room, tin shacks. “These people, the forgotten people, are frequently getting struck by lightning,” Muñoz said. Catatumbo Lightning strikes people three to four times more here than in the United States. Most fishermen understand fish bite best at dusk when Catatumbo Lightning brews. “We want to make life easier for them with lightning detection and prediction,” Muñoz said.

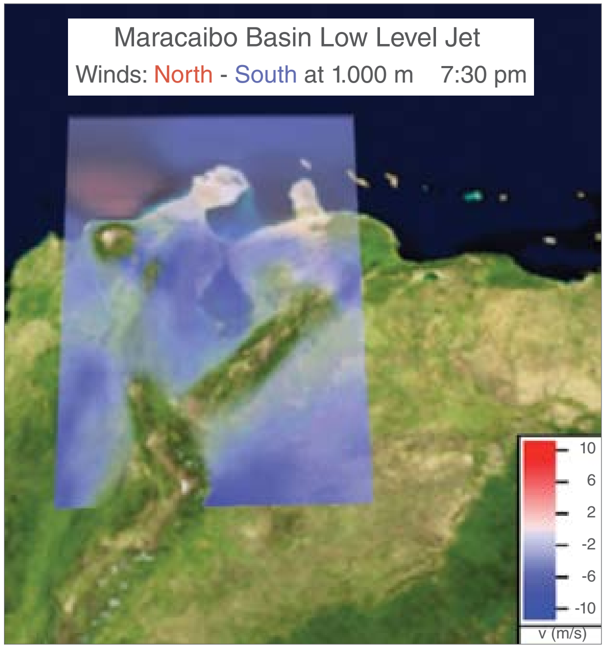
All thunderstorms follow a formula: rapidly rising warm air collides with moist air. Unstable air and moisture are key, and Catatumbo Lightning gets a boost from a unique topography. Mountain ridges cup three sides of Lake Maracaibo, leaving a narrow window open north to the Gulf of Venezuela. The inflowing Caribbean Sea provides an endless supply of warm water, while the hot tropical sun pulls additional moisture from the lake. At sunset, strong winds whip the mountains, jolting warm air up to form cumulonimbus clouds that rage inside. When water droplets of humid air collide with ice crystals from the cold air, it produces static charges that build up. The release discharges a zigzag of electrical energy strong enough to light 100 million bulbs. Ten minutes of Catatumbo Lightning could illuminate all of South America.

The team works to deploy a weather balloon with sensors attached to measure temperature, relative humidity, and pressure. (Courtesy H. P. Díaz/Centro de Modelado Científico)

So what makes Catatumbo Lightning consistent? In 2015, Muñoz and his team sent weather balloons onto Lake Maracaibo. They found that close to the surface, no more than one kilometer (0.62 mile) high, a swift ribbon of air—the Maracaibo Basin Nocturnal Low-Level Jet—transports moisture from the Caribbean Sea and Lake Maracaibo to its southern basin, where it interacts with the mountains. “When winds transport this moisture towards the mountains, there is nowhere for it to go, except to ascend really fast,” Muñoz said. “The winds are key. It has to do with how the winds are dancing.” The low-level jet generally occurs every day at the same time, but moisture levels change throughout the year. For instance, here El Niño years, like in 2010, are drier than La Niña years. So the researchers needed a seasonal-scale equivalent of the low-level jet. To find it they would need models and observations.

The right one

Models need training. For a model to accurately gauge present and future conditions, it must replicate past events. So if on a particular day, lightning struck 13,720 times, the model should show that. “To do that, you need a lot of years of



This map shows a snapshot of the north-south winds in the Maracaibo region at 7:30 p.m. (local time). The pattern, called the Maracaibo Basin Nocturnal Low Level Jet (MBNLLJ), modulates the daily cycle of lightning activity in the basin. More lightning is observed in the basin when winds are transporting moisture southwards, enhancing orographic convection between 7:30 p.m. and 4:30 a.m. Winds blowing southward are shown in blue, while the ones blowing northward are shown in red. Units are meters per second. (Courtesy Centro de Modelado Científico, Universidad del Zulia; and International Research Institute for Climate and Society, Columbia University)

data," Muñoz said. Luckily, satellite images from the NASA Global Hydrology Resource Center DAAC offered seventeen years of data, which were averaged to show seasonal patterns. Lightning density information was combined using two sensors: the Optical Transient Detector on the OrbView-1 satellite, and the Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) satellite. To compute monthly lightning patterns in the Maracaibo Basin, the scientists used the LIS Science Data set. Put together, they had a shot at teaching their model.

"Models are never quite right," Muñoz said, "but with actual observations from satellite data we could correct them." The team reproduced observed lightning frequency using multiple variables: sea surface temperature, humidity, wind, and Convective Available Potential Energy (CAPE), a measure of instability essential in storm development. When heat rises and clashes with cool air, the resulting turbulence ripples into severe storms.

Since multiple climate drivers tweak lightning activity at a seasonal scale, the team decided to couple certain variables, running different scenarios. "Maybe we are missing a lot of other climate variables, but one index in particular captured it," Muñoz said. "You only need one and we got it. That was cool." After months of study, the one index to explain the lightning phenomenon was the advection, or transport, of CAPE. The models became sensitive to lightning prediction when the researchers combined CAPE with the Maracaibo Basin Nocturnal Low Level Jet (MBNLLJ), the north-south wind pattern created by temperature differences between the Caribbean Sea and the lake basin.

Using MBNLLJ in the models accurately reflected daily lightning activity. Adding the Caribbean Low Level Jet helped the team look out months in advance. Adding global-scale drivers, like El Niño, gave insight into the extent of dryness for that year. Catatumbo Lightning is most active in the wetter months of September and October, and least active in the drier months of January and February. The team's predictions were slightly stronger during the minimum season, but in general the skill level was high enough that decision makers in the Lake Maracaibo Basin could use the model for human safety, and more.

An ancient lake

Lake Maracaibo is one of the oldest lakes on Earth. Its rich geological history has deposited the world's largest fossil fuel reserves, dwarfing those of Saudi Arabia. In the sixteenth century, Spaniards used tar from its large oil seepages to caulk their ships.

Today, more than 15,000 miles of oil and gas pipelines crisscross the lake floor. Oil leaks out of corroded pipes, and puddles of iridescent rainbows surface. "This used to be one of the top oil producers in the world," Díaz-Lobatón said. Political disorder and the recent, depressed oil market has slowed production, but at its height 90 percent of Venezuela's economy came from oil. And no matter the productivity level, real and false lightning alarms have hampered about 10 percent of its yearly extraction. "Lightning storms hinder a significant amount of production. The model could help address this," Díaz-Lobatón said. The oil industry could delay or reschedule their work.

Fueling fishing boats also sends fishermen into dangerous lightning. Lake Maracaibo spans 13,200 square kilometers (5,100 square miles), about the size of Connecticut. From Congo Mirador, a *palafito* village at the mouth of the Catatumbo River, to a fuel station requires a two-hour journey one way. Providing months-advance warning could help people take extra precautions. Fishermen could fish on milder nights, and the four-hour boat journey can be better planned for. "It's not about stopping things for months.

About the remote sensing data

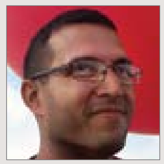
Satellites	Tropical Rainfall Measuring Mission (TRMM) and OrbView-1	TRMM	TRMM
Sensors	Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD)	LIS	LIS
Data sets	LIS/OTD 2.5 Degree Low Resolution Time Series (LRTS)	LIS 0.1 Degree Very High Resolution Gridded Lightning Climatology Data Collection	Lightning Imaging Sensor (LIS) Science Data
Resolution	10 kilometer	0.1 degree	4 to 7 kilometer
Parameter	Lightning density	Lightning density	Lightning density
DAAC	NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC)	NASA GHRC DAAC	NASA GHRC DAAC

It's about taking advantage of windows of opportunity, and not taking unnecessary risks when lightning activity is above normal," Muñoz said.

Being named the most lightning struck place on Earth has brought tourists to the area. But tourists do not stay. They do not spend money, so villagers continue to fish for subsistence. Danger and poverty will not go away anytime soon, but helping to reduce lightning risk can make a difference. "This is the first study to address seasonal predictability," Díaz-Lobatón said. "It helps people. That's what makes us happy. That's really what motivates us. That's the whole point."

