

Landsat

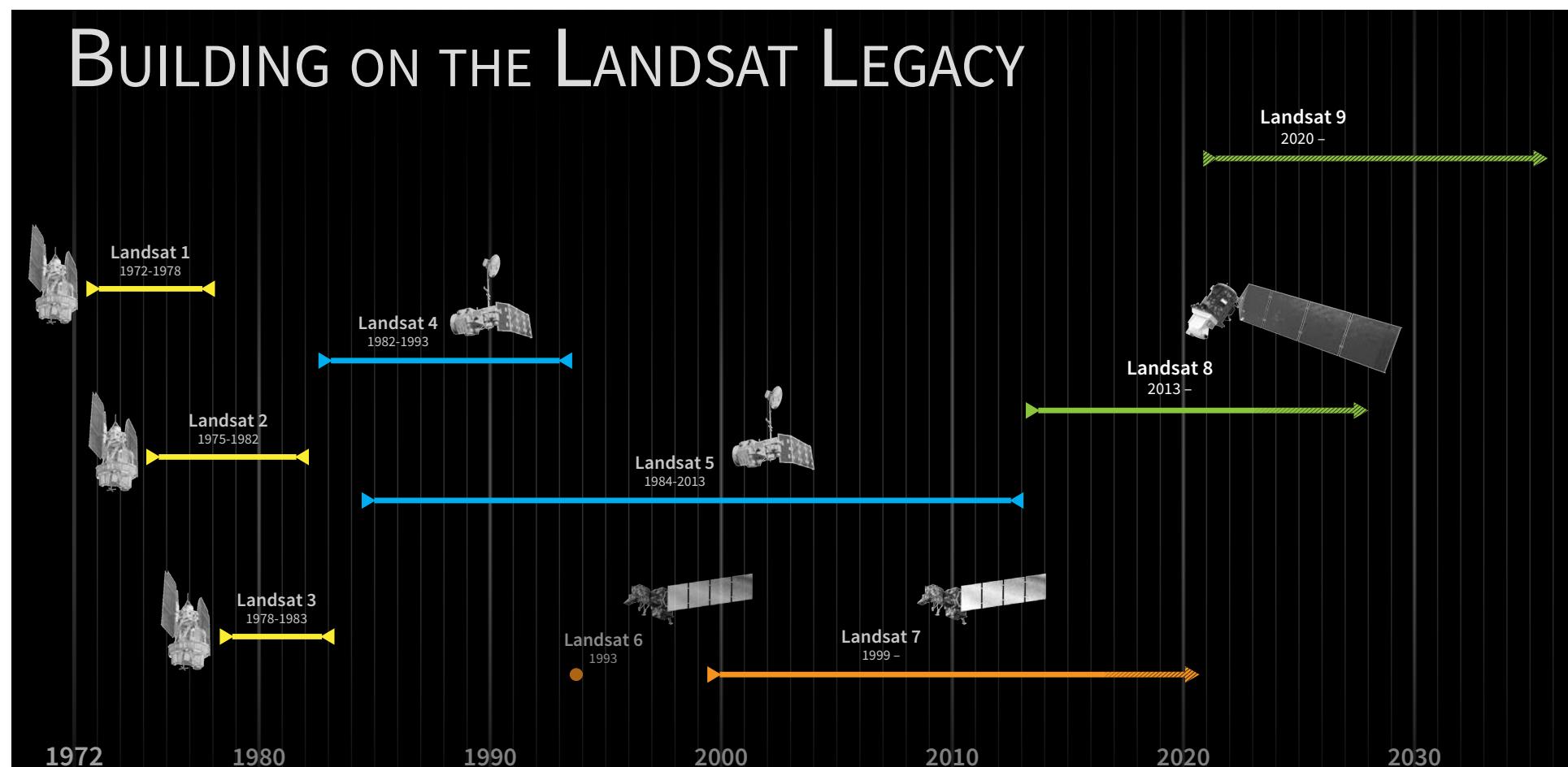
Benefiting Society for Fifty Years

Since 1972, data acquired by the Landsat series of satellites have become integral to land management for both government and the private sector, providing scientists and decision makers with key information about agricultural productivity, ice sheet dynamics, urban growth, forest monitoring, natural resource management, water quality, and supporting disaster response.

Landsat 9 continues the mission of unrivaled space-based Earth observation and will lead the Landsat program into its second half century of Earth imagery provided to users, worldwide, at no charge. More than 8 million Landsat scenes held in the USGS archive to date are used in conjunction with advanced geographic information systems, image processing software, and cloud computing capabilities to enable Landsat users to study changes on the Earth's surface across continental regions and extended time periods.

The Operational Land Imager 2 (OLI-2) and the Thermal Infrared Sensor 2 (TIRS-2) instruments onboard Landsat 9—which replicate the technologically-advanced instruments introduced onboard Landsat 8—allow for the collection of continuous high-quality data required for advancing Earth applications, including our ability to map surface temperature and surface water quality.

Landsat 9 will build on the Landsat legacy, achieving a half-century record of global Earth observations.



Landsat, Benefiting Society for Fifty Years

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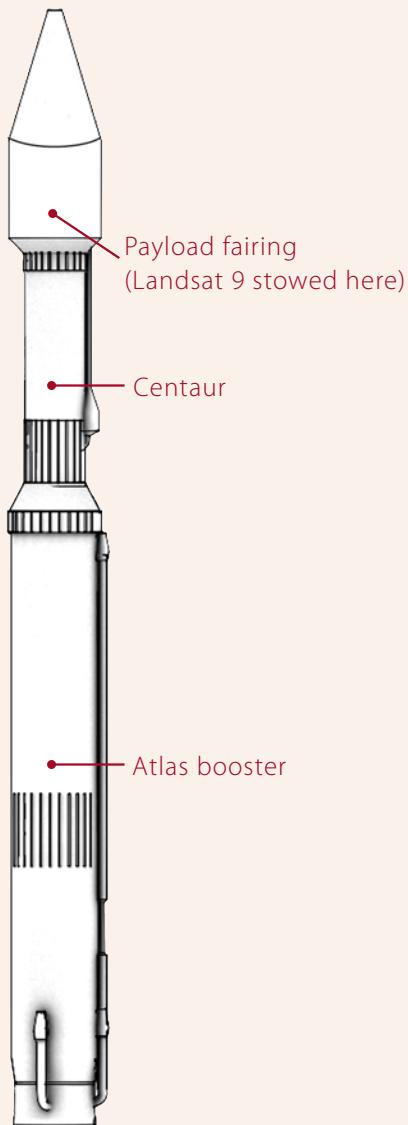
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Landsat 9 Hardware

Launch Vehicle

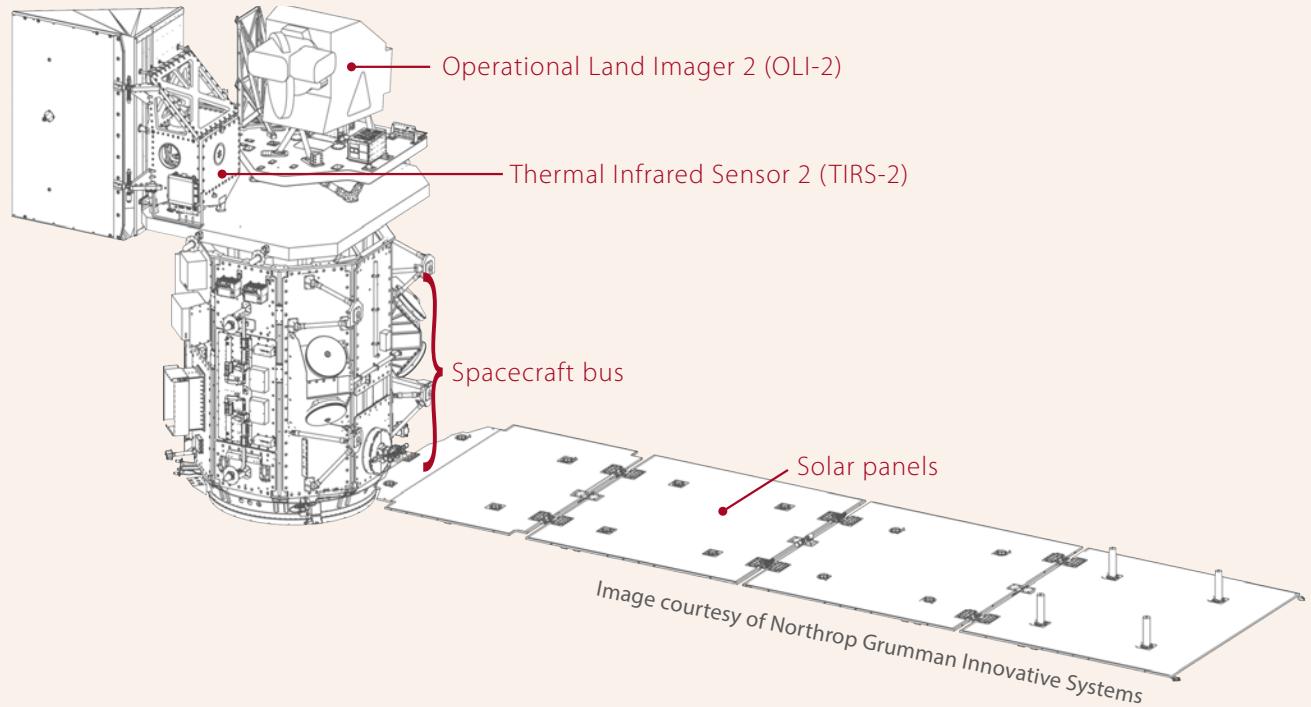
The Landsat 9 observatory will launch on an Atlas V 401 rocket from Space Launch Complex 3E at Vandenberg Air Force Base, California.



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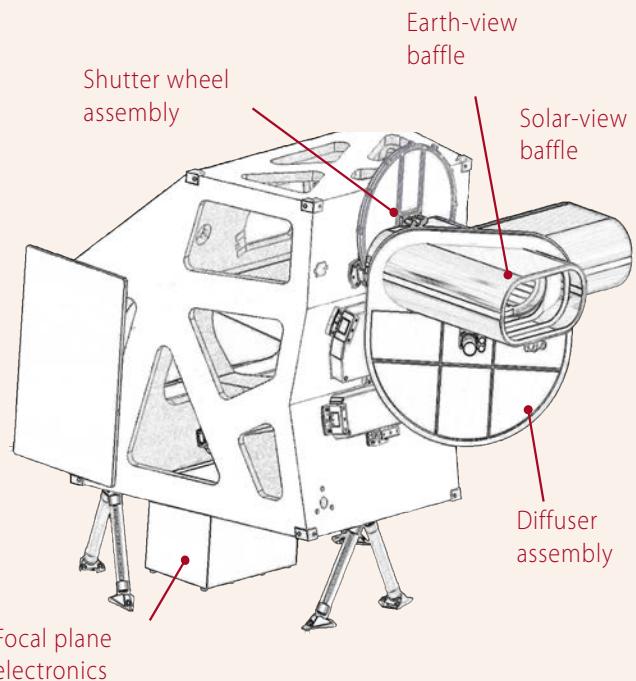
Spacecraft

The Landsat 9 spacecraft, built by Northrop Grumman Innovation Systems, supplies power, orbit and attitude control, communications, and data storage for the OLI-2 and TIRS-2 instruments. The spacecraft consists of the mechanical subsystem (primary structure and deployable mechanisms), command and data handling subsystem, attitude control subsystem, electrical power subsystem, radio frequency (RF) communications subsystem, the hydrazine propulsion subsystem, and thermal control subsystem.



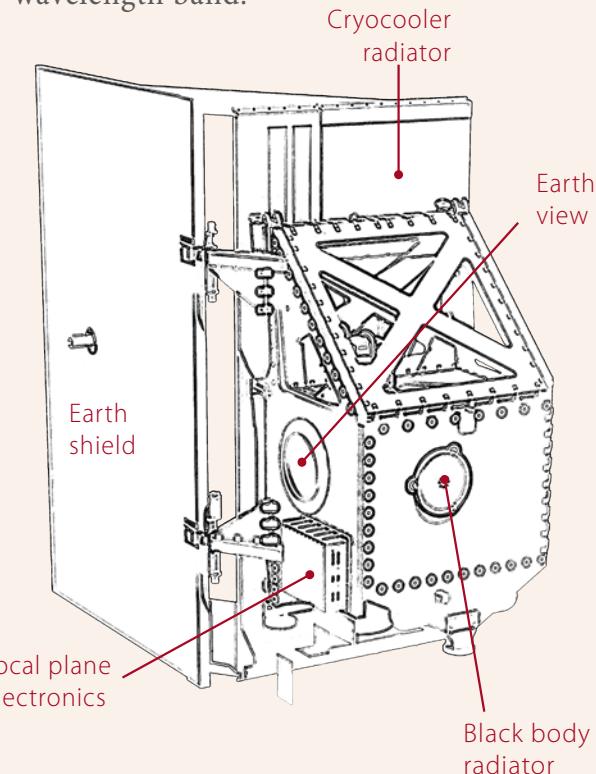
OLI-2

The Operational Land Imager-2 (OLI-2), built by Ball Aerospace & Technologies Corporation, is a push-broom sensor that uses long detector arrays, with over 7,000 detectors per spectral band, to image a 185-kilometer (115-mile) orbital swath. OLI-2 collects data in 15-meter panchromatic and 30-meter multispectral spatial resolutions. The OLI-2 instrument on Landsat 9 is a near-copy of the Landsat 8 OLI instrument, and, like Landsat 8, includes a blue coastal/aerosol band and cirrus cloud detection band that have proven useful. The OLI-2 instrument has a five-year design life.



TIRS-2

The Thermal Infrared Sensor-2 (TIRS-2) is a push-broom sensor with a 185-kilometer cross-track field of view. Its spatial resolution is 100 meters. TIRS-2 detects energy in two wavelengths of the electromagnetic spectrum dominated by thermal emission from the Earth's surface and thus can measure surface temperature. Built at NASA's Goddard Space Flight Center, TIRS-2 has a design life of five years and remedies the stray light issues that affect the Landsat 8 TIRS instrument that limited the radiometric accuracy of the longest wavelength band.





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Land conversion of the central Brazilian state of Mato Grosso from dense Amazon rain forest to pasture and agricultural lands has been well-documented by Landsat. The steady pace of forest clearing in the region is clearly shown in the natural-color Landsat 5 image acquired on April 9, 1986 (left) and the Landsat 8 image acquired on September 7, 2018 (right). Image credit: Allison Nussbaum



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Staying Alert: Spotting Deforestation with Landsat

Laura E.P. Rocchio

Forests are commodities. The biggest driver of deforestation worldwide is the economic value of trees and the land they stand on. With the high demand for agricultural land and wood products, deforestation has become an intractable problem.

To address this dilemma, the World Resources Institute, a not-for-profit, non-governmental research organization, released a Landsat-based alert system in 2016 as part of its Global Forest Watch (GFW) program. When a new road appears in the dense forests of Peru, or a baseball diamond-sized patch of forest is felled in the Republic of Congo or in Indonesia, anyone with an Internet connection can be alerted to the loss.