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

About the scientists



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Ángel G. Muñoz is a postdoctoral research associate at the Program in Atmospheric and Oceanic Sciences at Princeton University, and the National Oceanic and Atmospheric Administration. His research interests involve climate extreme events, sub-seasonal to decadal predictability, and climate services. The International Research Institute for Climate and Society of Columbia University supported his research. Read more at https://goo.gl/sc9HPn. (Photograph courtesy A. G. Muñoz)

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For more information

NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC)
http://ghrc.nsstc.nasa.gov

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

In the zone

“The life cycle of the snow petrel is tied to sea ice.”

Stephanie Jenouvrier
Woods Hole Oceanographic Institution

by Laura Naranjo

During the long winters that shroud Antarctica, the ocean surface freezes over into sea ice, effectively doubling the size of the continent. In summer, this sea ice cover shrinks to about 1.2 million square miles. It is tempting to imagine the ice as a frozen wasteland, but the Southern Ocean is one of the most biologically productive zones on Earth. The ebb and flow of sea ice supports a wild array of life, from fish and seabirds to seals and whales.

That sea ice is changing. Over the past several decades, temperatures around the continent have been rising. Unlike the Arctic, which has seen a

Snow petrels wait along ice edges, ready to snatch krill or fish that come near the ocean surface. (Courtesy D. Filippi, Institut Polaire Français Paul-Émile Victor/Centre national de la recherche scientifique/Sextant Technology Ltd.)

sharp drop in summer sea ice, increased warmth has brought more subtle change to Antarctica, altering the weather and winds that govern where sea ice forms. Stephanie Jenouvrier, an ecologist with the Woods Hole Oceanographic Institution, has been studying how Antarctic seabirds adjust to the changes. Because Jenouvrier's research found that climate change could threaten many seabirds' habitats, understanding their future means understanding Antarctic sea ice. When she teamed up with sea ice researcher Julienne Stroeve to look at the birds' icy habitat, the two researchers also learned more about the limits of sea ice satellite data.

A life on the ice

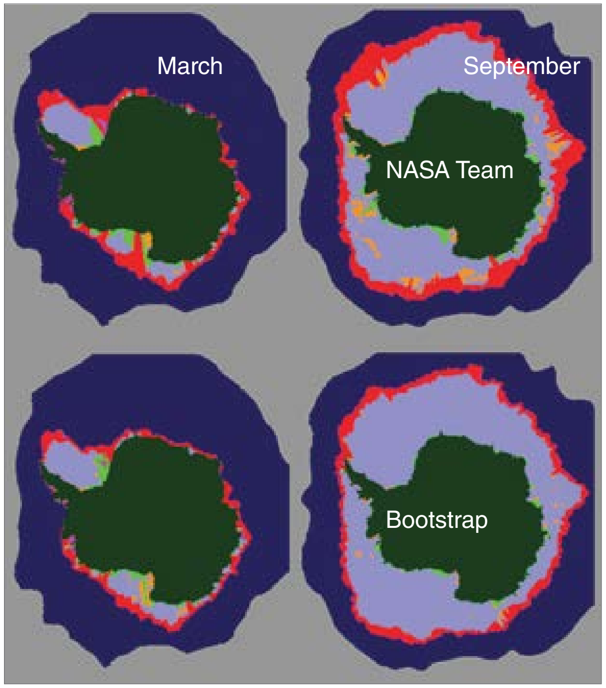
Sea ice harbors the key to South Pole survival: krill. These tiny shrimp-like creatures form the base of the Antarctic food chain. In dark winter months, krill survive by scraping algae from the underside of sea ice. During the brief summer, sea ice melts and sunlight floods the open ocean. Then the krill population booms. Swarms can cover more than 175 square miles and contain more than two million tons of krill. Seabirds like the snow petrel lurk along ice edges to snatch krill and fish swimming close to the surface. Emperor penguins dive for krill. Seals prey on krill while prowling for penguins and fish. Even massive blue whales filter and consume nearly four tons of krill daily.

For most of the Antarctic seabirds Jenouvrier studies, access to that movable feast depends on sea ice. A nearly solid cover of pack ice forms each winter from plates of ice, or floes, that slowly freeze together. Openings in pack ice are few and far between, making it difficult for seabirds to feed or seals and whales to surface for air. Further out, however, lies a broad transition between pack ice and open water. This region, called the Marginal Ice Zone (MIZ), is susceptible to winds and waves that fracture floes and prevent the ocean from freezing over. During the spring thaw, the MIZ temporarily expands slightly as the pack ice breaks into floes again.

The icebreaker *Aurora Australis* churns through pack ice surrounding East Antarctica. (Courtesy A. O'Connor)

In fact, the sea ice cover is almost constantly changing. Pack ice tends to grow and shrink consistently over the course of seasons, but the MIZ changes within hours or days, depending on weather and wind patterns. Additionally, sea ice around the Antarctic continent varies by region. For instance, despite recent record high ice extents around most of Antarctica, sea ice extent in the Bellingshausen and Amundsen Seas has decreased. Scientists suspect that strong winds are partly to blame, compacting ice against the coast. A compacted ice cover means fewer open areas where seabirds can feed, especially during winter when pack ice pushes the MIZ farthest from the coast. If this regional trend continues, seabird populations in this region may begin to decline.

Krill and seabird survival depends on a balance of pack ice and marginal ice. High pack ice extent nurtures a robust krill population, but can



This data image shows samples of sea ice classification from March (left) and September (right) 2013. The Marginal Ice Zone (red) represents sea ice concentration between 15 and 80 percent. Pack ice (light purple) shows greater than 80 percent sea ice concentration. Orange regions indicate broken ice areas; pink areas are open water; light green areas are potential coastal polynyas, or areas of open water. Dark blue represents open ocean. (Courtesy J. Stroeve, et al., 2016, *The Cryosphere Discussions*)

prevent seabirds from feeding on much of that feast. The Antarctic Peninsula has the opposite problem. Along the Peninsula, warm temperatures have led to lower winter sea ice extents, diminishing the amount of krill and forcing seabirds to compete for less food. Jenouvrier had studied how such changes affected penguins, and shifted to study snow petrels, another seabird that spends its entire life in Antarctica. Although snow petrels are not currently threatened or endangered, they will likely respond to changes in sea ice conditions that reduce krill abundance.

Snow petrels are the size of a pigeon, snowy white except for black eyes and beak. "The life cycle of the snow petrel is tied to sea ice," Jenouvrier said. "Sea ice does not affect their survival directly. It affects their ability to successfully breed." To breed, females must feed well during the previous winter. "The size and weight of a female before breeding will influence whether she will be able to raise a chick during the summer," Jenouvrier said. She hoped that mapping MIZ extent and variability would reveal correlations with snow petrel breeding success.

Defining the marginal ice zone

Stroeve, a scientist at the National Snow and Ice Data Center, works with the longest sea ice satellite records, dating to 1978. The data come from the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSM/I) instruments. Researchers can use these data to see how overall ice extent is changing around Antarctica. However, observing how pack ice and the MIZ are changing is more complicated, so Stroeve wanted to explore whether satellite data could help.

Stroeve uses computer algorithms to sort ice types, distinguish land ice from sea ice, and identify errors. Pack ice is defined as ice covering at least 80 percent of the ocean surface; ice cover of less than 15 percent defines the MIZ. But parsing pack ice from the MIZ was tricky. "I noticed that the results depended on which algorithm you used," she said.

Using more than one algorithm can help scientists root out trends, especially when studying daily, seasonal, and annual variations in Antarctic sea ice. Scientists frequently use one of two standard algorithms for data from SMMR and SSM/I, called NASA Team and Bootstrap. Each algorithm focuses on particular aspects of sea ice study. Jenouvrier said, "We know that NASA Team and Bootstrap algorithms give very different results, so we wanted to explore both." Both captured the total sea ice extent, as well as the timing of seasonal sea ice growth and retreat, but the MIZ in the NASA Team algorithm was twice as large the MIZ in the Bootstrap algorithm, when averaged over the entire year.

So the researchers and their colleagues compared the results to snow petrel records, pulling data from a French science station in East Antarctica. This long-term data set included the number of snow petrel chicks hatched from 1979 through 2014. Comparing the sea ice and snow petrel data confirmed that extensive winter pack ice impaired access to krill, which decreased snow petrel breeding success.

Jenouvrier said, "Krill are very dependent on sea ice. When you have years with higher winter sea ice you may have years with higher recruitment of krill." Yet the pervasive ice pack that fostered krill proved stressful for breeding snow petrels. Stroeve said, "When you look at winter ice conditions, we do notice that their breeding success reduced when there was a lot more consolidated winter ice, compared to if it had more broken MIZ ice." So if changes in the MIZ did not drive snow petrel breeding success, what did?

Location, location, location

Finding the answer may require zooming in to study how the mix of pack ice and MIZ is changing on a regional level. "Regional variations in sea ice will impact the bird populations in various areas of Antarctica differently," Stroeve said. The MIZ is already strongly influenced by wind and ocean conditions, which vary around the continent and are changing at different rates, and will be more sensitive to further changes, such as ice compaction from wind or warming ocean currents.

Studying the usefulness of each algorithm is only a first step in Jenouvrier's research on snow petrels. Jenouvrier said, "Imagine that you're an ecologist and you did not have a colleague like Julienne and you did not know the difference between the algorithms. We now encourage ecologists to use several algorithms, because it is very hard to say which one is the most valuable, especially for ecological applications."

Jenouvrier and Stroeve will continue studying the effects of sea ice changes on Antarctic seabirds. "One of the things we're going to do is validation with visible imagery to get a better handle on which algorithm to trust, in terms of these types of ecological studies," Stroeve said. The team will also compare their results with climate models to see how sea ice changes and variability might impact bird species in the future. For now, snow petrels continue to thrive as they flit, feed, nest, and breed against a backdrop of snow and ice.

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

About the remote sensing data

Satellites	Defense Meteorological Satellite Program (DMSP) F8, F11, F13, and F17, and Nimbus-7
Sensors	Scanning Multichannel Microwave Radiometer (SMMR) Special Sensor Microwave/Imager (SSM/I) Special Sensor Microwave Imager/Sounder (SSMIS)
Data sets	Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1 Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS, Version 2
Resolution	25 x 25 kilometer
Parameter	Sea ice concentration
DAAC	NASA National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC)

About the scientists

Stephanie Jenouvrier is an associate scientist at the Woods Hole Oceanographic Institution (WHOI). Her research focuses on understanding and predicting the effect of climate change on seabird dynamics and ecology, especially in the Southern Ocean. NASA supported her research. Read more at https://goo.gl/LyT4fc. (Photograph courtesy S. Jenouvrier, WHOI)

Julienne Stroeve is a senior research scientist at the National Snow and Ice Data Center (NSIDC). She studies Arctic and Antarctic sea ice using remote sensing in the visible, infrared, and microwave wavelengths. NASA supported her research. Read more at https://goo.gl/l3fnZI. (Photograph courtesy NSIDC)

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http://nsidc.org/daac

Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) – Special Sensor Microwave Imager/Sounder (SSMIS) Data
https://nsidc.org/data/smmr_ssmi

The power of particles

"It was hard to convince people this is actually happening."

Pablo Saide
National Center for Atmospheric Research

by Karla LeFevre

Early one April morning, a Yucatán farmer stooped over the stubble of his sugar cane field to set it on fire. Torching it would make a bed of rich ash for new seedlings. The smell of burning plant matter stung his nose as a great plume of smoke and soot rose up in the wind.

Just a few days later, a massive tornado tracked across Tuscaloosa, Alabama. Along with smoke particles, the wind carried all manner of debris: roofs and siding stripped from houses, uprooted trees, even SUVs and boats. A curtain of falling debris stretched across the sky for over 20 miles. A total of 122 tornadoes spun through the southeastern United States on April 27, 2011, killing 313 people, one of the deadliest outbreaks in U.S. history.

Were these two events connected? At the National Center for Atmospheric Research in Colorado, researcher Pablo Saide squinted at satellite images taken that week in April 2011. He spotted the giant smoke plume heading from the Yucatán towards the United States. Like other scientists,

Stairs and stripped trees are about all that remain after a tornado hit Lake Martin, Alabama, on April 27, 2011. (Courtesy lakemartinvoice/Flickr) he had suspected a connection between yearly field-clearing fires in the Yucatán and South America, and severe tornadoes in the southeastern United States. If he could show how they were connected, information on smoke could be added to severe weather forecasts to help save lives.

A meeting of masses

Scientists have long understood that smoke can intensify severe weather by increasing cloudiness, thunderstorm cloud heights, and lightning. But how smoke might worsen tornado outbreaks was not well understood, so weather forecast models could not use the smoke information to help predict dangerous conditions.

Tornadoes form when two different air masses meet during powerful storms. Under these conditions, cold air can trap warm air. With nowhere to rise, the warm air begins to spin. Sunlight pierces the storm clouds here and there, heating still more air on the ground. Energy builds, until eventually the spinning air mass has enough pent-up energy to bust through the cold air barrier and shoot skyward.

This happens over the southeastern United States each spring and summer as warm, wet air from the Gulf of Mexico meets cold, dry air from Canada. Scientists thought that tiny smoke and soot particles, or aerosols, influence convection by suppressing rain and causing more updraft, suggesting a connection to severe storms. But had this been seen in actual events?

Smoke signals

Saide traced the plume northward over the Gulf of Mexico, but it stopped short of the outbreak. He was looking for bright clouds. Aerosols like smoke and dust reflect and absorb sunlight, and even attract cloud droplets. This can make clouds brighter and affect temperature and wind. Brighter clouds mean less sunlight reaches the ground and more is scattered back into the atmosphere. These interactions get complicated quickly and are what scientists call feedback, clues to atmospheric behavior.

The images showed how much light was being scattered and absorbed by particles. Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on the NASA Terra and Aqua satellites had spied through a clear atmosphere to capture the aerosols and bright clouds that week in 2011. Yet MODIS sensors have a limited ability to see through clouds, and stormy conditions over the southeastern United States obscured their view of the lower atmosphere. Saide said, "When you have a tornado outbreak, you have a lot of clouds. But you need a clear sky to see the aerosols in the satellite data."

Hunting for smoke, Saide and his colleagues inspected fire emissions data, also from MODIS, on those days. Cloud thickness measurements revealed how much light was passing through the clouds instead of being reflected. A lot of smoke and soot had been pumped into the atmosphere, but more was needed to track the plume. Plume heights from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite helped create a clearer signal of the smoke. And measurements taken from the ground confirmed what the satellites had seen. Saide said, "We used a lot of data to figure out where the fires were. We really needed to get the particles right to have the feedback be accurate."

All that data meant they could simulate the conditions on the days leading up to the April 27 outbreak. Did the smoke reach the southeastern United States? Saide said, "In the model world you can turn off and on different processes, so we ran a couple of simulations, one with smoke and one without." Comparing the two made it clear that smoke was changing conditions as it traveled to the scene of the outbreak. But it did not get them close enough to the tornadoes.