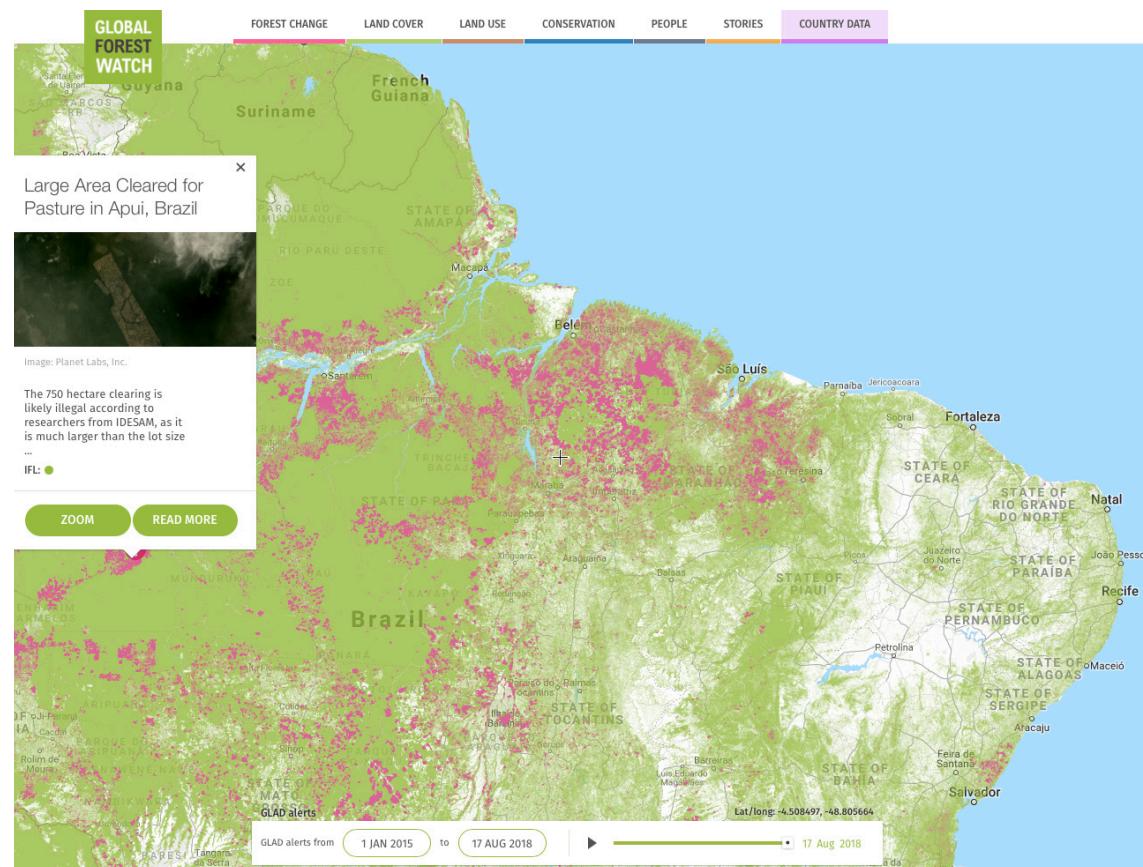
That's near-weekly alerts for changes smaller in size than a football field. That combined detail and pace makes this deforestation alert system revolutionary. Using Landsats 7 and 8 together, forests are potentially imaged every eight days. That revisit time, or data cadence, together with Landsat's 30-meter spatial resolution, allows land managers to know when small incursions into forests are being made—in time to respond before major damage has been done.

Caring about land stewardship goes beyond just forest managers. Frances Seymour, a senior fellow at the Center for Global Development, points out, "Government agencies,

civil society watchdogs, and companies trying to get deforestation out of their commodity supply chains can all use these alerts to target their efforts and mobilize quick response."

Global Forest Watch—whose goal is to provide decision makers with timely information about global forests—teamed up with the University of Maryland's Global Land Analysis and Discovery

(GLAD) team and scientist Matt Hansen to make these near-weekly alerts happen. The three essential ingredients are freely-available Landsat data distributed by the United States Geographical Survey (USGS), the Hansen-GLAD tree cover loss algorithms, and big data computing power like that of Google's Earth Engine. All of this is wrapped up and distributed via GFW's user-friendly mapping interface. ▶



Above: The protected forests of Alto Mayo, Peru. Photo credit: Bruno Locatelli, Center for International Forestry Research (CIFOR)

In-page: Pink pixels in the GFW-GLAD alerts indicate a change in forest cover. GFW provides weekly alerts as well as detailed, comprehensive yearly deforestation measurements made using Landsat data. A comprehensive view of deforestation that occurred between January 1, 2015–August 17, 2018 is shown here.

Opposite: Transporting logs along a logging road in Gunung Lumut, East Kalimantan, Indonesia. The detection of new roads in tropical forests is important since they are often a harbinger of deforestation. Photo credit: Jan van der Ploeg, CIFOR



Above: A red earthen road through an oil palm plantation in Brazil. The palm plantation replaced the native forest. Photo credit: Miguel Pinheiro, CIFOR

As of summer 2018, the GLAD alerts were tracking forest changes in 22 countries in South America, Central Africa, and Southeast Asia as well as Russia's Far East boreal forests.

Use of the alert system by stakeholders is growing. In Uganda, for example, the Jane Goodall Institute has taught government rangers how to access the GLAD alerts so they can respond to illegal deforestation events. And, the World Resources Institute has created a GLAD-based “Places to Watch” identification tool that provides a monthly list of locations where new deforestation is most concerning—like in remote undisturbed forests and protected areas.

“When old growth forests are logged, what is the legal context?” asked Hansen, “If such activity occurs in a protected area, it is likely illegal. However, official forest land use plans are lacking or not openly shared in many countries.”

That lack of transparency is a point of legitimate contention. The GLAD forest alert system increases transparency. It tracks forest exploitation, including the nascent stages—new access roads, selective tree removals—so all interested stakeholders in land use development and conservation can have the same set of facts.

“We hope the alerts stimulate improved, consensus-based planning on how remaining high-carbon-stock, high-biodiversity forests will be developed and protected,” Hansen said.

As climate change threatens humanity with destructive storms, drought, and sea level rise, tangible forest commodities (food, fuel, paper, and timber) must be weighed against the more indirect ones (carbon sequestration, biodiversity, and clean water). If the alert system can stem the exploitation of tropical old growth forests, the so-called high-carbon-stock, high-biodiversity forests where 90 percent of tree cover loss takes place, it could play a key role in keeping these forests intact and limiting their carbon emissions.

Forests and Climate Change

In December 2015, the Paris Agreement recognized the urgent need to respond to climate change and to attempt to keep global warming below 2 degrees Celsius. Drafters of the agreement specifically mentioned efforts to conserve and enhance forests for carbon mitigation.

Forests can be a carbon sink or source. At their height, the daily CO₂ emissions from the 2015 Indonesian fires, which consumed tropical forests and carbon-rich peatlands,

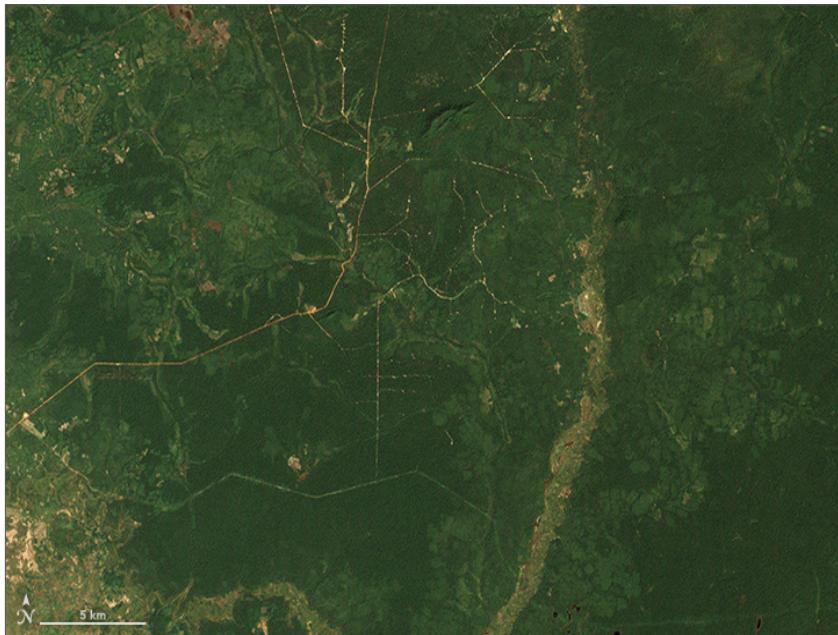
were on par with those from the daily economic activity of the entire U.S.

Policy programs like the United Nation’s Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (known as REDD+) aim to reduce emissions from tropical forests by giving intact forests an economic value—tropical nations are paid to preserve their forests (on the basis of performance). The linchpin for this type of policy concept is an accurate baseline of forest cover and an unbiased mechanism for monitoring change.

The GLAD forest alert system gives timely forest cover information to any and all stakeholders so they can work together to use forests sustainably and plan for long-term conservation, balancing their need for increased tangible forest commodities with their commitments to emission reduction. It puts tools in the hands of all levels of government, private industry, and locals keen to prevent the irreversible loss and degradation of their forests.

“There’s no question that the revolution in remote sensing technology in recent years has already had a dramatic impact on forest management throughout the tropics,” said Seymour. ▶

How Landsat Helps: FOREST MANAGEMENT



The Landsat 7 and 8 images shown here capture the immense loss of forest that took place in Cambodia between 2000 and 2015. Investment in rubber plantations has been a major economic driver behind Cambodia's rapid forest clearing. Image credit: NASA Earth Observatory

"These systems have changed the politics of forest management both within and between countries. They have empowered environmental activists and indigenous peoples to make visible what is really going on in the world's forests, and how it diverges from what is legal and sustainable."

Making GLAD Alerts Possible

The opening of the Landsat archive by the U.S. Geological Survey in 2008 was the spark that made massive operational systems like the GLAD alert system possible. In his 2016 Environmental Research Letters paper about the system, Hansen penned, "An alert system

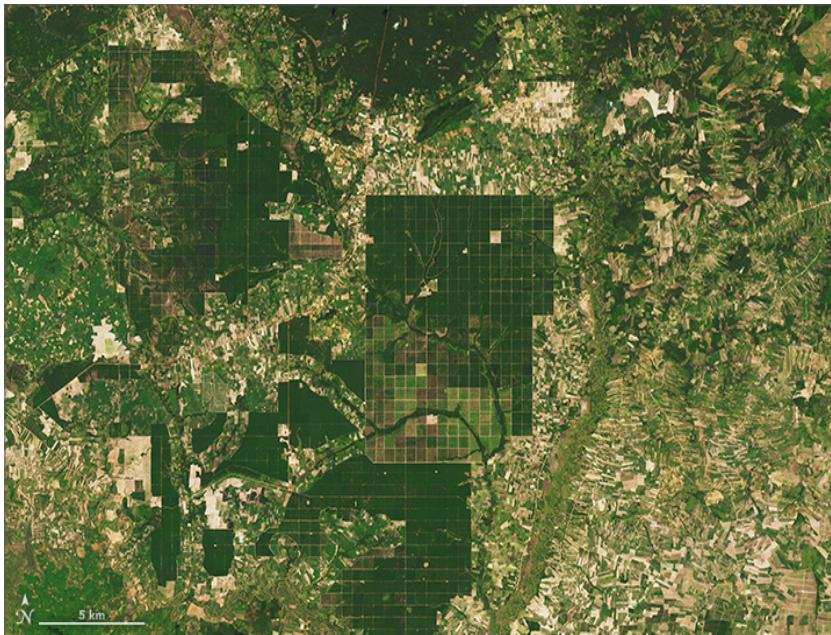
operating at the scale presented here depends on systematic global acquisitions, robust preprocessing, and free and accessible data. Only Landsat has these criteria at medium spatial resolutions, with Sentinel aspiring to emulate Landsat."

In the February 2016 issue of *Nature Climate Change*, a team of authors led by Johannes Reiche, from Wageningen University in the Netherlands, explained that the opening of the Landsat archive catalyzed important developments in forest monitoring, allowing the shift to global data time series analysis at a medium spatial resolution. Likewise, in the same publication, Douglas Morton, a research scientist at NASA Goddard, wrote: "Free

and open access to the Landsat archive has already spurred scientific innovation and provided a foundation for REDD+ monitoring, reporting and verification."

Landsat imagery is used to inform forest change assessments by a majority of tropical countries. But there are some serious limitations—cloud cover chief among them. Clouds are a persistent feature of humid tropical forests, and many Landsat data collects are obscured by cloud cover.

To counter cloud limitations, researchers have called for acquiring data more often. Greater image cadence—a faster drumbeat of data—would help dodge clouds issues. ▶



Above: A portion of the Congo River, northeast of Kinshasa. Forests provide many ecosystem services like keeping water clean. Photo credit: Ollivier Girard, CIFOR



“It’s getting harder and harder for government officials and private companies to escape accountability for deforestation that happens on their watch.”

— Frances Seymour, senior fellow at the Center for Global Development

A lumber truck near Ngon, a village in Cameroon. Photo credit: Olliver Girard, CIFOR

How Landsat Helps: FOREST MANAGEMENT

If the GLAD alerts incorporate data from the European Space Agency's Copernicus Sentinel-2 satellites together with both Landsats, the data cadence will reach a three-day repeat.

Another way to deal with persistent cloud cover is to look right through it. This is where radar could help. In their paper, Reiche and co-authors posit that an operational radar program following in the mold of Landsat is needed. Along those lines, the Brazilian Deforestation and Alert System added Sentinel-1 radar data to its workflow.

To help capture the three-dimensional structure of forests that is important for biomass measurements, upcoming lidar and radar missions such as NASA's Global Ecosystem Dynamics Investigation lidar (GEDI), NASA-ISRO Synthetic Aperture Radar mission (NISAR) and ESA's Biomass mission are currently in progress.

And lastly, being able to access fine-resolution data from commercial satellites and microsat constellations when areas of potential deforestation are found can give land managers a virtual magnifying glass for identifying hard-to-spot forest degradation.

As climate change raises the stakes, affecting the planet's health as well as ours, such an ensemble of data will give our remaining tropical forests a fighting chance.

As Seymour explained, "It's getting harder and harder for government officials and private companies to escape accountability for deforestation that happens on their watch." ■

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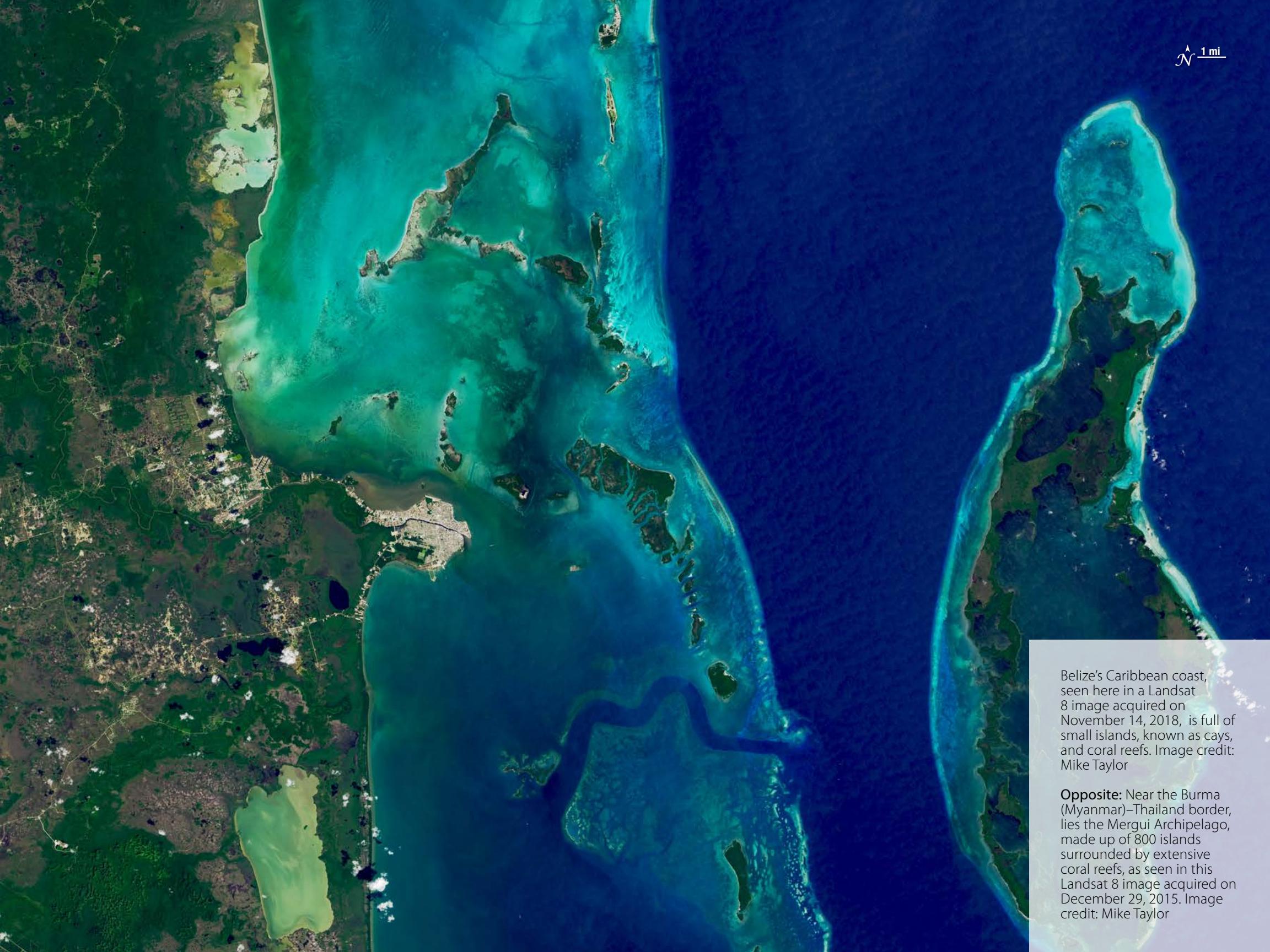
Where the farmland southeast of Salem, Missouri meets the Mark Twain National Forest. Satellites weren't watching as American settlers made their march westward denuding the virgin forest that blanketed the United States from the east coast to the Mississippi. No aerial archive shows the mighty oaks, beech trees, and hemlocks that once stood there being cleared for farmland, logged for lumber, and burned for fuel. The use and commodification of forests is an old, old story—but modern technology and climate change have greatly modified the script. Image credit: Mike Taylor