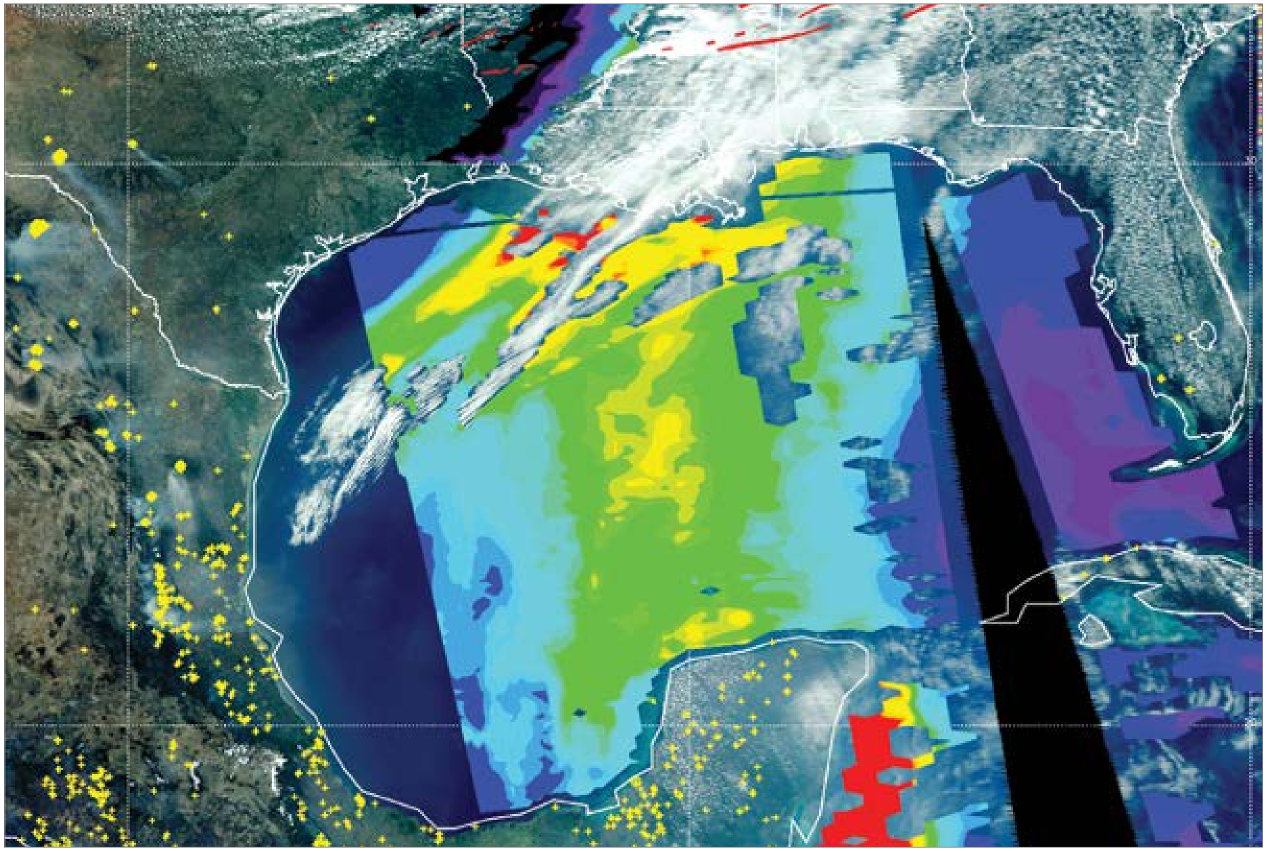
The tracks of our twisters

Forecast models that the National Weather Service uses to predict severe weather cannot spot tornadoes. Instead of focusing on smaller regions where tornadoes form, these models keep tabs on the entire continent. To get around this limitation, Saide and his team looked for weather that accompanies tornadoes, the same conditions used in tornado forecasts. Low clouds blanketing the sky and a lot of low altitude wind shear are often spotted before strong tornado outbreaks, for instance.

Next, they fed the smoke data through a weather forecast model that also forecasts air quality by accounting for particles and gases. "The cool thing about this model is that it can represent interactions between aerosols and weather," Saide said. They ran simulations, with and without smoke, to see if smoke and soot were affecting the conditions where tornadoes formed. Indeed they were and for the first time they could see how.

Slow and low

Saide said, "It was hard to convince people this is actually happening." How clouds and sunlight interact with aerosols is still a big question in climate science. But no previous study had looked at the same conditions used to predict tornadoes. By doing so, the team found that smoke affects precisely where, when, and how much energy is released as tornadoes. The air



This image shows conditions captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Aqua satellite on April 27, 2011 over the southeastern United States, Central America, and the Gulf of Mexico. Tornado tracks from local reports for April 26 to 28, 2011 were obtained by the National Oceanic and Atmospheric Administration (NOAA) Storm Prediction Center and are shown as red lines (upper right). The background is a true color image of clouds and smoke, with yellow showing fire emissions, and with a cloudy overlay showing aerosol optical depth (AOD). Red, green, and purple indicate high (1.0), medium (0.6), and low (0.1) AOD values. (Courtesy B. Pierce, NOAA NESDIS STAR)

masses carrying smoke and soot aerosols reflect heat more efficiently, and that causes the temperature difference between the front air masses to be much sharper.

Scott Spak, a researcher at the University of Iowa, said, "We found that smoke causes the tornadoes to wait just a little longer until the situation becomes just a little more unstable."

That waiting creates a lower cloud base. It in turn changes the difference in wind between the surface and the cloud level from which tornadoes come down.

Like winding up a spring, that lower cloud base traps even more spinning wind beneath it. "You're compressing the building of energy," Spak said, "and the fact that there's more wind shear means you have more likelihood of forming a twister rather than just different wind at different levels." The result is a lot of power waiting to be unleashed.

Smoke and forecasting

These findings have explained how smoke can play a role in forming tornadoes, and are novel in that they were the first to come from a real-world case study, but Saide cautions that it is just one study. He is repeating this exercise for multiple outbreaks over multiple years to see if the results are similar to those of the April 27, 2011 outbreak.

Saide said, "We get at this tornado likelihood kind of indirectly by using environmental conditions." Their plan is to run the model at a higher resolution to capture conditions directly. "If we continue to find that these interactions are important, we need to add aerosol interactions to weather forecasting," he said.

For timely results, weather prediction models need to run in hours, however, and the team's current model takes days. Finding simpler aerosol models that still yield good results is a big priority.

"What I find really exciting is that we're starting to understand just how important such tiny particles can be," Saide said.

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

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About the remote sensing data

Satellites	Terra and Aqua	Terra and Aqua	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)
Sensors	Moderate Resolution Imaging Spectroradiometer (MODIS)	MODIS	Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), Imaging Infrared Radiometer (IIR), Wide Field Camera (WFC)
Data sets	Aerosol Product (MYD04), Cloud Product (MOD06_L2), Geolocation Fields (MOD03, MYD03)	Thermal Anomalies and Fire (MOD14 and MYD14)	CALIOP Level 3 Aerosol Profile
Resolution	1 kilometer	1 kilometer	0.1 degree
Parameters	Aerosol optical depth, cloud optical depth, geolocation data	Fires and biomass burning	Plume heights
DAACs	NASA MODIS Level 1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (MODAPS LAADS DAAC)	NASA Land Processes DAAC (LP DAAC)	NASA Atmospheric Science Data Center DAAC (ASDC DAAC)

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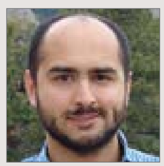
About the scientists

Brad Pierce is a scientist at the Center for Satellite Applications and Research, a branch of the National Oceanic and Atmospheric Administration National Environmental Satellite, Data, and Information Service (NOAA NESDIS). His research interests include global and regional air quality forecasting, trace gas and aerosol satellite data assimilation, satellite visibility retrieval, and stratospheric intrusions. (Photograph courtesy B. Pierce)



Pablo Saide is an engineer at the National Center for Atmospheric Research. His research interests include atmospheric sciences and chemistry, particularly regional weather, and air quality modeling and forecasting. NASA, the U.S. Environmental Protection Agency, the National Institutes of Health, NOAA, and the Fulbright-CONICYT scholarship program in Chile supported his research. (Photograph courtesy P. Saide)

Scott Spak is an assistant professor at the University of Iowa. His research interests include aerosol impacts on climate, Earth and human systems modeling, and air quality. Read more at https://goo.gl/0GxJYx. (Photograph courtesy S. Spak)

For more information

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NASA MODIS Level 1 and Atmosphere Archive and Distribution System DAAC (MODAPS LAADS DAAC)
https://ladsweb.nascom.nasa.gov

Tracking the itinerant

"I love the idea that you can measure this world."

Nikita Zelensky
Stinger Ghaffarian Technologies

by Agnieszka Gautier

The largest recorded iceberg, Iceberg B-15, rivaled Connecticut in size when it calved from Antarctica's Ross Ice Shelf in March 2000. Giant chunks eventually wandered into the Southern Ocean. Twelve years later it was gone. Ice shelves secure glaciers in place. Both birth icebergs as a natural process, much like shedding dead skin cells, but ice shelf calving does not add to sea level rise because its ice already floats in water. Glacier calving and melting, however, account for half of sea level rise by draining ice from land to ocean. When ice shelves collapse, glaciers speed up, dumping more ice into the ocean.

Warming waters yield the other half of sea level rise. Like mercury in a thermometer, water expands as it warms. Sea levels climbed faster in the twentieth century than in the previous 3,000 years, and are accelerating. Conservative sea level estimates foresee a one- to four-foot rise by the year 2100, with the last twenty-four years of satellite measurements averaging an annual

Iceberg B-15A floats in the Ross Sea, Antarctica. Iceberg B-15A is a fragment of the much larger iceberg (B-15) that broke away from the Ross Ice Shelf in March 2000. (Courtesy J. Landis, National Science Foundation)

3.4-millimeter global rise. Monitoring rates of change in millimeters requires precise measurements. "To model that you have a simple approximate for a very complex reality," said Nikita Zelensky, a chief scientist at Stinger Ghaffarian Technologies. Measuring a moving, bulging ocean is no easy task. How do scientists get accurate sea level measurements?