Satellite Data Requirements:

- ⌚ 8-day revisit (w/ L7)
- 📏 $\leq 30\text{ m}$ resolution
- ⚙️ Vis, NIR, SWIR, TIR
- 🛣 Continuous spatial coverage
- ⟳ Archive continuity & consistency
- ✈ Rapid delivery of free, unrestricted data
- ☒ Geolocation ≤ 0.5 pix
- 🛠 $\leq 5\%$ radiance calibration
- 👁 8-bit data digitization



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Belize's Caribbean coast, seen here in a Landsat 8 image acquired on November 14, 2018, is full of small islands, known as cays, and coral reefs. Image credit: Mike Taylor

Opposite: Near the Burma (Myanmar)-Thailand border, lies the Mergui Archipelago, made up of 800 islands surrounded by extensive coral reefs, as seen in this Landsat 8 image acquired on December 29, 2015. Image credit: Mike Taylor



Avoiding Rock Bottom: How Landsat Aids Nautical Charting

Laura E.P. Rocchio

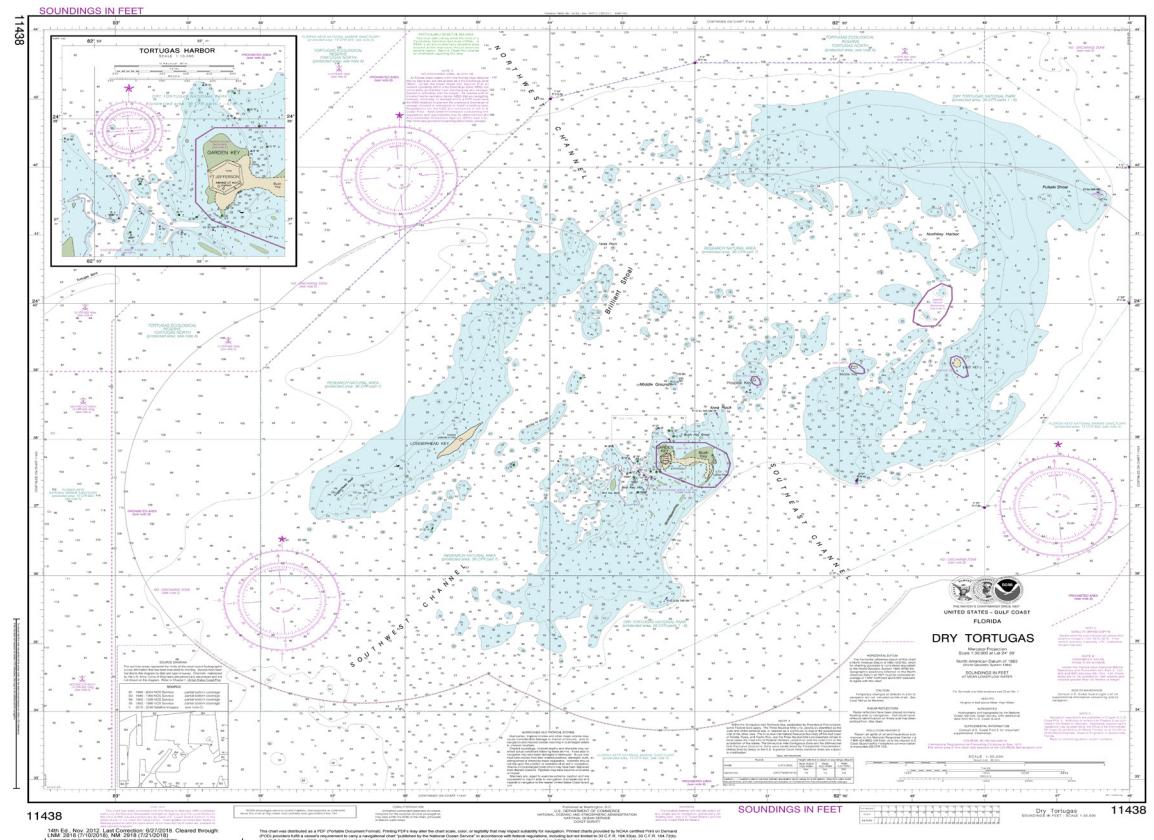
On the most recent nautical chart of the Dry Tortugas, a grouping of islands that lies seventy miles west of Key West, Florida, Landsat data provided the estimated water depths for areas too shallow and difficult to be reached by the National Oceanographic and Atmospheric Administration's (NOAA) surveying ships.

It was sometime between 1840 and 1939 that the sections of water surrounding the islands were last formally surveyed. Since that time, Dry Tortugas National Park was established and the park—along with its hundreds of shipwrecks, pristine beaches, and clear water—has become popular with recreational boat cruisers. Recent and accurate depth information is essential for boaters, especially in the shallows. Using bathymetry measurements made from Landsat between 2015 and 2016, NOAA was able to provide sailors updated depth estimates in five locations, including the area around Garden Key where the historic Fort Jefferson, a popular destination, is located. As the National Park Service tells visitors to its website, NOAA's chart of the area is "indispensable for safe boating on these waters."

In NOAA's Office of Coast Survey, the Marine Chart Division is responsible for updating the suite of over 1,000 nautical charts that keep mariners in U.S. waters safe. Their mandate covers all U.S.

territorial waters in the U.S. Exclusive Economic Zone (EEZ), a combined area of 3.4 million square nautical miles that extends 200 nautical miles offshore from the nation's coastline. The U.S. has the largest EEZ of all nations in the world but, as of 2015, it ranked behind 18 other nations in the number of vessels with

hydrographic surveying capabilities (the ability to measure and map water depths). The job is sizable and expensive. While the Army Corps of Engineers is responsible for maintaining the depth of shipping channels, providing bathymetry everywhere else in U.S. waters is NOAA's duty. ▶



Above: Chart inlay of Tortugas Harbor which surrounds Garden Key where Fort Jefferson is located. The depth measurements around the key (within the thick purple line) were made using Landsat data.

In-page: The most recent NOAA nautical chart of Florida's Dry Tortugas (Chart 11438). The purple polygons, including the area around Garden Key where Fort Jefferson is located, indicate chart regions that use Landsat-derived bathymetry as source data.

Opposite: Recreational boaters anchored off of Fort Jefferson. The fort, located on Garden Key in the Dry Tortugas National Park, Florida, is a popular destination for cruisers.

Photo credit: Varina Patel



Above: Close-up of Bechevin Bay from NOAA Chart 16520: "Unimak and Akutan Passes."

Keeping waterways safe is a massive undertaking

The responsibilities of NOAA's Marine Chart Division are immense. Charged with providing accurate charts for mariners, NOAA cartographers need to know when existing charts are out-of-date. To determine if charts are current, they employ lots of tools. They monitor navigation hazard reports submitted by mariners; they watch ship traffic patterns using vessel positioning information (via the Automatic Identification System); and, more and more, they are turning to satellites like Landsat for information.

The field of Satellite Derived Bathymetry (SDB), has been around for nearly a half century, but the advent of free Landsat data in 2008 together with the 2013 launch of the more-advanced Landsat 8 satellite, and a shift in thinking about SDB products, have led to a reinvigorated use of satellite data in NOAA's Marine Chart Division.

The concept of SDB is that shorter wavelengths of light penetrate water to differing degrees. The smaller wavelengths (e.g. blue and green light) penetrate water more than longer wavelengths (e.g. near infrared, shortwave infrared). When water is clear and the seafloor bottom is bright (e.g. sandy), estimates of depth

can be made by modeling the depth of light penetration based on the amount of reflectance measured by the satellite. And when multiple visible-wavelength spectral bands are used together, the effects of seafloor reflectance variability and water turbidity are lessened. However, these modeled depth measurements typically do not meet hydrographic accuracy standards, so in the past SDB measurements were eschewed.

"There's been a shift in the way we think," explained Lieutenant Anthony Klemm, an Operations Officer on the NOAA hydrographic surveying ship *Thomas Jefferson* and a former NOAA Corps Officer with the Office of Coast Survey's Marine Chart Division. "In the past, if a measurement wasn't made by the Army Corps or a NOAA survey ship, we didn't want to use it, but now we are opening up to other technologies to evaluate the health of our current chart suite."

Because of this sea change in thinking and faced with the daunting job of deciding which charts were most in need of updating, NOAA hydrographers revisited the use of SDB using freely available satellite data such as Landsat as a viable tool to help them do their jobs.

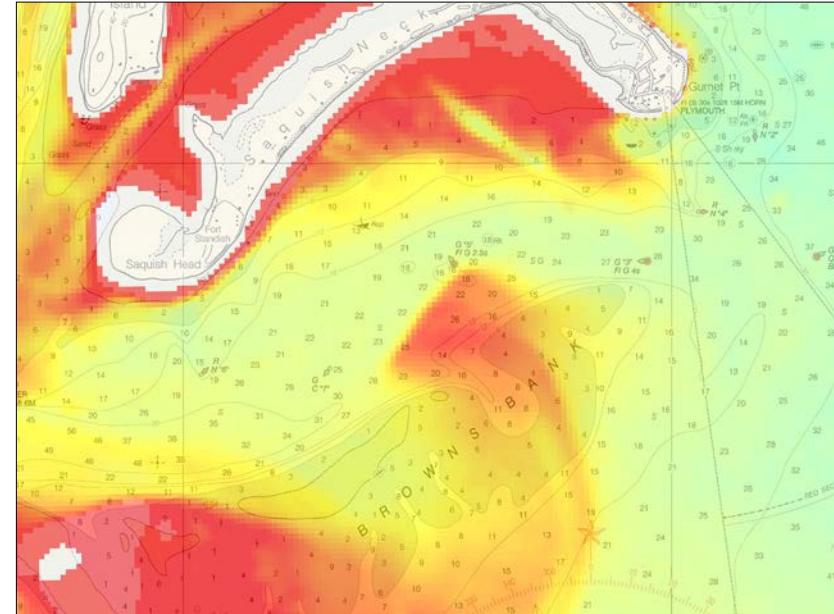
"NOAA has now been using Landsat imagery for chart adequacy assessment

and mission planning," said Shachak Pe'eri, Branch Chief of the NOAA Chart Standards Group and a Research Professor at the Joint Hydrographic Center at the University of New Hampshire.

The Joint Hydrographic Center, a think-tank of researchers investigating technology and mapping challenges in NOAA's Office of Coast Survey, realized that Landsat SDB could be an important reconnaissance tool. A single Landsat image is about 100 nautical miles across and affords a wide overview of a coastal area. Maps of SDB can be compared with existing nautical charts. Places where depth patterns do not match are more closely examined. Has the seafloor changed in this area? If an area looks shallower than what is presented in the chart and if there is a reasonable amount of vessel traffic or corroborating mariners' reports in the area, the chart location is tagged as a higher-priority candidate for hydrographic mapping—i.e. sending out a hydrographic ship to make depth measurements using sonar (multi-beam or single-beam).

Multi-beam sonar provides very accurate and comprehensive bathymetry, but for the amount of water NOAA is responsible for charting, these expensive ships are in short supply. ▶

How Landsat Helps: BATHYMETRY



A Landsat 8 image showing the location of Massachusetts' Plymouth Bay (left). The right image shows Satellite Derived Bathymetry measurements overlaid on a chart of Plymouth Bay. The red indicates shallow waters. Here, the SDB indicates that the shoaling of Brown's Bank has shifted since the chart's creation.

Klemm, who is currently onboard a hydrographic vessel, knows well the amount of time and effort that goes into gathering bathymetry information. He is excited about the prospect of formally incorporating Landsat SDB into his workflow.

"SDB products to evaluate the current state of existing bathymetry representation is pretty amazing because of the temporal resolution of the satellite data—a little over every two weeks and you get a new shot of an area," Klemm described. Landsat 8's orbit places it back over a given location every sixteen days. Because satellites like Landsat can

provide "quantifiable information related to the amount of change since the last hydrographic survey," as Pe'eri wrote, SDB information can figure prominently into the determination of where new hydrographic surveys are most needed.

Pe'eri and Klemm helped to craft NOAA's policy on the use of SDB. They outlined how to use SDB to prioritize hydrographic surveys using a chart adequacy assessment procedure they developed. They also helped formulate a policy on how to update charts with features found using satellite imagery, like the process used to updated the Dry Tortuga chart.

"These charts are considered intermediary, but they can be made publicly available and used until a proper hydrographic survey can be performed," Pe'eri explains.

Landsat is good at identifying new shoals and mapping shallow areas where survey vessels cannot go. NOAA thinking is that it is better to amend charts to tell mariners that satellites indicated a shoal, even though exact depths cannot be provided until the next hydrographic survey. ▶



Above: Visiting Fort Jefferson on Garden Key in the Dry Tortugas, a family poses for a photo on top of the nineteenth-century fort, with the shallow turquoise Gulf waters stretching out behind them. Photo credit: Andrzej Sienko, National Park Service



Above: This circular islet is in a section of Alaska's Prince William Sound known as Dangerous Passage. Accurate nautical charts are indispensable for safe sailing. Photo credit: Mandy Lindeberg, NOAA

In-page: The second (left) and third (right) editions of Defense Mapping Agency chart 61610. The third edition, released on August 28, 1976, shows the newly discovered Colvocoresses Reef and the adjusted position of Speakers Bank.

Landsat provided the information needed for both chart adjustments.

Deriving bathymetry with Landsat for 46+ years

Uncharted shoals have sunk many ships. In the late 1960s, research groups began to experiment with remote bathymetry using multispectral airborne data in an effort to make measurements over large tracts of coastal waters in search of navigational hazards and shifting bathymetry. With the launch of Landsat 1 in 1972, these newly developed methods could be used with data collected by

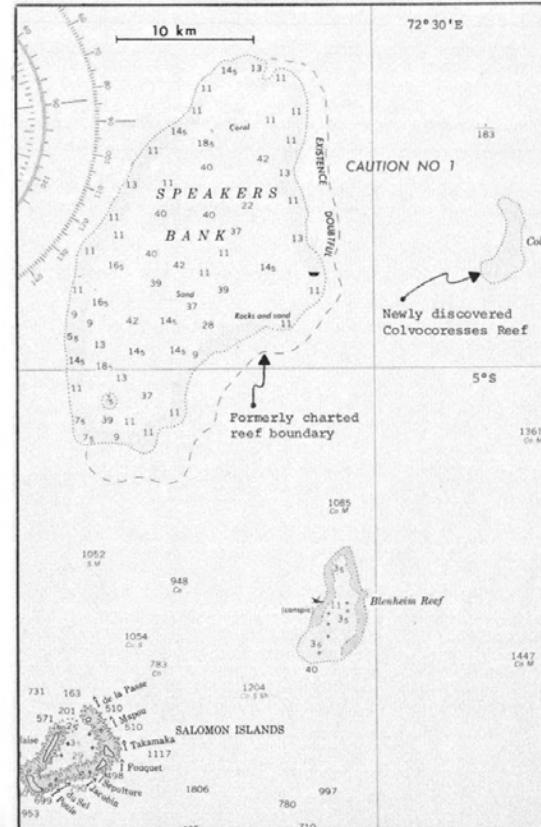
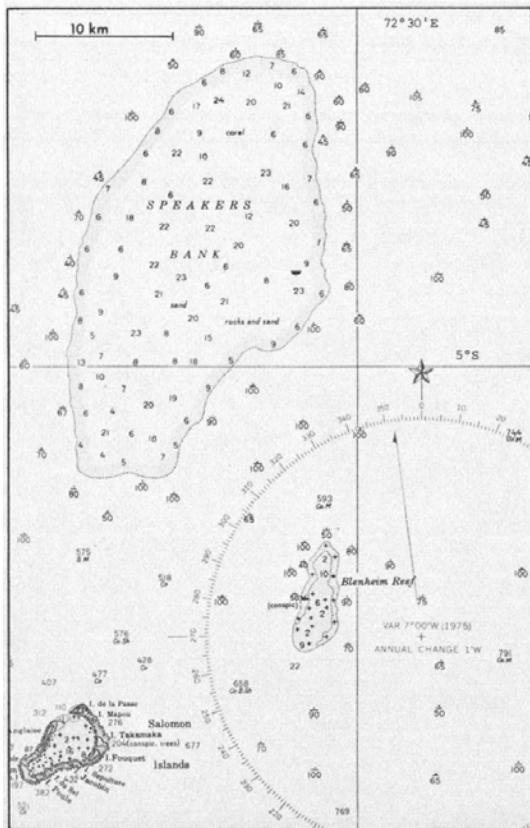
the satellite's Multispectral Scanner System and its 100 nm-wide images—satellite derived bathymetry was born.

In 1975, NASA teamed with famed oceanographer Jacques Cousteau to conduct an ocean bathymetry experiment using Landsat data to measure water depth in the Bahamas and off of Florida's eastern coast. Cousteau's ship, Calypso, anchored over a study site as Landsats 1 and 2 collected data from overhead, while they simultaneously took depth measurements

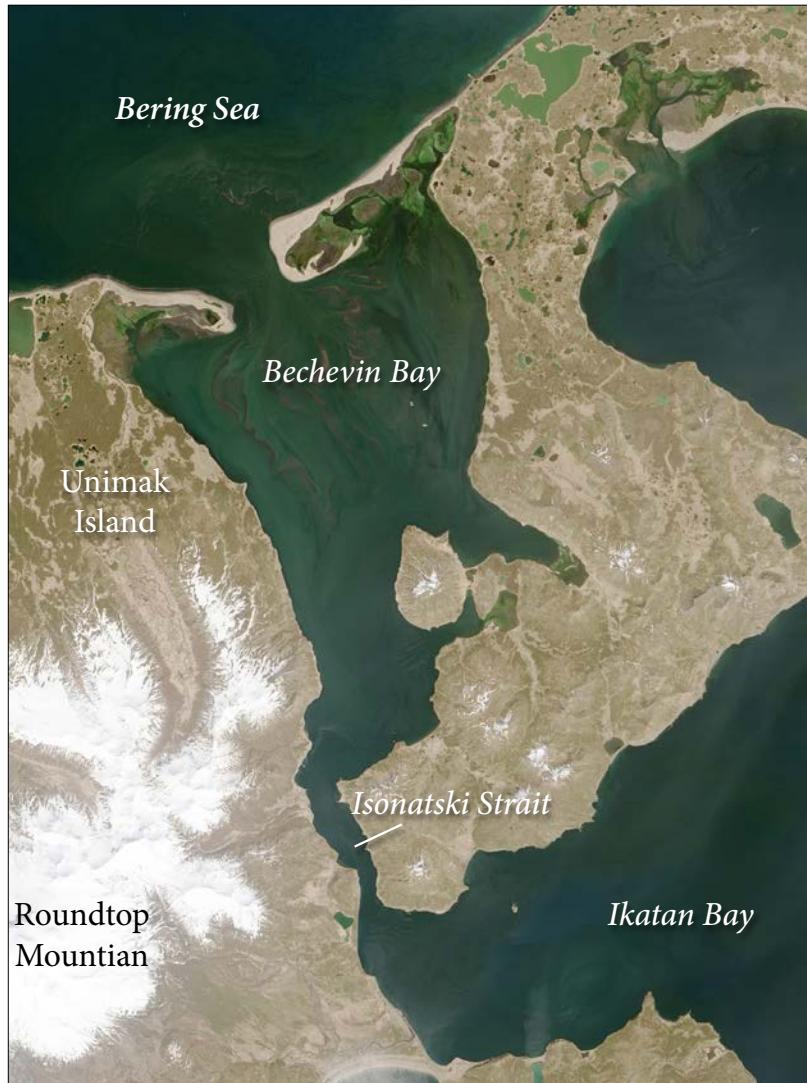
using the ship's sonic depth finder. In this pre-GPS timeframe, LORAN-C radio measurements were used for locating the boat position. Divers also plunged to the seafloor to take in situ reflectance measurements with a submarine photometer. This early experiment proved the feasibility of mapping shoals in clear water to depths equal to or greater than those needed for safe shipping.

The International Hydrographic Office, an intergovernmental organization concerned with making the seas navigable, had once classified shoals as navigational hazards between 0 and 17 meters (56 feet) below the surface, but with the advent of supertankers with drafts of over 20 meters (65 feet) and the capacity to carry massive amounts of oil, shoal definitions had to be broadened.

A year later, a Landsat 2 image acquired on March 29, 1976, revealed a major uncharted 8-km-long reef in the Indian Ocean's Chagos Archipelago: "There was a major reef or bank where the chart showed safe, deep water and some banks appeared to be out of position by more than 15 km relative to the nearest land," wrote James Hammack, a participant in the NASA/Cousteau experiment and a cartographer with the Defense Mapping Agency's Hydrographic Center (DMA)(now part of the National Geospatial-Intelligence Agency). Within a few months, the newly found reef—named Colvocoresses Reef after ▶



How Landsat Helps: BATHYMETRY

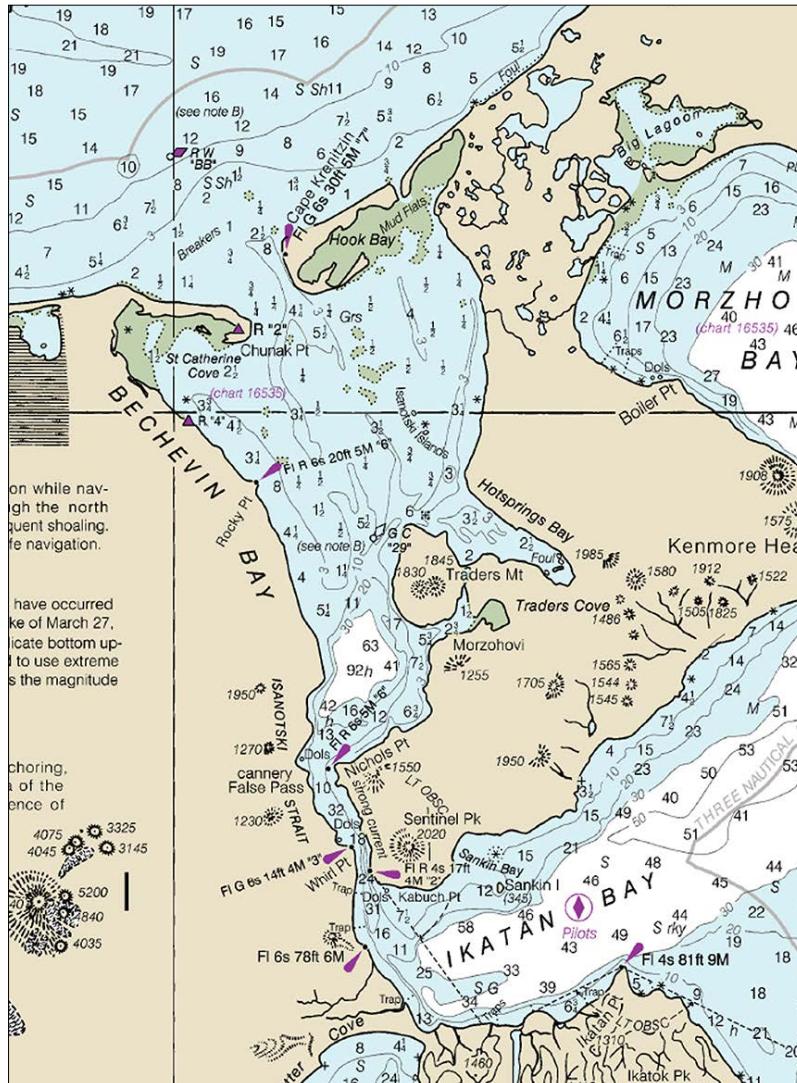


the USGS cartographer who identified the feature on the Landsat image—was added to DMA nautical chart 61610. In the interim, Notice to Mariners were sent out to warn sailors in the region.

Based on the success of the NASA/Cousteau and Chagos Archipelago experiments, DMA requested that Landsat data be collected globally over coastal areas. This data was used to “augment the

completeness” of its nautical chart products. DMA also used Landsat data to visually verify ship-reported navigational hazards.

Some other documented cases of Landsat data providing critical information to navigation include a safe deep passage through Papua New Guinea’s Star Reefs, which was first discovered using Landsat imagery. The Australian Royal Navy ship Flinders confirmed this passageway,



which enabled ships to more quickly travel from Australian ports to East Asian ones. Likewise, British Admiralty Chart 322 of the Red Sea near Al Qunfida had to be completely revised after it was compared with Landsat data.

In 2006, 75 shallow-water features such as reefs, shoals, and seamounts were discovered or found mislocated with the use of Landsat 7. ▶



Above: Anthony Klemm, a NOAA Corps Officer, in New York Harbor, aboard the NOAA Ship *Thomas Jefferson*, a hydrographic survey ship based out of Norfolk, VA. Photo credit: NOAA

In-page: Landsat 8 image of In Bechevin Bay, the easternmost passageway between the Gulf of Alaska and the Bering Sea (left). This natural color, pansharpened image was acquired on May 14, 2014. Image credit: Joshua Stevens and Jesse Allen, NASA Earth Observatory. NOAA nautical chart of Bechevin Bay (right).



Above: The NOAA hydrographic surveying ship *Thomas Jefferson* at sea in 2010. Lieutenant Anthony Klemm is currently an Operations Officer on this vessel. Photo credit: NOAA

Opposite In-page: A natural-color Landsat 8 image of the Beaufort Sea near Point Barrow, Alaska. Researchers are developing ways to estimate seafloor depth in turbid waters by combining suspended sediment swirl analyses with multi-date satellite-derived bathymetry measurements. Image credit: NASA Earth Observatory

Landsat aids hydrographic offices around the world

The International Hydrographic Organization (IHO) and the United Nations' Intergovernmental Oceanographic Commission jointly create an authoritative, publicly available, global bathymetry map known as the General Bathymetric Chart of the Oceans, or GEBCO. GEBCO charts have been published since 1903. Despite this heritage, only about a tenth of the ocean floor has been mapped.

GEBCO is no stranger to SDB. They have been aware of its capabilities for decades. But now that Landsat data are publically and freely available, Landsat is being used more often—as is data from the European Space Agency's Copernicus Sentinel-2 satellites, with spectral bands similar to Landsat 8.

NOAA, as a major Landsat user, has been sponsoring international GEBCO students from around the world and teaching them how to use SDB to update charts in their home offices. NOAA's fourth SDB training was held in July 2018 as part of the Chart Adequacy Workshop. The 2018 workshop participants—from Madagascar, Mexico, Nigeria, Peru, Australia, Greece, Ireland, Japan, Latvia, Poland, St. Vincent and the Grenadines, Trinidad and Tobago, and Taiwan—learned about SBD and how to find land-water boundaries with satellite imagery, among covered topics.

The GEBCO companion how-to guide for creating bathymetric charts, called The GEBCO Cookbook, includes a chapter on using Landsat to derive bathymetry. For cash-strapped national hydrographic offices, using free Landsat data to assess the adequacy of existing charts is essential, allowing them to allocate scarce resources with maximum impact to mariner safety. GEBCO students also use the European Space Agency's Copernicus Sentinel-2 data and some commercial WorldView imagery. Students often like to use Landsat data because of its deep archive, which they use to produce time series showing shoreline and shoal trends over decades. SDB alone does not meet IHO accuracy standards, but its use as a complementary prioritization and planning tool is key.

SDB measurements can also “be used to infill regions in remote or inaccessible areas where no (or poor) bathymetry data exists,” shares Stephen Sagar, an Aquatic Remote Sensing Scientist with Australia’s National Earth and Marine Observation Group.

NOAA: thinking big about SDB

Water clarity has been a limiting factor when it comes to SDB. If waters are too turbid (full of sediments that obscure light reflectance from the seafloor), then bathymetric measurements cannot be made.

The inability of longer wavelengths, such as shortwave infrared light, to deeply

penetrate water allows hydrographers to map shoreline change. But when concentrations of suspended sediments are great enough to thwart penetration by shorter wavelengths, SDB by definition suffers. But in NOAA's Marine Chart Division, researchers are thinking outside of the SDB-box.

Pe’eri, in a collaborative study with NOAA and the U.S. Coast Guard, has pioneered turbidity mapping as a proxy for bathymetric measurements. In enclosed waterbodies with strong currents, such as bays and sounds, turbid channels show up on Landsat imagery—and these turbid channels illuminate where currents are carving deeper channels that are safe for boat passage.

In the Arctic, where near-shore changes occur rapidly because of seasonal sedimentation and erosion, new SDB techniques like turbidity mapping are preventing maritime mishaps. In Bechevin Bay, where the easternmost passageway between the Gulf of Alaska and the Bering Sea provides fisherman with a shortcut for three ice-free months a year, the location of sand bars can shift significantly because of melting ice in this narrow passage. With the help of Landsat SDB turbidity maps, the new locations of these sandbars can be estimated. Recently, this has led to the discovery of a new, straighter, and more geologically stable channel. ▶

How Landsat Helps: BATHYMETRY



"SDB estimated from Landsat turbidity maps can help guide NOAA charting craft when they are mapping the channel each year and placing channel marking buoys. This saves time and it makes the process safer," Pe'eri said. "With insufficient knowledge of sandbar locations, the NOAA craft risk running aground and crew can be thrown overboard when that happens."

Pe'eri's team has also developed a multi-image method to help separate clear and turbid waters using Landsat data. Techniques such as turbidity mapping will grow increasingly important for navigation planning as warming waters enable more industrial development of the Arctic and set the stage for international shipping routes.

NOAA's Marine Chart Division has made Landsat a prominent tool in their charting toolbox—especially Landsat 8 with its new deep blue band, improved signal-to-noise, and greater dynamic range (12-bit).

"Landsat 8 is overwhelmingly better," Pe'eri shared, citing the new satellite's additional cirrus band which helps him better account for atmospheric noise that can compromise accurate SDB and Landsat 8's better radiometric resolution (which means more signal, less noise, and more measurement fidelity). After Landsat 9 launches in late 2020, Pe'eri and others will evaluate its data and once it checks out, will add it to their toolbox. But it's not just SDB that this innovative office is utilizing.

They are also watching traffic patterns using the Automatic Identification System (AIS) and even light communication from recreational boaters, fishermen, tugboats, and larger vessels, and—together with bathymetry measurements—they are prioritizing which charts are in perilous need of revision.

"We're making charts safer up there," Klemm said, talking about the work done in Alaskan waters, "and that's so exciting." ■

This article was originally published on July 23, 2015 on the NASA Landsat Science website. Updates to the article were made in August 2018.

Satellite Data Requirements:



16-day revisit



30 m resolution



Vis, NIR, SWIR



Global coverage



Archive continuity & consistency



Free, unrestricted data



Geolocation ≥ 15 m



$\leq 5\%$ radiance calibration



12-bit data digitization

A satellite map showing a desert landscape. In the center-right, a large, dark blue reservoir is surrounded by a green agricultural area with a grid pattern. To the left of the reservoir, a winding river flows through a valley. The terrain is mostly brown and tan, indicating arid land. A small town or city is visible near the river's mouth. The map includes a north arrow and a scale bar.