Caught in a drift

One task of altimeter satellites is measuring sea surface height, which can get down to the centimeter, but for scientists to use that precise measurement, they need to know the satellite's location at all times. To know that scientists have to understand Earth's atmosphere and refraction, and factor in a satellite's shape and reflective properties. They have to know the laws of physics that allow a satellite to orbit Earth and how a myriad of forces—ocean tides, moon and sun perturbations, and solar photon pressure—impact it over time. More nuanced forces like Earth's heating and cooling also act on the satellite. "That's a whole family of unruly relatives we're trying to better understand," Zelensky said. But gravity is the kicker.

Earth's gravity field reflects Earth's mass distribution, which gets rattled by the global water cycle, movement in the atmosphere, and mass transport in the ocean. "What we're concerned about is how accurately we model the variations in Earth's gravity field over time," said Frank Lemoine, a geodesist with NASA. To measure ocean surfaces, scientists use an idealized Earth that averages gravitational pull. Gravity, like water, shifts. The ocean stirs continuously. It rises and falls with tides and currents, while changes in winds and salinity, or density, fluctuate currents. Temperature change is not uniform

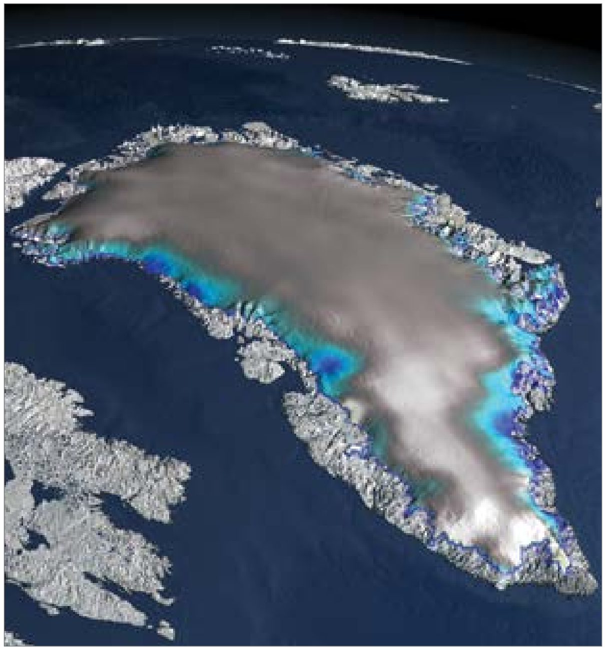
The Mount Stromlo Satellite Laser Ranging (SLR) facility in Canberra, Australia is part of a worldwide network of SLR stations. (Courtesy M. Ames)

around the globe, so parts of the ocean will warm faster than others, causing sea levels to rise disproportionately.

Altimeter satellites easily measure these changes by calculating sea surface height from a stable reference point, Earth's center of mass. "But one of the challenges of using altimeter data from any satellite is to compute where the satellite is as a function of time," Lemoine said. Because altimeter satellites measure the radar pulse bounce from satellite to ocean surface in centimeters, knowing their precise location is critical. The challenge has been in determining Earth's center of mass—a nuanced, fickle point because of continuous mass redistribution on Earth's surface.

Earth is also not perfectly round. Squished at the poles, Earth bulges at its midsections. Beyond that, its crust is dynamic, jolted by earthquakes, while also slowly rebounding from the last Ice Age when giant ice sheets crept over the Northern Hemisphere, deforming the ground. So scientists use a theoretical sphere, a geoid, which maps the lands and oceans under the influence of Earth's gravity. But gravity does not pull everywhere equally, turning the geoid into a bumpy ball.

"The paradox is that to use altimeter satellites to monitor our changing Earth, in particular ocean state changes, this Earth dynamically affects how accurately we can compute the satellite orbit," Lemoine said. Defining Earth's center of mass is



This visualization from the Ice, Cloud, and land Elevation Satellite (ICESat) shows changes in elevation over Greenland. ICESat's precise elevation change measurements, combined with other technologies, provide a comprehensive look at the behavior of Earth's ice sheets—critical for quantifying forecasts of sea level rise. Changes are shown between 2003 and 2006. White regions indicate a slight thickening, while blue shades indicate ice sheet thinning. Gray indicates no change in elevation. (Courtesy NASA Goddard Space Flight Center Scientific Visualization Studio)

like reaching a mirage. Earth is subtly and constantly changing shape. To measure changes in sea level, these shifts must be defined. "To measure the ocean surface, you need a stable reference frame," Lemoine said.

A calculated change

So for decades scientists have been refining the International Terrestrial Reference Frame (ITRF), a constellation of fixed reference points used to define Earth's shape. The ITRF is derived from mathematical computations that use lasers, satellites, and radio telescopes to compare measurements and edit out errors. The network includes data from a high-precision network of Global Navigation Satellite System (GNSS) receivers, Satellite Laser Ranging (SLR), a French network of precise satellite tracking instruments called DORIS, or Doppler Orbit and Radiopositioning Integrated by Satellite, and Very Long Baseline Interferometry (VLBI). When used together they increase accuracy. And an improvement to one component improves the overall ITRF.

The ITRF is the foundation of geodetic measurement accuracy. The heart of sea level measurements lies in precise orbit determination (POD), which relies on the ITRF's tracking stations to measure the exact location of a satellite relative to the Earth's center of mass. Each system within the ITRF has its strengths and weaknesses. For example, SLR ranging stations do not have good geographic coverage. They are mostly in the Northern Hemisphere, mostly on continents, and they do not pierce clouds well. DORIS complements SLR.

"When you have DORIS and SLR, for precise orbit determination, we see a good marriage providing much better orbit," Zelensky said. DORIS peppers a series of beacons on Earth, and each beacon transmits two frequencies. Altimeter satellites such as TOPEX/Poseidon and Jason-3 have receivers that measure the change in each frequency, thus calculating the satellite's velocity. Though the measurement is not as strong as SLR, it has a strong network geometry and functions in all types of weather.

Orbit error from POD is the largest component of sea level measurement inaccuracy. Altimeter satellites Jason-2 and Jason-3 have already reduced their orbit error to 1 centimeter (0.39-inch). So Zelensky focused on SARAL (Satellite with ARgos and ALtiKa), a French/Indian altimeter that maps the sea surface. SARAL contributes to the ITRF as part of the DORIS satellite constellation. If Zelensky could reduce SARAL's orbit error to 1 centimeter, the ITRF could get a boost. "I think we're pretty much there," Zelensky said. To get there Zelensky and Lemoine used DORIS and SLR to better locate the receiver on SARAL. Knowing its shape and placement allowed them to include that geometry into models.

Infinite quest

Lemoine and Zelensky also wanted to improve the DORIS component of the ITRF. Every time a satellite moves over a beacon, DORIS measures the shift, revealing where the satellite is but also where that fixed reference on the surface of Earth begins. Zelensky and Lemoine had to account for a multitude of minute details. The geometrical shape of the satellite and where on the satellite the receiver actually resides make a difference in the calculations, as does the location of the face center, or height, on ground antennas. Even the delay of a signal as it travels through the atmosphere had to be corrected. The researchers' efforts resulted in better station coordinates over a 22-year period to be added to an updated ITRF.

The ITRF gets adjusted every few years. A new realization was released earlier this year, extending the time span from 1979 to 2015, and providing more reference points with more accurate models that track station coordinates. "The ITRF is almost out of date the day it is created because there is a lag—time it takes to analyze the data—so it can be used for a while, a couple of years, but then the predictions degrade," Lemoine said. Every time it gets reanalyzed a community of people implement improvements over the longest time series possible. For DORIS and SLR data, which are both archived at the NASA Crustal Dynamics Data Information System (CDDIS), the data stretch back to 1990 and 1976, respectively.

"The whole process of doing precision orbit modeling, whether it is for precise determination of altimeter satellites, figuring out where they are, or for determining fixed points on the ITRF, is a tremendously multi-disciplinary problem," Lemoine said.

According to Pythagoras, a sixth century BCE philosopher and teacher, numbers are the essence and source of all things. Scientists continue to embrace mathematics to unlock the mysteries of the world. "I love the idea that you can measure this world. Through abstraction and mathematical modeling we have a window at better describing Earth," Zelensky said.

Since ITRF stations are glued to Earth's shifting crust, the ITRF needs to be continuously updated. "The problem is never going to go away, and the demands on accuracy are only going to increase," Lemoine said. Though satellites help see the world, it is up to scientists to do the math.

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

About the data

Platforms	Satellite Laser Ranging stations	Doppler Orbit and Radiopositioning Integrated by Satellite (DORIS)
Data set	Satellite Orbit Predictions	
Spatial extent	Bounding rectangle: (90.0 degree, -180.0 degree, -90.0 degree, 180.0 degree)	
Temporal coverage	1976 to present	1990 to present
Temporal resolution	1 day	1 day and multi-day
Parameters	Orbit predictions	Precise orbit determination
DAAC	NASA Crustal Dynamics Data Information System (CDDIS)	NASA CDDIS

About the scientists

Frank Lemoine is a scientist at NASA Goddard Space Flight Center in Greenbelt, Maryland. His research interests include the analysis of space geodesy data for precise orbit determination, the determination of mean sea level, and determination of the International Terrestrial Reference Frame. NASA supported his research. Read more at https://goo.gl/j1ZtQg. (Photograph courtesy F. Lemoine)

Nikita Zelensky is a scientist in the Geodynamics Department at Stinger Ghaffarian Technologies, Inc., in Greenbelt, Maryland. His research interests include satellite geodesy and celestial mechanics, focusing on precise orbit determination of altimeter satellites. NASA supported his research. (Photograph courtesy N. Zelensky)

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http://ids-doris.org
International Laser Ranging Service (ILRS)
http://ilrs.gsfc.nasa.gov
International Terrestrial Reference Frame
http://itrf.ign.fr

Crisis in the Crescent

"When agriculture collapsed in Syria, there was a real dearth of cultivation."

Colin P. Kelley
The Center for Climate and Security

by Laura Naranjo

The Tigris and Euphrates Rivers tumble down the mountains of Turkey, crossing Syria and Iraq as they meander toward the Persian Gulf. Together, the rivers irrigate the Fertile Crescent, an arc of rich land that fostered Mesopotamian and Middle Eastern cultures. For thousands of years, through the rise and fall of civilizations, the Fertile Crescent flourished as an oasis of arable land amid bone-dry deserts.

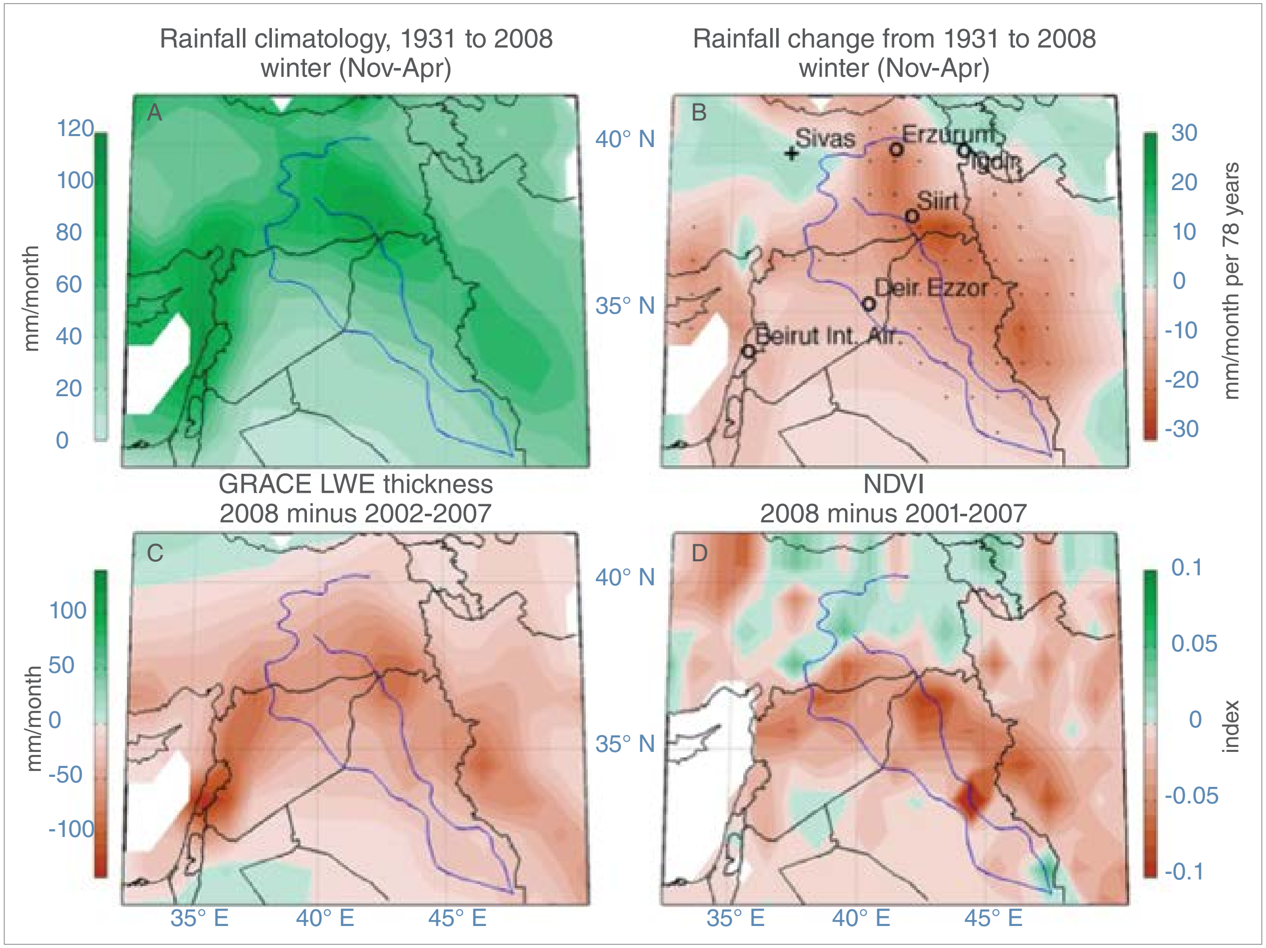
By the twentieth century, however, even this fertile region began to dry out. Much of the Middle East now struggles under the weight of political unrest, warfare, and population pressures that

A Bedouin shepherd tends his sheep amid a parched landscape in Syria. (Courtesy J. Werner) have stressed water supplies. At the same time, rising temperatures and persistent drying are transforming the region's story from one of richness and fertility to one of sand and dust. Could a concurrence of climate phases coupled with a long-term drought spell the end of the Fertile Crescent? Two scientists approach the problem from opposite directions, only to reach similar conclusions.

Dust and drought

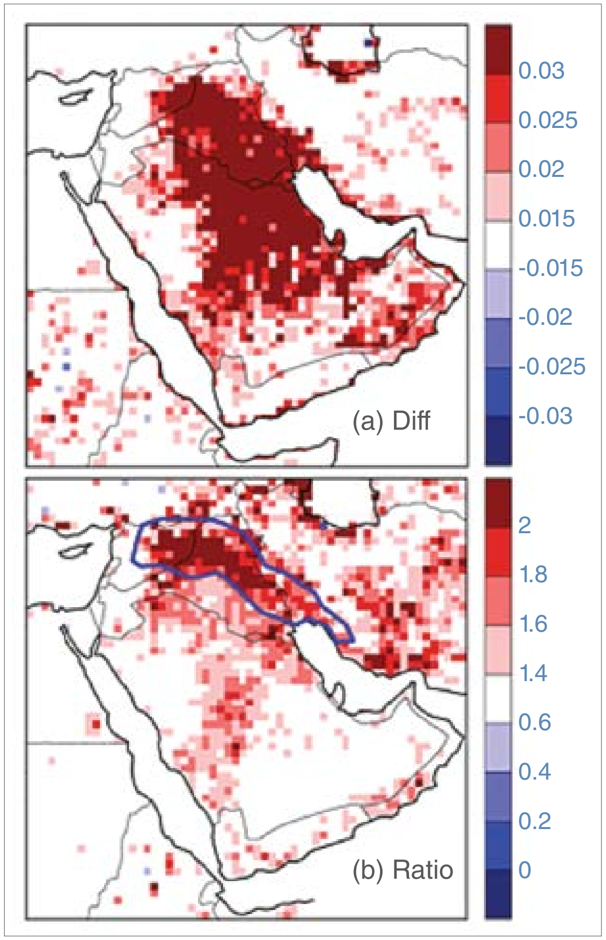
Climatologist Colin Kelley was studying rainfall across the Mediterranean when he spotted extensive drought in Syria, at the center of the Fertile Crescent. The drought started in the winter of 2006-2007 and lasted for three years, preceding the 2011 Syrian uprising. Kelley pivoted to study the Syrian drought. "We wanted to put the drought in context," he said. This drought followed several multi-year droughts in the 1980s and 1990s, so Kelley wondered if the most recent drought punctuated the drying trend, serving as a catalyst for the uprising.