N 2 mi



These Landsat images of Las Vegas and Lake Mead provide an example of the mission's ability to monitor change over time. The rapid growth of the city and the ongoing drawdown of the reservoir between 1985 (Landsat 5 image, left) and 2018 (Landsat 8 image, right) is clearly visible. While the Las Vegas Valley relies on Lake Mead for 90 percent of its water supply, Nevada receives only 4 percent of the lower Colorado basin water allotment—most of the water is used to water California crops. Image credit: Allison Nussbaum



Addressing the Water Consumption Riddle

Peggy Connot and
Steve Young

The answer to this riddle could end up rippling across the country and the planet—from places like the Upper Klamath and Rio Grande basins to every other arid and semi-arid landscape where water consumption drives community discussion. When it comes to water, when does less actually mean more?

Dr. Gabriel Senay, a research physical scientist, and his colleagues at the U.S. Geological Survey's (USGS) Earth Resources Observation and Science

(EROS) Center are using data acquired from Landsat satellites to help divine an answer to that very question in the Upper Klamath River Basin of southern Oregon. With climate variability and drought having resulted in insufficient water for agriculture and aquatic life, including fish listed as endangered, regulators want to know if controlling water consumption from streams flowing into Upper Klamath Lake can help them better manage the basin's water resources at sustainable levels.



That's where Senay and his colleagues come in. EROS scientists use remotely sensed data scaled to Landsat 30-meter resolution and energy-balance principles to model the rates of evapotranspiration (ET) from the fields in the Upper Klamath River Basin. In a vegetated field, ET accounts for the movement of water to the air from soil and any waterbodies (evaporation), and from the movement of water within the plants and subsequent loss of water as vapor through stomata in the plant leaves (transpiration).

Plants regulate their tissue temperatures by balancing energy inputs and outputs. As water and nutrients are transported from the soil to the plant's leaves, transpiration plays a major role in regulating leaf temperature, balancing incoming energy from sunlight and outgoing energy from release of water vapor through the leaf surface.

What Senay and others understand is that through principles of ET and energy balance, a fully transpiring vegetated area can appear up to 40 degrees Fahrenheit cooler than bare areas with little ET. Using this knowledge in combination with local weather datasets for irrigated lands, Senay provides increasingly accurate and repeatable estimates of actual ET in a given landscape. ▶



Above: Water managers discuss the complexities of the Rio Grande Watershed and its history, as well as the need for runoff forecasts for downstream water users. The discussion took place in April 2018 near Embudo, New Mexico. Photo credit: Lindsay Hastings, USGS

In-page: A Klamath Tribes hydrologist makes a discharge measurement in the Sprague River between Beatty and Bly, OR. Irrigation lines extend on both sides of the river. Photo credit: Terrence Conlon, USGS Oregon Water Science Center

Opposite: Bathtub rings on Elephant Butte, a major reservoir on the Rio Grande. As of June 30, 2012, the reservoir was at only 12 percent of capacity. Photo credit: Zack Guido, Climate Assessment for the Southwest



Above: The Upper Rio Grande Basin Focus Area Study is looking at water use, availability, and change in the Upper Rio Grande Basin, covering 670 miles from its headwaters in Colorado through New Mexico and northern Mexico to Ft. Quitman, Texas. Photo credit: USGS

Understanding ET to Help Solve the Water Consumption Riddle

Upper Klamath is important. It provides a home to endangered sucker fish. It also is the source of water for irrigation on the Bureau of Reclamation's Klamath Project. Droughts in recent years in the Upper Klamath River Basin have forced regulators to reduce or curtail irrigation withdrawals from streams. What those regulators need to know in order to wisely manage the water is how much additional water is flowing into Upper Klamath Lake because of the reduction in irrigation.

With his ET work, Senay offers a way to measure the amount of irrigated water that plants are consuming. Figuring out whether a reduction in irrigation translates into more water flowing into Upper Klamath Lake requires acquiring ET data during a year when irrigation is reduced and comparing it with a year when there is normal irrigation.

"Gabriel's work is really valuable," says Terrence Conlon, Studies Chief with the USGS Oregon Water Science Center in Portland, OR. "It's going to do a lot to move things forward as far as understanding how water management in the upper basin affects downstream flows."

Using independent Landsat satellite data from space for their ET maps, Senay and his group started working on the Upper Klamath River Basin issue in 2017 with funding from the Bureau of Reclamation. To begin with, they tapped into Landsat's rich, dense archive to produce a pair of ET maps from 2004 and 2006—representing a dry year and a wet year back when much less water regulation was occurring. Then they averaged the two to arrive at a baseline for comparing water usage in 2013, 2014, 2015, and 2016—years when more significant water management occurred.

While 2013 showed significant decreases in water consumption and irrigation along the tributaries upstream from Upper Klamath Lake, other years weren't so definitive, Senay said. That wasn't necessarily surprising, Conlon added.

In 2013, curtailment of irrigation in the upper basin was widespread, "so that was probably the clearest response to the management, and the easiest to say that there was a change" in water consumption, Conlon said. In years after 2013, however, the management of irrigation was more variable, including allowing irrigators to turn diversions back on if stream gages showed acceptable streamflow amounts would allow for it. "So, from a

scientific standpoint of trying to tease things out, now it's not kind of black and white; it's a lot of grays," Conlon said.

Certainly, there are other ways to measure water consumption in the upper basin, such as looking at streamflow in years with reduced irrigation and trying to compare it with years of normal irrigation. Tamara Wood of the USGS Oregon Water Science Center has developed a model using regression techniques that predicts streamflows during a year with normal irrigation based on snow accumulation, precipitation, and other climate variables. That streamflow model includes a way to overcome what is a common concern in all the various methods of study—finding a year with normal irrigation that had similar snowpack and precipitation to compare to a year with water management.

Senay's method of using a fixed year for comparison isn't dependent on streamflows, but rather bases consumption strictly on what is being consumed by plants on a field-to-field basis. So, while the streamflow model provides an estimate of flow into the lake from irrigation management at a point in a stream, "[Senay's model] provides an estimate of flow and can show where the changes in irrigation occur, and how much they contribute to the change in flow into Upper Klamath Lake," Conlon said. ▶

Using Landsat to Locate Areas Susceptible to Future Flooding

The Upper Klamath isn't the only beneficiary of Senay's work. The use of Landsat's 30-meter resolution and thermal imaging capabilities to create detailed water consumption maps quickly and easily is proving crucial to resource management decisions in other parts of the country as well. The Upper Rio Grande Basin is a good example.

With water so valuable to agricultural, municipal, industrial, and recreational users throughout the Upper Rio Grande Basin, "it becomes really important to understand how much evaporates, when it evaporates, and where it evaporates, so we can better manage what's left of our surface water for our streamflow and for our groundwater," said Kyle Douglas-Mankin, a supervisory research hydrologist working for the USGS on the Upper Rio Grande Basin Focus Area Study. "Gabriel's work," Douglas-Mankin continued, "helps us do that."

Changes in climate and ongoing drought have reduced reservoir water supplies and turned groundwater into a crucial component for water availability in the Upper Rio Grande Basin. It also has meant an increased use of groundwater by agriculture, towns and cities, and for downriver delivery under the Rio Grande Compact involving Colorado, New Mexico, and Texas. With groundwater

withdrawals now exceeding recharge rates in many parts of the basin, new sources of available groundwater must be identified.

Aligning Water Use with Water Availability

Congress envisioned such a difficult challenge when it enacted the SECURE Water Act in March 2009, giving rise to a research program within the USGS called the National Water Census (NWC). Focusing on water availability and use, the NWC was implemented in February 2010 through an initiative within the Department of Interior

called WaterSMART (Sustain and Manage America's Resources for Tomorrow).

A key component of WaterSMART is the focus area studies. Among the first of the studies launched was one involving the Upper Rio Grande Basin. The Rio Grande runs 670 miles from its headwaters in Colorado through New Mexico and northern Mexico to Ft. Quitman, Texas. Along its river corridor, it is a primary source of irrigation water for food, fiber and feed production, and it also supplies municipal water to the cities of Albuquerque, Las Cruces, El Paso, and Ciudad Juarez. ▶



Above: The Upper Rio Grande Basin Focus Area Study includes parts of Colorado, New Mexico, Texas, and Mexico.

In-page: Evapotranspiration (ET), the combination of evaporation from wet soils and water bodies, as well as transpiration through plants, is the primary way water is lost from the Upper Rio Grande Basin. A study looking at consumptive water use in the basin uses satellite data to quantify where and when ET occurs. Photo credit: USGS



Above: The Wood River in southern Oregon is one of the large tributaries where regulators have reduced or curtailed irrigation in recent years to manage the amount of water flowing from the river into Upper Klamath Lake. Photo credit: Terrence Conlon, USGS Oregon Water Science Center

In-page: Evapotranspiration (ET) distribution for the San Luis Valley using Landsat data for 2018. High ET values correspond to higher water use (high irrigation). Image credit: USGS National Land Cover Database

Douglas-Mankin is working to develop a watershed model for the entire upper basin that not only captures water balance throughout the basin at a fairly fine resolution, but also looks at streamflows. He knows that some of the rain that falls will recharge the groundwater. Some will impact streamflows. But what Douglas-Mankin hopes to get from Senay and his ET modeling is a better understanding of how much of the rainfall ends up evaporating or transpiring into the air.

"How much water is left that we can use for whatever we want to use it for?" Douglas-Mankin said. "Maybe that's drinking water, or for new agricultural development, or for maintaining streamflow for native fish. The data Gabriel provides lets us make sure we're accounting for—what happens to the water in evapotranspiration so that we have a better chance of estimating what goes to the streams and what goes to the groundwater."

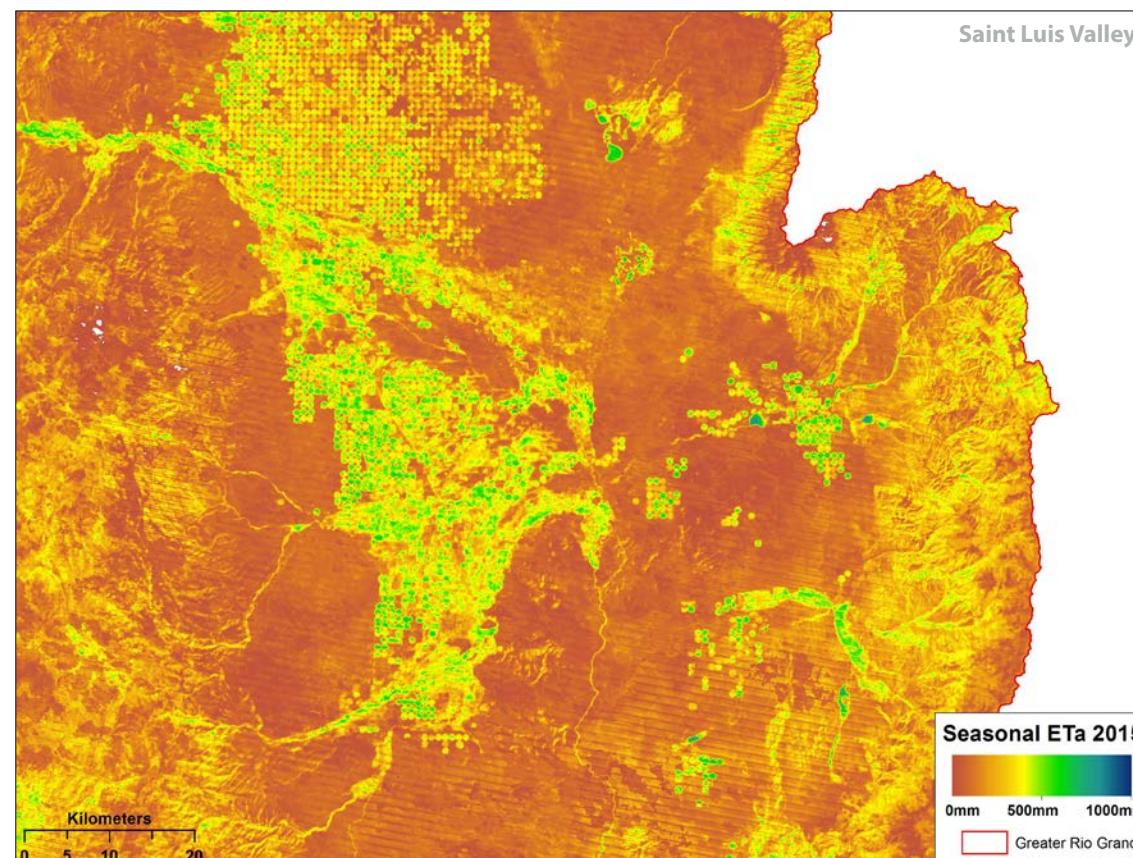
Douglas-Mankin said Senay's monthly and seasonal ET maps at Landsat scale help to improve the measurement of water consumption on irrigated farm fields and also help to quantify water consumption through evaporation and transpiration in wetlands and other riparian ecosystems.

Senay's ET work has an application in urban settings like Albuquerque, New Mexico, as well. In particular, using Landsat data back to 1984 can help reveal what impact urbanization has had on water consumption and climate in New Mexico's largest city.

"When we start paving over things or we start irrigating lawns, how is that going to affect the climate of the city?" Douglas-Mankin said. "This gives us a new tool to look at that. With Gabriel's work getting down to finer spatial and temporal resolutions, we can observe smaller lots and objects—from city blocks to backyard garden plots—with a revisit frequency of about a couple weeks."

ET Helps in Addressing Urban Heating

As he collects evaporation rates from the ground, Senay can tell where lawns are being irrigated, or where water isn't evaporating from ground surfaces because they've been paved over. Urban heating then can be addressed by planting more trees that transpire to help cool the air and also shade homes, thus reducing air conditioning costs to homeowners and businesses. ▶



How Landsat Helps: AGRICULTURE

In Albuquerque, property owners are also reducing the size of their lawns to save on watering.

Another area of interest in Senay's work is east of Albuquerque, where rural developments are growing and expanding. As that happens, city and county officials need to know how much water is available to support wells and other water needs.

"One of the first things you need to understand in terms of how much groundwater is going to be able to recharge the subsurface groundwater aquifer—is how much water is lost to evaporation before it even makes it too far into the soil," Douglas-Mankin said. "We're using Gabriel's data to help the county understand how much of the rainfall is evaporated and where this happens within that area." ■

This is a combination of two stories that ran on the EROS external website (eros.usgs.gov) under Latest Headlines. One story ran on June 27, 2018, and the other on April 26, 2018.



The Rio Grande River making its way through Albuquerque, New Mexico. Much of the city's municipal water supply comes from the river. Researchers are using Landsat-based ET maps to access and address the impacts that urbanization has had on water consumption. Photo credit: Fotolia images

Satellite Data Requirements:

- ⌚ 8-day revisit (w/ L7)
- $\leq 30\text{ m}$ resolution
- ☀ Vis, NIR, SWIR, TIR
- ⚡ Continuous spatial coverage
- ⟳ Archive continuity & consistency
- ✈ Rapid delivery of free, unrestricted data
- ☒ Geolocation $\leq 0.5\text{ pix}$
- ✖ $\leq 5\%$ radiance calibration
- 👁 8-bit data digitization



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On July 18, 2018, Landsat 8 captured an elegant swirl of blue-green algae on the Baltic Sea where the summertime blooms were larger than normal and contributed to an Ireland-sized “dead zone.” Image credit: Joshua Stevens

Opposite: Landsat 8 captured an algae bloom on Lake Okeechobee on July 2, 2016. That summer, harmful algae blooms caused a four-county state of emergency in Florida. Image credit: Allison Nussbaum



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Satellites on Toxic Algae Patrol

Laura E.P. Rocchio

The world over, a tiny organism is causing a big problem. Cyanobacteria, unicellular algae that live mostly in fresh water, are growing in abundance. When this booming growth occurs, the resulting algal blooms can be a nuisance to people, plants and animals, or worse—toxic. Satellites, including Landsat, are being harnessed to track these harmful algal blooms because water managers across the globe need to know when and where blooms are happening to protect people.

Cyanobacteria's harmful algal blooms are responsible for a laundry list of water woes. Here are just a few examples:

- In 2014, a three-day “Do Not Drink” order in Toledo, Ohio caused a loss of drinking water for nearly half a million people.
- In Florida in July 2018, seven counties were placed under a state of emergency because of widespread harmful algal blooms. Two years prior, “guacamole-like” algal blooms caused a four-county state of emergency and the surface water of some lagoons were completely obscured by the upturned white bellies of thousands of dead fish.
- In 2016, the 150 square mile Utah Lake was closed to recreation for the first time in history.
- For two brief periods in May and June 2018, Salem, Oregon issued

“Do Not Drink” advisories for vulnerable populations after harmful algal blooms were identified over the city’s Detroit Lake water intake.

- By mid-summer 2018, fishing, boating, and swimming had been intermittently banned in lakes and reservoirs throughout the U.S., including Diamond Valley Lake in California and Lake Pontchartrain in Louisiana. Even the lake in Central Park had a bloom status listed as “confirmed with high toxins.”

The cyanobacteria that cause harmful algal blooms (HABs) can create toxins responsible for an array of human ailments. The list is long: headaches, diarrhea, stomach cramps, nausea, vomiting, neurological impairments, respiratory ailments, swimmer’s itch, rashes, and compromised liver and kidney functioning. Pets that drink cyanotoxins can become sick and die. Ecologically, HABs can be devastating, poisoning wildlife and prompting advisories not to eat exposed fish and shellfish. And hazardous and non-hazardous algal blooms alike can create oxygen-deprived “dead zones” in the waters they occupy once they reach high concentrations.

Increasingly, water managers are turning to satellites to monitor inland waters. Landsat is among the satellites being tapped to give managers a full picture of where and when harmful

algal blooms are affecting their lakes—providing a map of this growing cyanobacteria problem. To safeguard human health and the environment, water managers must be ever vigilant, spot checking their waters for HABs. They need timely information about their lakes, ponds, and reservoirs to make the right call, because keeping people safe from HABs often means depriving them of access to their recreational and drinking waters. This is a big job. In the U.S. alone there are 17 million hectares (over 65,000 square miles) of fresh water and spot checking alone cannot give managers a complete picture of the health of their water bodies. ▶



Above: A young girl holds her nose to avoid the unpleasant smells caused by an algal bloom on Tainter Lake in Menomonie, Wisconsin in October 2014. Photo credit: Dick R., National Environmental Education Foundation

In-page: In June 2016 next to a Harsha Lake boat ramp in Ohio’s East Fort State Park, a danger sign warned the public that algal toxins were at unsafe levels and that all contact with the water was to be avoided. Photo credit: Clermont County, Ohio government

Opposite: An algal bloom in October 2016 colored the waters of The Lake in New York’s Central Park green. Photo credit: Neil Howard



Above: A hazardous algal bloom containing the toxin microcystis covered large portions of western Lake Erie in September 2017. Swirls of algae can be seen south of the Detroit River's mouth in this natural-color Landsat 8 image. Image credit: USGS EROS

Don't Feed the Algae

Cyanobacteria are naturally present in waters, but usually at levels that don't create a threat. When conditions are right, they grow quickly and their toxins become overabundant. When this happens, cyanobacteria grow dense enough to be visible to the naked eye, turning into what is often described as slimy goop, scum, or "pea soup." Even when no toxins are present, this unsightly surface scum can cause waters to smell bad and taste bad.

More and more often, conditions are right. A combination of warm, still waters, lots of sunshine, and plentiful nutrients can lead to a bloom. Inadvertently, we are feeding cyanobacteria with the fertilizers we put on crops and lawns. Rains wash these nitrogen and phosphorus nutrients into streams and rivers, turning them into arteries delivering food to cyanobacteria.

As the nutrients feed the growth of cyanobacteria, the possibility of an algal bloom grows. A quarter of all U.S. freshwater water bodies suffer from this type nitrogen and phosphorus pollution. At the same time, our climate is warming—and warming lakes along with it. As nutrient-rich, warm waters increase so does the likelihood of a bloom. The U.S. Environmental Protection Agency

estimates that somewhere between 30 to 48 million Americans use drinking water from lakes and reservoirs susceptible to HABs. Conventional water treatment methods have improved their ability to filter cyanotoxins over the last decade, but they can still be overwhelmed during severe bloom events—and cyanotoxins can't be boiled away.

Blooms in Lake Erie, which provides drinking water to 11 million people, prompted the U.S. and Canada to agree in 2016 to take measures to reduce phosphorus going into the lake by 40%. They want to stop feeding the algae.

As decision makers grapple with the best ways to make conditions less favorable for cyanobacteria, water managers, with limited resources, need to know the locations of blooms each day in order to keep people safe. Satellite-based alert tools are part of their solution.

The Color Cyan

Cyan is a color between blue and green, and it lends its name to both cyanobacteria (also known as blue-green algae) and the colorless, odorless, and dangerous cyanotoxins that some contain. When harmful algal blooms occur, they color the water, and satellites can observe those color patterns.

Not all algal blooms contain cyanobacteria and it is only some species of cyanobacteria that produce cyanotoxins—and these cyanotoxins cannot be directly detected from space. Satellites help by providing bloom maps that can inform managers when and where to directly sample and test waters for any lurking cyanotoxins. Those samples are then sent to labs to determine if cyanotoxins are in the water. Microcystin, a liver toxin that causes gastrointestinal ailments, is among the cyanotoxins managers track.

Satellites provide the big-picture view of algal bloom patterns by making quantitative measurements of the color of the water, which is directly related to absorption of light by the pigments that algae use in photosynthesis. They can also measure water's surface temperature and estimate the amount of suspended matter and dissolved organic matter that water contains. These metrics add to managers' informational arsenal against HABs.

Early Warning, Satellites and Solutions

Tracking and predicting the movement of cyanobacteria in inland waters is a complex problem. ▶

How Landsat Helps: WATER

Specially-designed ocean color satellites have tracked ocean algae for decades. These sensors make many measurements in the visible spectrum, including a narrow band of red light (620 nanometers) that can provide a telltale sign of the presence of cyanobacteria. But their spatial resolution, while appropriate for ocean monitoring, is often too coarse for the inland waters where HABs pose threats to humans. So, in addition to ground-based measurements, scientists are using an array of land observation satellites with finer spatial resolution, each sensor adding a needed measurement to create a future operational algae alert product.

"No one technology is going to be the silver bullet, there is no one solution fits all," explained Dr. Blake Schaeffer, a research ecologist with the U.S.

Environmental Protection Agency. "Each technology has its pros and cons."

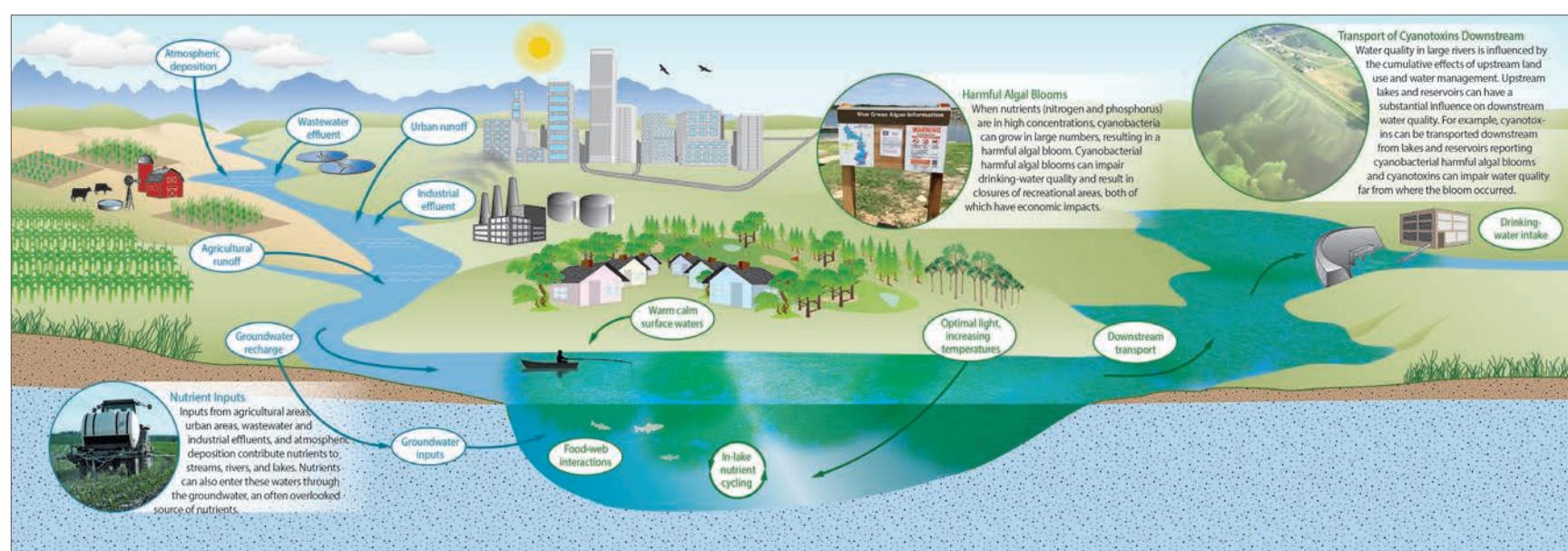
Landsat is contributing to these products in three main ways. The first is with its spatial resolution. Researchers found that by using Landsat, with its 30-meter spatial resolution, they could monitor 170,240 (62%) of lakes and reservoirs in the U.S., including, approximately 95% of the public water surface intake locations, where water for public drinking water is sourced. "That's where Landsat comes in with its power of resolution and the number of water-bodies it can resolve," Schaeffer noted.

Thermal measurements are another contribution that Landsat is making to cyanobacteria tracking. HABs typically occur when waters are warmer. By using Landsat's thermal measurements

to monitor surface water temperatures researchers can establish where conditions are favorable for HABs.

Landsat's long historical archive is also an asset. Landsat has been collecting 30-meter data since the early 1980s. Using this data, researchers were able to go back and establish algal bloom patterns since 1984 for Lake Erie, expanding the known record of bloom occurrence by two decades and helping scientists understand long-term algal bloom trends, distribution, and timing, all of which have implications for current water management efforts.

As Schaeffer acknowledged, "Landsat is unique in that it can go back to the 1980s at high spatial resolution." In the HAB early warning and prediction puzzle, Landsat is a valuable piece. ▶



The nutrients that feed cyanobacteria-containing harmful algal blooms come from many sources. Creeks, streams, and rivers serve as arteries delivering overabundant nutrients to water bodies. When these nutrient-rich waters are warm, still, and exposed to a lot of sunshine, algal blooms are more likely to form. Image credit: USGS



Above: Canoes on Lake Hope in Ohio float on waters covered with a blue-green Hazardous Algal Bloom (HAB) in August 2010. Photo credit: Ohio EPA



Above: The gloved hands of a USGS scientist gathering algae samples from Binder Lake in Iowa for lab analysis in 2006. The analysis found that microcystins were present. Photo credit: Jennifer L. Graham

Locating Harmful Algal Blooms with Landsat

Cyanotracker is an early warning system developed at the University of Georgia that uses Landsat and the European Space Agency's (ESA) Copernicus Sentinel-2 and Sentinel-3 data to provide near real-time monitoring of HABs in inland lakes, reservoirs, estuaries, and coastal lagoons around the world. It relies on a network of ground sensors and incident reports of HABs from social media, citizen scientists, and news reports to find HABs. Once a HAB

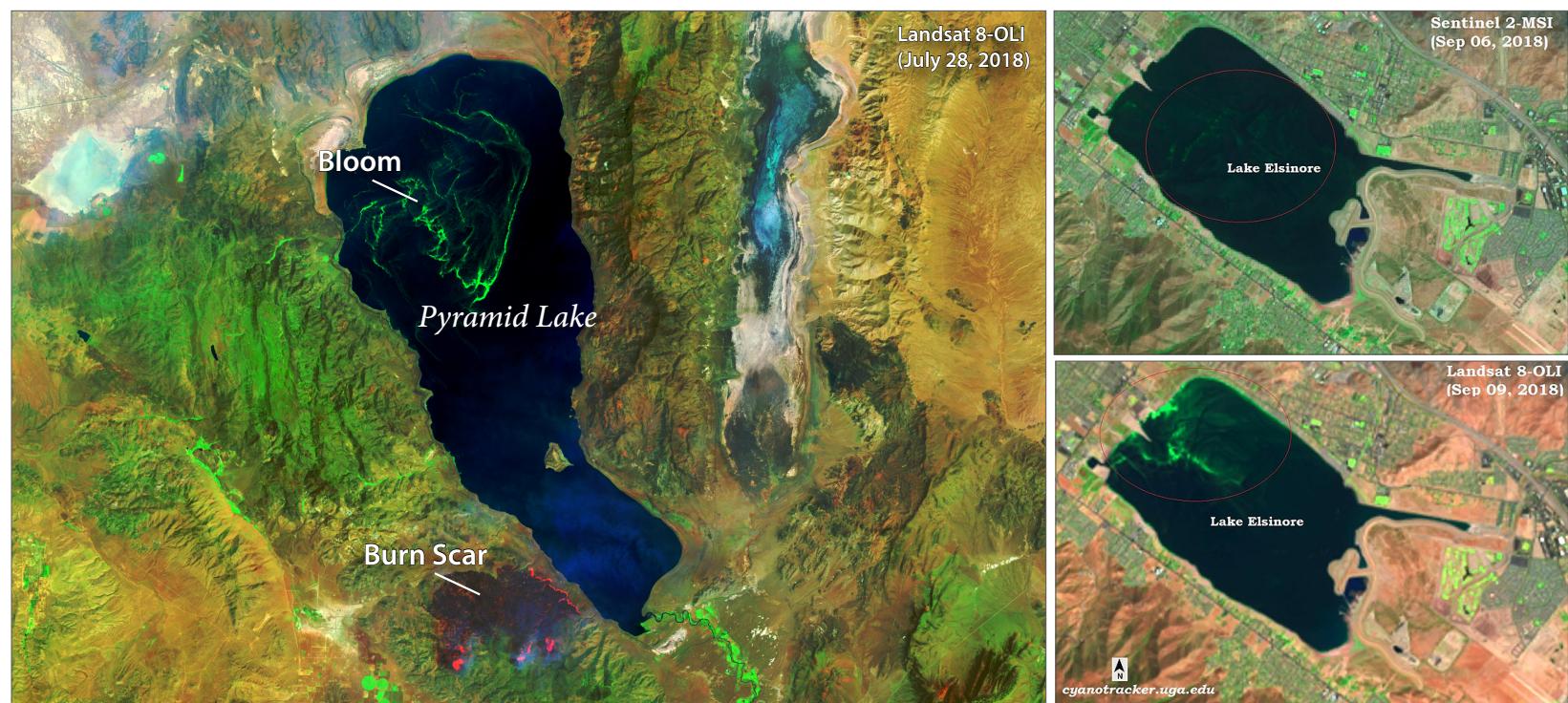
is reported, Cyanotracker uses the satellite data to map the spatial development of the bloom. These maps are widely distributed to water managers via social media.

Cyanotracker was first to highlight an algal bloom in Lake Pontchartrain in March 2018 with Landsat 8 and Sentinel-2. It then used Sentinel-3's Ocean Land Color Instrument (OLCI) to confirm the presence of cyanobacteria.

"We are successfully implementing a cross-calibration approached between

Landsat 8 and Sentinel-2 to increase the temporal frequency much needed for HAB monitoring," explained Dr. Deepak Mishra and Abhishek Kumar, Cyanotracker team members from the University of Georgia.

The Landsat 8 repeat coverage of a location is every 16 days, but together with the two satellites that comprise the Sentinel-2 mission (-2A and -2B) this frequency increases to 3-4 days and with the launch of Landsat 9 in late 2020, this will increase to every 1-2 days. ▶



The University of Georgia's early warning system Cyanotracker uses both Landsat 8 and Sentinel-2 to show algal bloom progressions such as the one seen in California's Lake Elsinore in September 2018; water samples there showed high levels of microcystins (top right). Cyanotracker used Landsat 8 to show a large algal bloom in Nevada's Pyramid Lake in July 2018 (bottom right).