Even as modernization swept across the Middle East during the twentieth century, agricultural villages and nomadic Bedouin herders relied on rivers and wells to irrigate crops and water herds of sheep and cattle. Between 2006 and 2009, these water sources dried up, forcing farmers and shepherds to abandon their land. In addition, military operations destabilized the Middle East, and by 2010, Syrian cities had absorbed more than one million Iraqi refugees—not insignificant, considering Syria's 2010 population was 21 million. "Population growth increases the demand for water," Kelley said. By the 2011 uprising, drought, national policies, and a swelling refugee population had crippled the agricultural economy in Syria.



The Fertile Crescent has been steadily drying since 1931, and recent changes have exacerbated the trend. Map A shows winter precipitation from 1931 to 2008. Map B shows winter rainfall change from 1931 to 2008. Map C shows a steep decline in groundwater between 2008 and the mean of the previous six years using data from the Gravity Recovery and Climate Experiment (GRACE) satellites. Map D shows a decline in vegetation between 2008 and the mean of the previous seven years using Normalized Difference Vegetation Index data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instrument. (Courtesy C. P. Kelly, et al., 2015, *PNAS*)

Kelley and his colleagues searched for evidence among the data. Ground measurements of agricultural production were sparse, so Kelley and his colleagues looked at imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the NASA Aqua and Terra satellites. MODIS can measure the greenness of land surfaces, as a proxy for crops and vegetation. The data revealed a decrease in vegetation abundance during the most recent Syrian drought, beginning in 2006, which corresponded with skyrocketing prices for imported wheat and rice. But changes on the surface only told part of the story. In addition to irrigation, farmers rely



These plots show the ratio of change in dust activity across the Arabian Peninsula between 2008 and 2012, compared to the time period 2001 to 2005. The blue polygon shows the area of greatest vegetation decline. Data are from the Multi-angle Imaging Spectroradiometer (MISR) satellite instrument. (Courtesy M. Notaro, et al., 2015, *Journal of Geophysical Research: Atmospheres*)

heavily on groundwater. So Kelley also needed to know whether groundwater supplies had been depleted. Again, however, ground measurements were largely unavailable, so Kelley relied on data from the Gravity Recovery and Climate Experiment (GRACE) satellites, which can detect groundwater by measuring small gravity changes. "GRACE measures actual soil moisture as well as subsurface water, including underground aquifers," Kelley said. GRACE data showed a clear decline in both surface moisture and groundwater supplies.

In addition, historical climate data revealed an unrelenting rise in temperatures across the region, which further dried out the soil and increased evaporation. "When agriculture collapsed in Syria, there was a real dearth of cultivation," Kelley said. "So all of a sudden, there's a lot more soil that's exposed to the wind." And when the shamal winds sweep in, the deserts take flight.

Dust in the wind

Beginning around 2007, researchers at King Saud University in Saudi Arabia had noticed a distinct uptick in dust storms sweeping across the Arabian Peninsula. To understand the rise, they partnered with climatologist Michael Notaro, who studies vegetation and rain in the context of global climate processes. They hoped he could help them discover the dust's origin and improve the seasonal predictability of dust activity.

The Middle East is second to the Sahara Desert as a source of sand and dust. Dust storms are nothing new here, but they have become more frequent. In April 2015, a massive dust storm billowed across the Arabian Peninsula, turning bright blue skies an ominous orange. Clouds of sandy grit enveloped entire cities, snarling traffic. Flights to the United Arab Emirates and Qatar had to be diverted or delayed. Schools in Saudi Arabia's capital, Riyadh, cancelled classes. The storm was so large that it was clearly visible from space.

Notaro and his graduate student, Yan Yu, along with Olga Kalashnikova at the NASA Jet Propulsion Laboratory (JPL) dug into the problem. At first, they discovered that there was little existing research to build on, so they attacked the problem step by step. First, they analyzed observations from ground-based meteorological stations across Saudi Arabia dating back to the mid-1970s. These data revealed that the dusty season tended to run February through June, although dust storms could batter the peninsula well into August.

Next, in collaboration with JPL, they looked at atmospheric dust, available to form these towering storms, using remote sensing. They retrieved data from the Multi-angle Imaging Spectroradiometer (MISR) instrument on the NASA Terra satellite. MISR can distinguish dust—which typically consists of non-spherical particles—from spherical particles, such as water droplets and other chemical particles in the atmosphere. This helped the researchers coax out an intriguing trend. Consistent between the MISR data and station observations, they discovered anomalously high levels of dust in the atmosphere between 2007 and 2013—coinciding with the most recent drought across the Fertile Crescent.

What caused this change? Were shifting winds kicking up more dust from the same locations, or were newly desertified regions—perhaps those in Syria—adding dust? So the researchers compiled wind trajectories for all past recorded dust events, looking backwards in time to trace where the dust came from. "The Rub' al Khali Desert in the southern peninsula is a major dust source to the peninsula," Notaro said. In Arabic, Rub' al Khali means "empty quarter," an apt description for one of the world's largest deserts. But the Rub' al Khali was not the only source. "There were also some key remote sources of dust from outside of Saudi Arabia," Notaro said. Although the Sahara Desert to the west contributed dust, the wind trajectories and MISR data both pointed to the north, where the shamal winds—a northwesterly wind from the mountains of Turkey—blew down toward the Tigris and Euphrates River basins across Syria and Iraq. "We ended up with greater dust generation and transport when the northerly winds blew out of the Fertile Crescent to the Arabian Peninsula," Notaro said.

Once Notaro and his colleagues discovered when dust storms occurred across Saudi Arabia, and where the dust came from, they needed to understand why the storms had rapidly increased. Had something converted the Fertile Crescent into a dust bowl?

A larger climate shift

"Since 1931, the whole Fertile Crescent has been experiencing a drying trend," Notaro said. Over the course of his research, he had also analyzed MODIS vegetation data for the region, and had become familiar with Kelley's research. While Kelley zoomed in to investigate groundwater, Notaro zoomed out. He suspected larger-scale climate factors might have helped trigger the drought. In particular, Notaro looked at the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), a similar but longer-term pattern that shifts between warm and cool phases over decades rather than years. When the cool phases of these related patterns are in sync, as occurred during the Fertile Crescent drought, they can amplify changes in precipitation and surface water that lead to drier conditions.

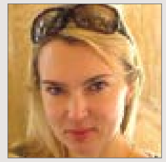
A massive sandstorm engulfs Riyadh, the capital of Saudi Arabia, on March 10, 2009. (Courtesy Associated Press)

In its positive phase, the PDO can bring more rainfall to the Mediterranean and Middle East. The Tigris and Euphrates Rivers, along with their tributaries, rely almost entirely on winter rainfall. In 2006, the PDO shifted to a negative phase, reducing rainfall across the Fertile Crescent. At about the same time, the ENSO cycle shifted from a wet El Niño phase to a drier La Niña phase. Notaro thinks synergy between the two states may have coincided with the most recent Syrian drought. "There's a very clear regime shift around 2006," he said. "When you have both La Niña and a negative PDO, they can reinforce each other." Indeed, the winter of 2007-2008 proved to be the driest in Syrian climate records.

When the wind trajectory, vegetation, and climate data were compiled, Notaro concluded that the regime shift seemed to be associated not only with drought across the Fertile Crescent, but the increase in dust storms as well. Prior to the Syrian agricultural collapse, the highest levels of atmospheric dust were contained over the Rub' al Khali Desert. Afterward, high levels of atmospheric dust extended across Syria, Iraq, and northern Saudi Arabia.

Drought, heat, population pressures, and civil unrest spread havoc across the Syrian countryside, driving farmers and shepherds to seek refuge in cities. Less agriculture led to more untended soil, and ultimately, more dust as surrounding deserts closed in. Kelley likened the situation to the 1930s Dust Bowl across the United States prairies. "Why that drought occurred and why this drought occurred is different," Kelley said. "But what we're seeing here is similar, so it's possible that these mega dust storms that occurred in the U.S. during the Dust Bowl may be what we're starting to see here."