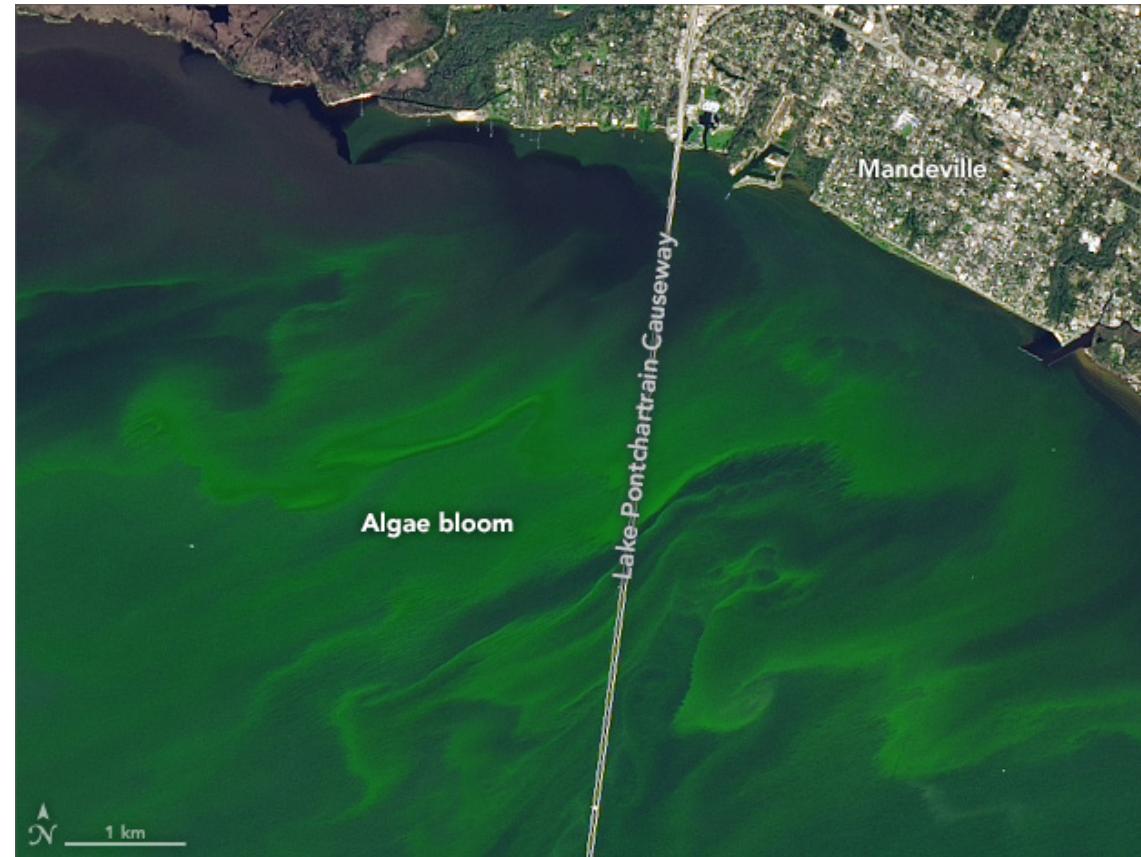
How Landsat Helps: WATER

"The ultimate societal benefit of the Cyanotracker warning system," said Mishra and Kumar, "is to enable early detection and timely implementation of preemptive measures to reduce the frequency and severity of future HAB events while ensuring environmental conservation and sustainability."

UNESCO's International Hydrological Program has created a World Water Quality Portal which aims to inform science-based decision making for water managers of UN member states. The portal, developed by EOMAP Germany, is currently using Landsat 8 and Sentinel-2 data to provide key indicators of water quality—turbidity, chlorophyll-a, Harmful Algal Blooms, organic absorption and surface temperature—for seven demonstration sites around the world.

At NASA's Goddard Space Flight Center, a project directed by Landsat Science Team member Dr. Nima Pahlevan is developing a satellite-based near real-time water quality monitoring tool supported by existing field monitoring equipment that will alert water managers to potentially hazardous water quality conditions. These warnings will come with confidence levels that will help avoid false alerts.

"The radiometric quality and precision of Landsat 8 is really beneficial," Pahlevan said, helping to detangle signal from noise. He added that the coastal/aerosol band on Landsat 8 (which will also be on Landsat 9) is



Warm temperatures just before spring began, coupled with a slug of nutrients from run-off, caused an early algal bloom on Louisiana's Lake Pontchartrain in March 2018. The Cyanotracker team using Landsat gave quick notice of this event to water managers via social media. Image credit: NASA Earth Observatory

very helpful when trying to measure dissolved organic matter in waters.

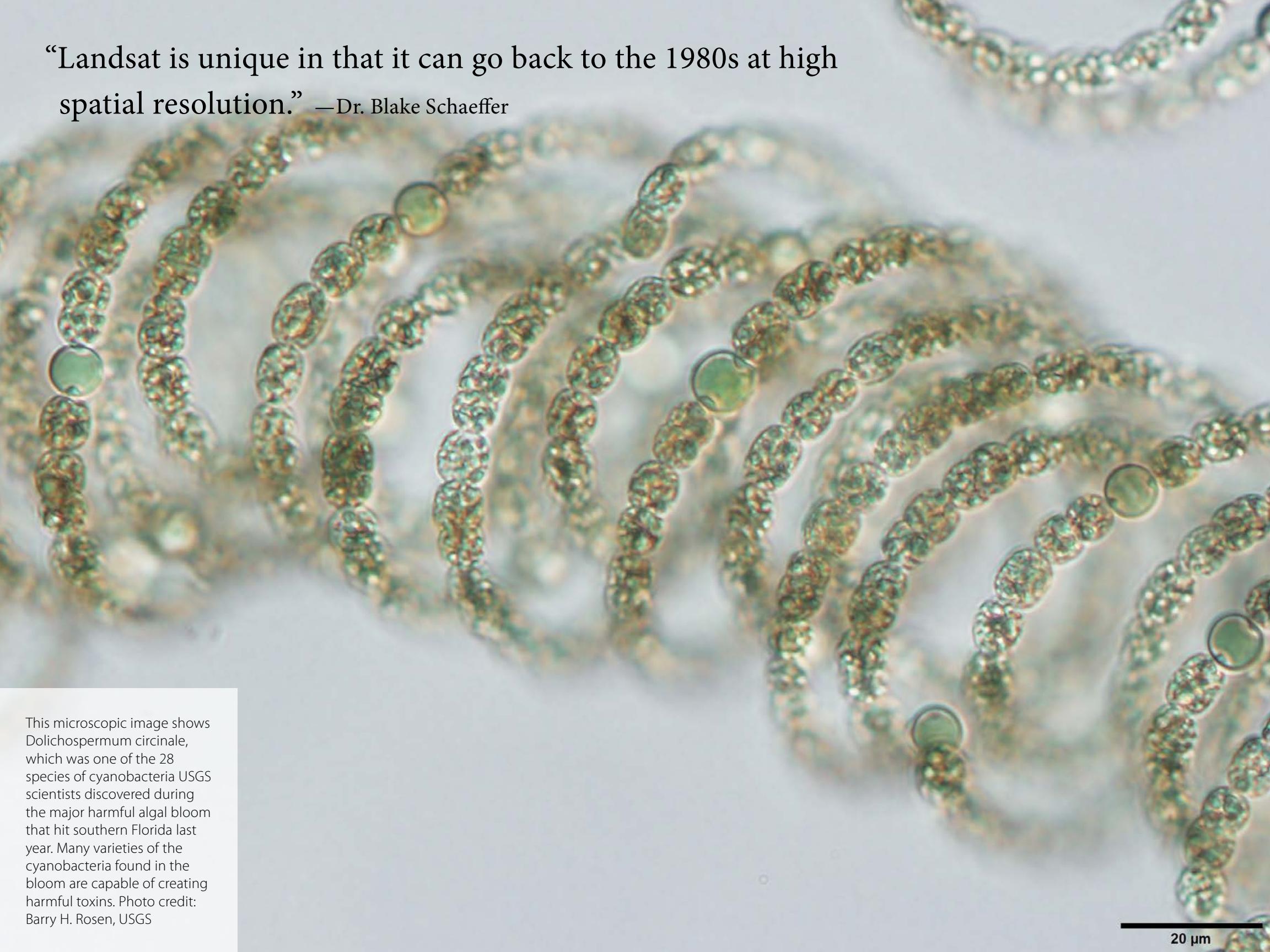
As part of CyAN, Schaeffer and collaborators worked with USGS to determine if the USGS Landsat thermal product could be used to reliably map inland water temperatures. They found that it could.

This has two big implications for HAB monitoring. First, it allows scientists to look back in time to see when water temperatures triggered blooms and to see how environmental events like storms or droughts affected water temperatures. Secondly, it means Landsat water surface temperature information could be incorporated into future forecasting models. ▶



Above: EPA scientist gathering water samples on Concord River in Boston. Photo credit: Eric Vance, EPA

“Landsat is unique in that it can go back to the 1980s at high spatial resolution.” —Dr. Blake Schaeffer



This microscopic image shows *Dolichospermum circinale*, which was one of the 28 species of cyanobacteria USGS scientists discovered during the major harmful algal bloom that hit southern Florida last year. Many varieties of the cyanobacteria found in the bloom are capable of creating harmful toxins. Photo credit: Barry H. Rosen, USGS

20 µm

"The Landsat temperature product would definitely be something that could be a staple in terms of the forecast models that would be built going forward," Schaeffer said. "Temperature and nutrients are essential requirements when building the formulation of what drives these blooms."

HAB forecasting is still an evolving science, but when water quality researchers talk with water managers about what they need, they all want the same thing: "Everybody is really interested in being able to forecast when and where cyanobacterial blooms will occur," Schaeffer explained. "And that's really hard right now, but we know that one of the main drivers is temperature."

Better Together

CyAN, the World Water Quality Portal, and Cyanotracker—all of these projects are refining the HAB alert algorithms used to process satellite data into actionable information.

With the help of satellites like Landsat, HAB monitoring is happening across the globe. Satellite information is becoming a strategic asset for water managers protecting people from hazardous algal blooms, and upcoming missions like Landsat 9 and the NASA Plankton, Aerosol, Cloud, ocean Ecology (PACE) satellite will provide further information.

Meanwhile, HAB forecasting is on the horizon and satellites are poised to



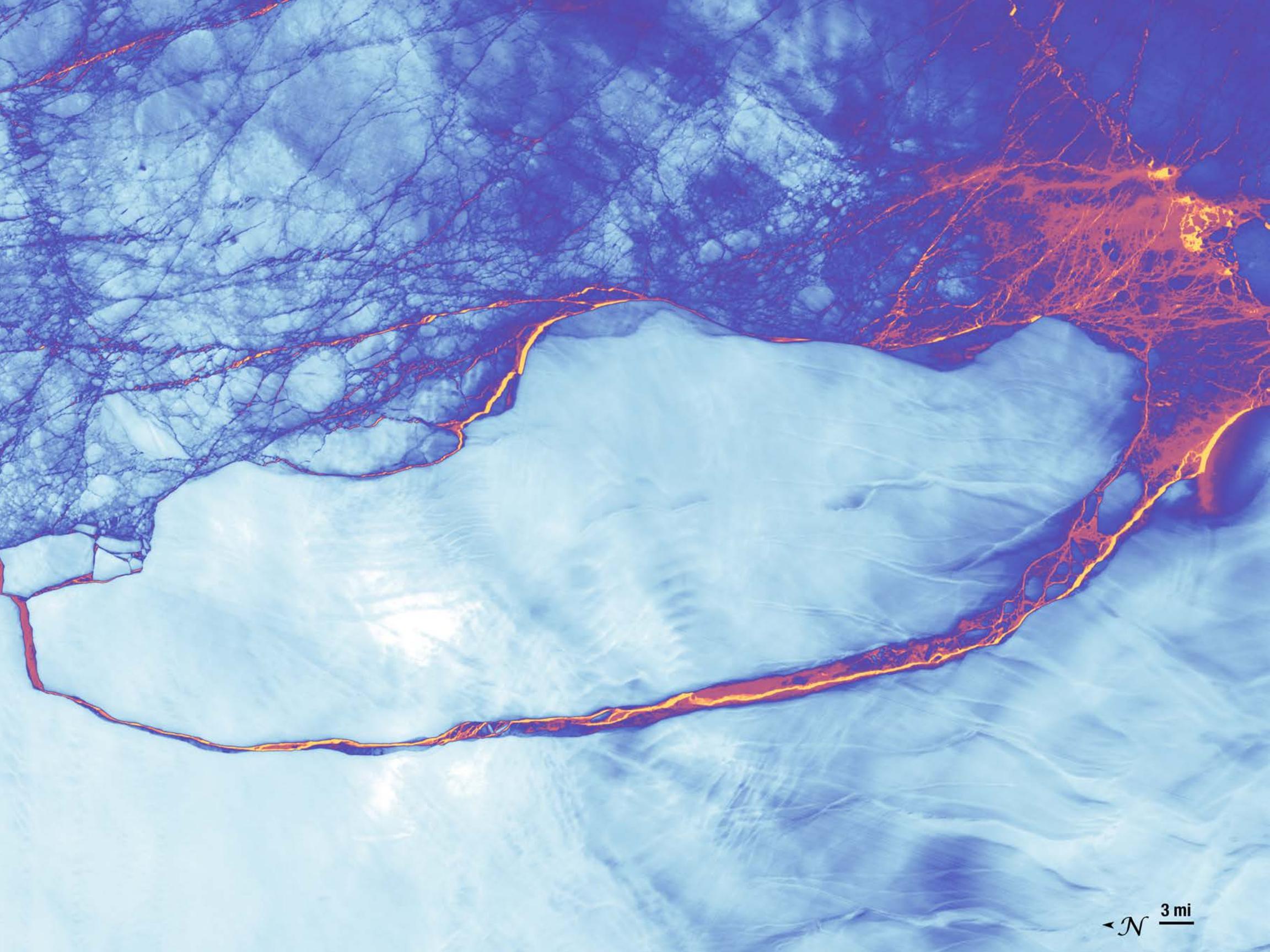
A warning sign not to swim in the water because of a blue-green algal bloom is taped to a piling near University Bay on the University of Wisconsin Madison's campus. Satellites are aiding the development of HAB forecasting models that will keep people safe from toxic waters. Photo credit: Donna K., National Environmental Education Foundation

help. The use of satellite data, together with ground measurements, citizen scientist observations, and modeling is what will eventually make HAB forecasts possible. As Schaeffer said, "It's when we figure out how to merge all that information together that we'll get the big comprehensive picture." ■

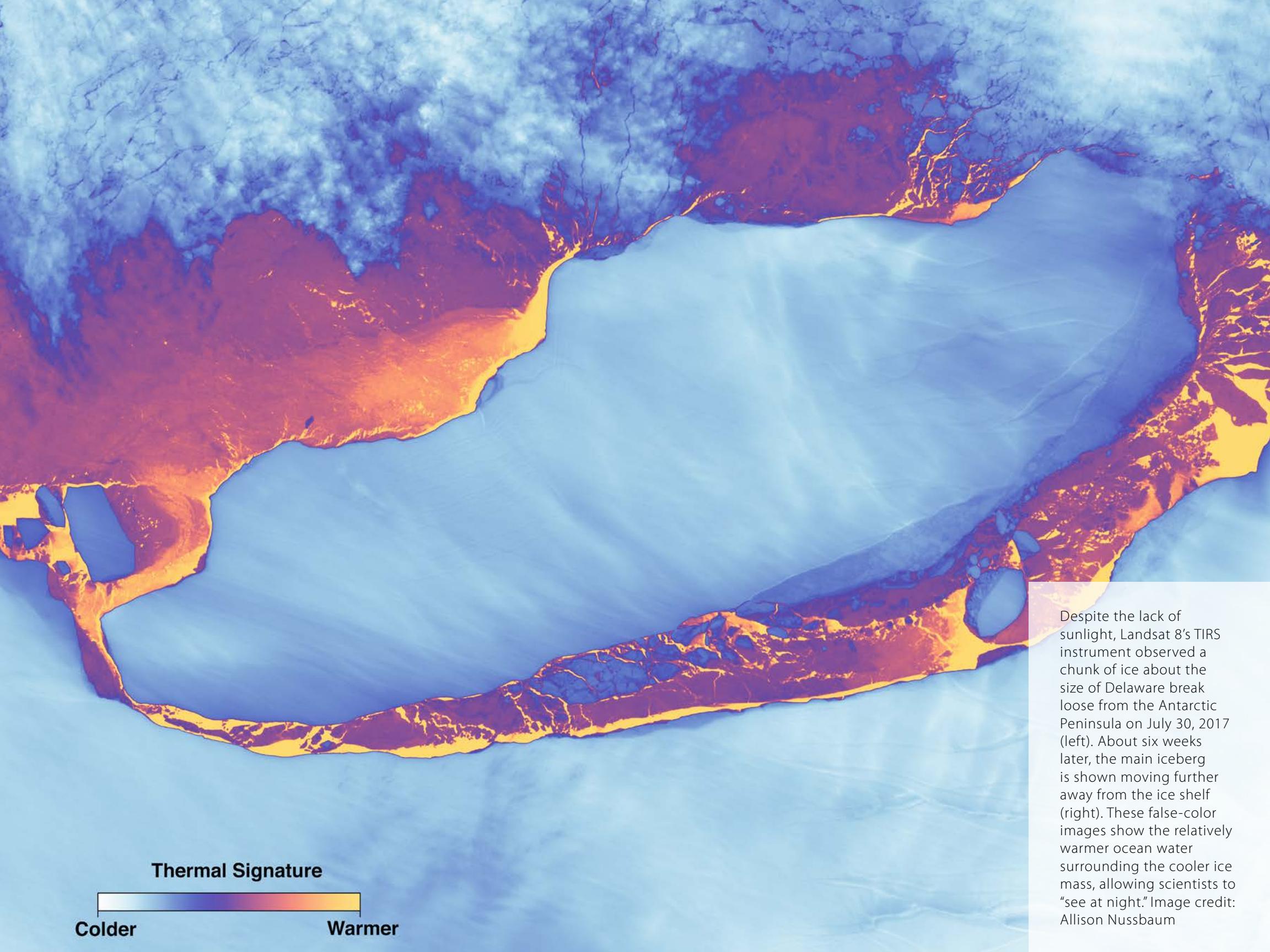
This article was originally published to the NASA Landsat Science website on October 11, 2018.