About the scientists



Olga Kalashnikova is a research scientist at the NASA Jet Propulsion Laboratory (JPL). She uses remote sensing to study aerosol optical properties and is a member of the Multi-angle Imaging Spectroradiometer (MISR) science team. The University of Wisconsin-Madison Climate, People, and Environment Program supported her research. Read more at https://goo.gl/7SNNtJ. (Photograph courtesy O. Kalashnikova)

Colin P. Kelley is a senior research fellow at the Center for Climate and Security. His research focuses on climate variability and change, particularly drought, in semiarid and arid regions that are especially vulnerable. The Office of Naval Research, the National Oceanic and Atmospheric Administration, and the Department of Energy supported his research. Read more at https://goo.gl/X69lsc. (Photograph courtesy C. P. Kelley)

Michael Notaro is the associate director and senior scientist for the Nelson Institute Center for Climatic Research at the University of Wisconsin-Madison. He studies land-ocean-atmosphere interactions, climate change impacts on ecosystems, monsoon dynamics, and dust storm mechanisms. The University of Wisconsin-Madison Climate, People, and Environment Program supported his research. Read more at https://goo.gl/Z8ofxG. (Photograph courtesy D. M. Zimmerman)

Natural variations, such as a swing back to wetter phases of PDO and ENSO patterns, may temporarily relieve drought conditions in Syria and reduce dust storms plaguing the Arabian Peninsula. Long-term climate models, however, indicate temperatures in the region will continue to rise, in response to rising levels of greenhouse gases, and the hot, dry trend will continue. Notaro said, "This is all one big story, connecting drought, land use, agriculture, politics, and climate change."

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

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About the remote sensing data

Satellites	Terra	Terra and Aqua	Terra and Aqua	Gravity Recovery and Climate Experiment (GRACE)
Sensors	Multi-angle Imaging Spectroradiom-eter (MISR)	Moderate Resolution Imaging Spectroradiometer (MODIS)	MODIS	K-Band Ranging System
Data sets	MISR Component Global Aerosol Product	MODIS Aerosol Product (MOD04_L2 and MYD04_L2)	MODIS Vegetation Indices Monthly L3 Global 0.05Deg CMG (MOD13C2)	RL05.DSTvSCS1409 GRACE Tellus Monthly Mass Grids – Land
Resolution	0.5 degree x 0.5 degree grid	10 x 10 1-kilometer pixel array	0.05 degree (5600-meter)	4,000 x 4,000 kilometer
Parameters	Aerosol optical depth	Aerosol optical depth	Vegetation	Gravity
DAACs	NASA Atmospheric Science Data Center Distributed Active Archive Center (ASDC DAAC)	NASA MODIS Level 1 and Atmosphere Archive and Distribution System DAAC (MODAPS LAADS DAAC)	NASA Land Processes DAAC (LP DAAC)	NASA Physical Oceanography DAAC (PO.DAAC)

and Science (EROS) Center, Sioux Falls, SD (https://lpdaac.usgs.gov), at https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod13c2.

Notaro, M., Y. Yu, and O. V. Kalashnikova. 2015. Regime shift in Arabian dust activity, triggered by persistent Fertile Crescent drought. *Journal of Geophysical Research: Atmospheres* 120: 10,229–10,249. doi:10.1002/2015JD023855.

Swenson, S.C. 2012. GRACE monthly land water mass grids NETCDF Release 5.0 PO.DAAC, CA, USA. doi:10.5067/TELND-NC005.

Vose, R. S., R. L. Schmoyer, P. M. Steurer, T. C. Peterson, R. Heim, T. R. Karl, and J. K. Eischeid. 1998. Global Historical Climatology Network, 1753–1990. ORNL DAAC, Oak Ridge, TN, USA. doi:10.3334/ORNLDAAC/220.

About the data

Platforms	Temperature, sea level, and pressure stations	
Data sets	Global Historical Climatology Network, 1753-1990	NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA)
Resolution		0.5 degree x 0.66 degree grid
Parameters	Temperature, precipitation, sea level pressure, and station pressure	850 hPa v-wind, humidity and 500 hPa vertical motion
DAACs	NASA Oak Ridge National Laboratory DAAC (ORNL DAAC)	NASA Goddard Earth Sciences DAAC (GES DAAC)

For more information

NASA Atmospheric Science Data Center Distributed Active Archive Center DAAC (ASDC DAAC)
https://eosweb.larc.nasa.gov

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

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

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

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

NASA Physical Oceanography DAAC (PO.DAAC)
http://podaac.jpl.nasa.gov

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

NASA Multi-angle Imaging Spectroradiometer (MISR)
http://terra.nasa.gov/about/terra-instruments/misr

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

Global Historical Climatology Network (GHCN)
http://daac.ornl.gov/CLIMATE/guides/CDIAC_NDP41.html

NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA)
http://gmao.gsfc.nasa.gov/merra

About the NASA Earth Observing System DAACs

Alaska Satellite Facility Distributed Active Archive Center (DAAC)

SAR Products, Change Detection, Sea Ice, Polar Processes, Terrestrial Ecology, Geophysics
Geophysical Institute, University of Alaska Fairbanks
Fairbanks, Alaska
+1 907-474-5041
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https://www.asf.alaska.edu

Atmospheric Science Data Center DAAC

Radiation Budget, Clouds, Aerosols, Tropospheric Chemistry
NASA Langley Research Center
Hampton, Virginia
+1 757-864-8656
https://eosweb.larc.nasa.gov

Crustal Dynamics Data Information System

Space Geodesy, Solid Earth
NASA Goddard Space Flight Center
Greenbelt, Maryland
+1 301-614-6542
Carey.E.Noll@nasa.gov
http://cddis.gsfc.nasa.gov

Global Hydrology Resource Center DAAC

Hydrologic Cycle, Severe Weather Interactions, Lightning, Atmospheric Convection
NASA Marshall Space Flight Center
Huntsville, Alabama
+1 256-961-7932
support-ghrc@earthdata.nasa.gov
https://ghrc.nsstc.nasa.gov

Goddard Earth Sciences DAAC

Global Precipitation, Solar Irradiance, Atmospheric Composition and Dynamics, Water and Energy Cycle, Global Modeling
NASA Goddard Space Flight Center
Greenbelt, Maryland
+1 301-614-5224
gsfc-help-disc@lists.nasa.gov
http://disc.sci.gsfc.nasa.gov

Land Processes DAAC

Surface Reflectance, Radiance, and Temperature; Topography; Radiation Budget; Ecosystem Variables; Land Cover; Vegetation Indices
U.S. Geological Survey Earth Resources Observation and Science (EROS) Center
Sioux Falls, South Dakota
+1 605-594-6116, +1 866-573-3222
LPDAAC@usgs.gov
https://lpdaac.usgs.gov

MODIS Level 1 and Atmosphere Archive and Distribution System DAAC

MODIS Radiance and Atmosphere
NASA Goddard Space Flight Center
Greenbelt, Maryland
+1 800-596-8132
modapsuso@lists.nasa.gov
https://laadsweb.nascom.nasa.gov

National Snow and Ice Data Center DAAC

Snow, Sea Ice, Glaciers, Ice Sheets, Frozen Ground, Soil Moisture, Cryosphere, Climate Interactions
University of Colorado Boulder
Boulder, Colorado
+1 303-492-6199
nsidc@nsidc.org
http://nsidc.org/daac

Oak Ridge National Laboratory DAAC

Biogeochemical Dynamics, Ecological Data, Environmental Processes
Oak Ridge National Laboratory
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+1 865-241-3952
uso@daac.ornl.gov
http://daac.ornl.gov

Ocean Biology DAAC

Ocean Biology, Sea Surface Temperature
NASA Goddard Space Flight Center
Greenbelt, Maryland
http://oceancolor.gsfc.nasa.gov

Physical Oceanography DAAC

Gravity, Sea Surface Temperature, Sea Surface Salinity, Ocean Winds, Ocean Surface Topography, Ocean Circulation, Ocean Currents
NASA Jet Propulsion Laboratory
Pasadena, California
podaac@podaac.jpl.nasa.gov
http://podaac.jpl.nasa.gov

Socioeconomic Data and Applications Center

Human Interactions, Land Use, Environmental Sustainability, Geospatial Data
CIESIN, Earth Institute at Columbia University
Palisades, New York
+1 845-365-8920
ciesin.info@ciesin.columbia.edu
http://sedac.ciesin.columbia.edu

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