Satellite Data Requirements:

-  8-day revisit (daily preferred)
-  30 m resolution or better
-  Vis, NIR, SWIR, TIR
-  Global coverage
-  Archive continuity & consistency , interoperability with Sentinel-2
-  Rapid delivery of free, unrestricted data
-  Coregistered geolocation
-  ≤ 5% radiance calibration
-  12-bit data digitization



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Despite the lack of sunlight, Landsat 8's TIRS instrument observed a chunk of ice about the size of Delaware break loose from the Antarctic Peninsula on July 30, 2017 (left). About six weeks later, the main iceberg is shown moving further away from the ice shelf (right). These false-color images show the relatively warmer ocean water surrounding the cooler ice mass, allowing scientists to "see at night." Image credit: Allison Nussbaum



Landsat Provides Global View of Speed of Ice

Kate Ramsayer

Glaciers and ice sheets move in unique and sometimes surprising patterns, as illustrated by satellite-based technology that maps the speed of flowing ice in Greenland, Antarctica, and mountain ranges around the world.

With imagery and data from Landsat 8 scientists are providing a near-real-time view of every large glacier and ice sheet on Earth. The NASA-funded Global Land Ice Velocity Extraction project, called GoLIVE, is a collaboration between scientists from the University of Colorado, the University of Alaska, and NASA's Jet Propulsion Laboratory in Pasadena, California. It uses Landsat 8 imagery to better understand how ice flow is changing worldwide—and how this change impacts sea level.

"We are now able to map how the skin of ice is moving," said Ted Scambos, senior research scientist at the National Snow and Ice Data Center at the University of Colorado Boulder and the Colorado lead for the GoLIVE project. When he and his colleagues first shared these results at the 2016 American Geophysical Union's Fall Meeting in San Francisco, Scambos remarked "From now on, we're going to be able to track all of the different types of changes in glaciers—there's so much science to extract from the data."

With a near-real-time view of how glaciers and ice sheets are moving, researchers can integrate information

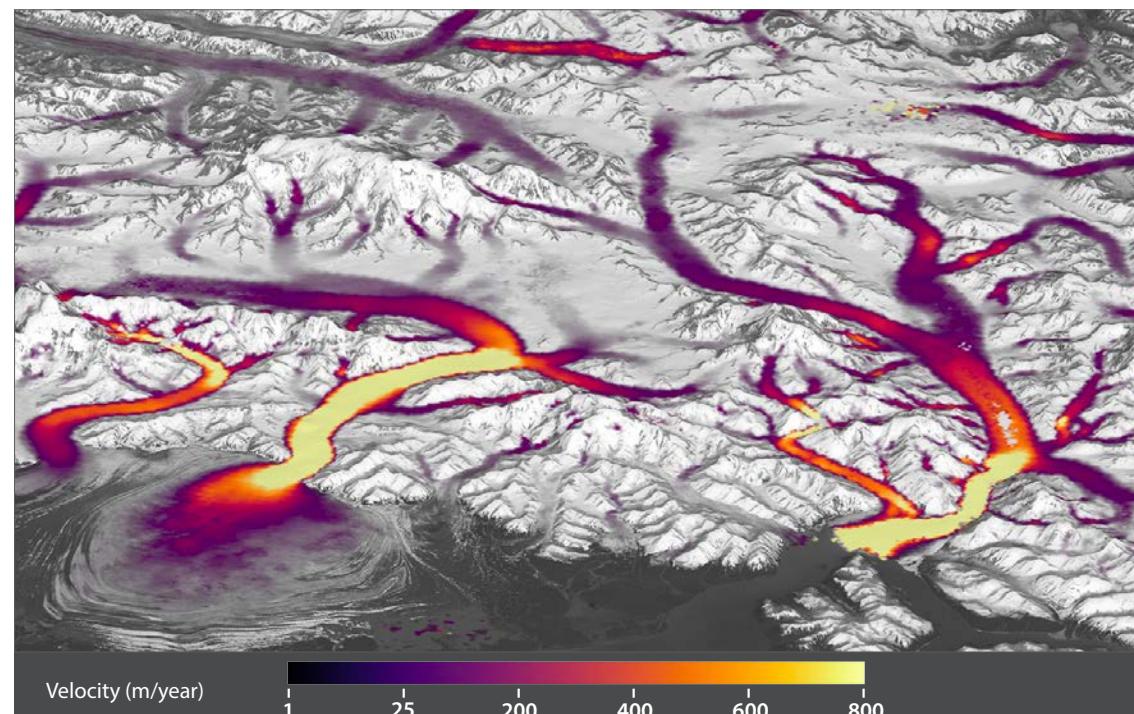
about atmosphere and ocean conditions to determine what causes these ice sheets to change—and what that change means for how much ice is flowing into the ocean. That could help provide critical information to coastal communities that could be most impacted by rising oceans.

"We can use the method to identify which areas to keep an eye on, or which events might lead to a rapid change," Scambos said.

To map the ice, the GoLIVE team has written software that is able to follow the surface's subtle features, like bumps or a dune-like pattern, as they flow toward the ocean. The Landsat 8 satellite collects

images of Earth's entire surface every 16 days. By comparing images taken from the same location, but at different times, the researchers use their software to track the features and determine the speed of the flowing ice.

Several new capabilities of Landsat 8 enable researchers to generate these global maps. The satellite can take 700 images a day—far more than its predecessors—which means it captures nearly every scene over land, every day, in all the sunlit parts of its orbit. Previous Landsat satellites often did not have the capacity to collect frequent data over remote sites like Antarctica. ▶



Above: The terminus of Exit Glacier in Alaska's Kenai Fjords National Park. Photo credit: I-pic, Fotolia images

In-page: A map of ice velocity in southeastern Alaska based on GoLIVE data and showing both the Malaspina and Hubbard glaciers. Image credit: Joshua Stevens, NASA Earth Observatory using Landsat-derived ice velocity data courtesy of Alex Gardner, NASA Jet Propulsion Laboratory/California Institute of Technology and ASTER data

Opposite: A rock outcropping along the Fleming Glacier on the west Antarctic Peninsula that feeds the accelerating glaciers in Marguerite Bay. Photo credit: NASA, Operation Ice Bridge



Above: A Landsat 8 image of glaciers extending from Cook Ice Cap that tops Grande Terre Island in the Kerguelen Archipelago. Image credit: Joshua Stevens, NASA Earth Observatory

The imaging system on Landsat 8 is also far more sensitive than past Landsat sensors, allowing it to distinguish far more subtle differences in shading and surface texture. This improved sensitivity, increased frequency of data collection, plus faster and more precise software, has revolutionized the extent to which ice flow speed can be mapped. These features will be continued in the Landsat 9 satellite, scheduled for launch in 2020.

Alaska

In Alaska, researchers can observe surging glaciers in almost real time, according to scientist Mark Fahnestock of the University of Alaska, Fairbanks. Often glaciers in Alaska and the Yukon in Canada are so remote that speedup events can go unnoticed for months, until a pilot flying over the region reports disrupted ice, he explained.

"By measuring ice flow all the time, we can identify a surge as it starts, providing an entirely new way to follow this phenomenon," he said. "We can also follow large seasonal swings in tidewater glaciers, as they respond to their environment. Scientists need to see all of this variability in order to identify trends that we need to worry about." The speed of the glacier,

combined with other information such as elevation change from NASA's Operation IceBridge campaign and other sources, provide researchers in Alaska with a better sense of the entire picture of changing ice.

Greenland

Twila Moon, another research scientist at the National Snow and Ice Data Center uses the global maps to expand the research she does on Greenland glaciers. With the new database, she can study the movements of more than 240 glaciers, which comprise nearly all of the outlets from the ice sheet. Several glaciers in northwest Greenland have accelerated speed in the last few years, while some glaciers in the southeast experienced a large jump in speed, followed by a plateau.

With Landsat 8 making a pass every 16 days, Moon can also measure seasonal changes. Most glacial movement occurs in cyclical patterns throughout the year, but movement patterns may vary. While most glaciers speed up in the warmer summer months, Moon has found several that slow down dramatically in the mid-to late-summer. The Heimdal Glacier in southeast Greenland, for example, can move more than 10 meters per day (33 feet per day) in early summer, then drop

to less than 6 meters per day (20 feet per day) by August or September. "We can group these glaciers by looking at the similarities in their behavior," Moon said. "It's providing an opportunity to get at the underlying drivers of why they change."

With measurements of what seasonal shifts do to glacier speed, scientists can extrapolate what will happen to those glaciers as global temperatures continue to climb, she explained. With fast-moving Greenland glaciers ending in the ocean, these studies can help scientists estimate how much new ice and water enters the Arctic Ocean. That new water can have both global and local impacts, including changing the local ecosystems, ocean flow patterns, and raising sea level.

"We're approaching a point where we have enough detailed information at different locations that we can start to answer important questions about what makes glaciers tick," Moon said.

Antarctica

Tracking the changes in speed in Antarctica is key because of the sheer size of the ice sheet and its potential to contribute to future changes in sea level. Almost 2,000 cubic kilometers (480 cubic miles) of ice flows into the surrounding ocean each year. ▶

How Landsat Helps: CLIMATE

Alex Gardner, a research scientist at NASA's Jet Propulsion Laboratory (JPL) combines the detailed Antarctic ice cover seen by Landsat 8 with an earlier continental mapping of glacier flow based on radar data. By piecing the data together, he is working to understand decadal changes in ice flow for the entirety of the Antarctic Ice sheet.

"Seemingly small changes in ice speed on some of these very large glaciers can have a real impact," Gardner said. "The question is, how sensitive are these ice sheets to changes in the atmosphere and the ocean? We could wait and see, or we could look to the past to help inform what is most likely to happen in the future."

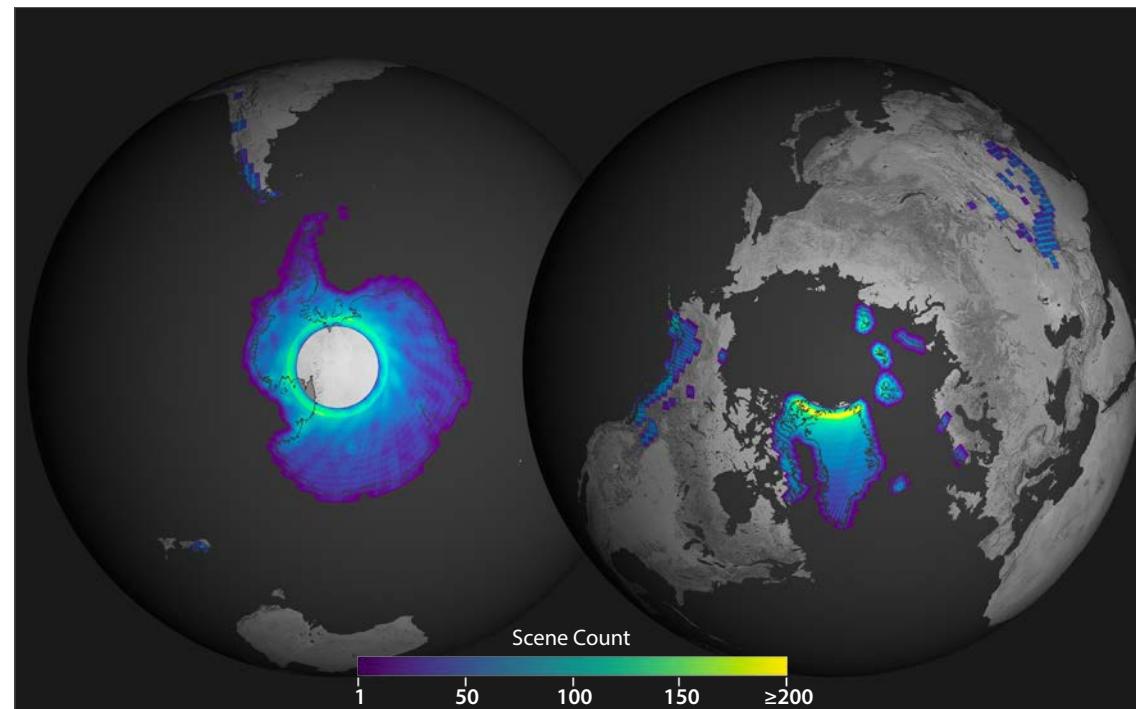
Landsat 8 images combined with those from earlier Landsat satellites reaching back to the 1980s, give researchers decades worth of imagery to investigate these links.

Using Landsat data, Gardner and Catherine Walker, a research scientist at JPL and now at NASA's Goddard Space Flight Center in Greenbelt, Maryland, located Antarctica's fastest accelerating glaciers. They found that between 2008 and 2015, glaciers on the western side of the Antarctic Peninsula dramatically and unexpectedly increased their flow rate after being relatively stable for the prior two decades. This finding helped illustrate how vulnerable the West Antarctic Ice Sheet is to increasing ocean temperatures.

While the ice flow of the West Antarctic Ice sheet accelerated, Gardner and Walker found that flow rates of the East Antarctica Ice Sheet remained remarkably stable during the same period.

More recently, researchers led by Karen Alley from the National Snow and Ice Data Center found that in addition to flow rate, they could also reliably measure how much ice stretches, bends, and

compresses as it flows. This information, known as strain rate, can show where ice is thickening or thinning and can improve predictions of where crevasses may form and how fast calving events will happen. With some modeling, strain rate can even show how firmly the ice is bound to the bedrock below, Scambos explained. ▶



Landsat 8 has a higher imaging capacity than earlier Landsat satellites, so its data archive grows quickly. This image shows all of the cloud-free Landsat 8 images captured over regions of perennial ice cover during 2015. In just one year, some locations had as many as 200 clear observations, while regular cloud cover limited the usable observations in other areas. Image credit: Joshua Stevens, NASA Earth Observatory



Above: A field of crevasses on Antarctica's Pine Island Glacier; close by the glacier transitions from a grounded ice sheet to a floating ice shelf. Photo credit: Ian Joughin, University of Washington

“From now on, we’re going to be able to track all of the different types of changes in glaciers—there’s so much science to extract from the data.”

—Ted Scambos, Senior Research Scientist NSIDC

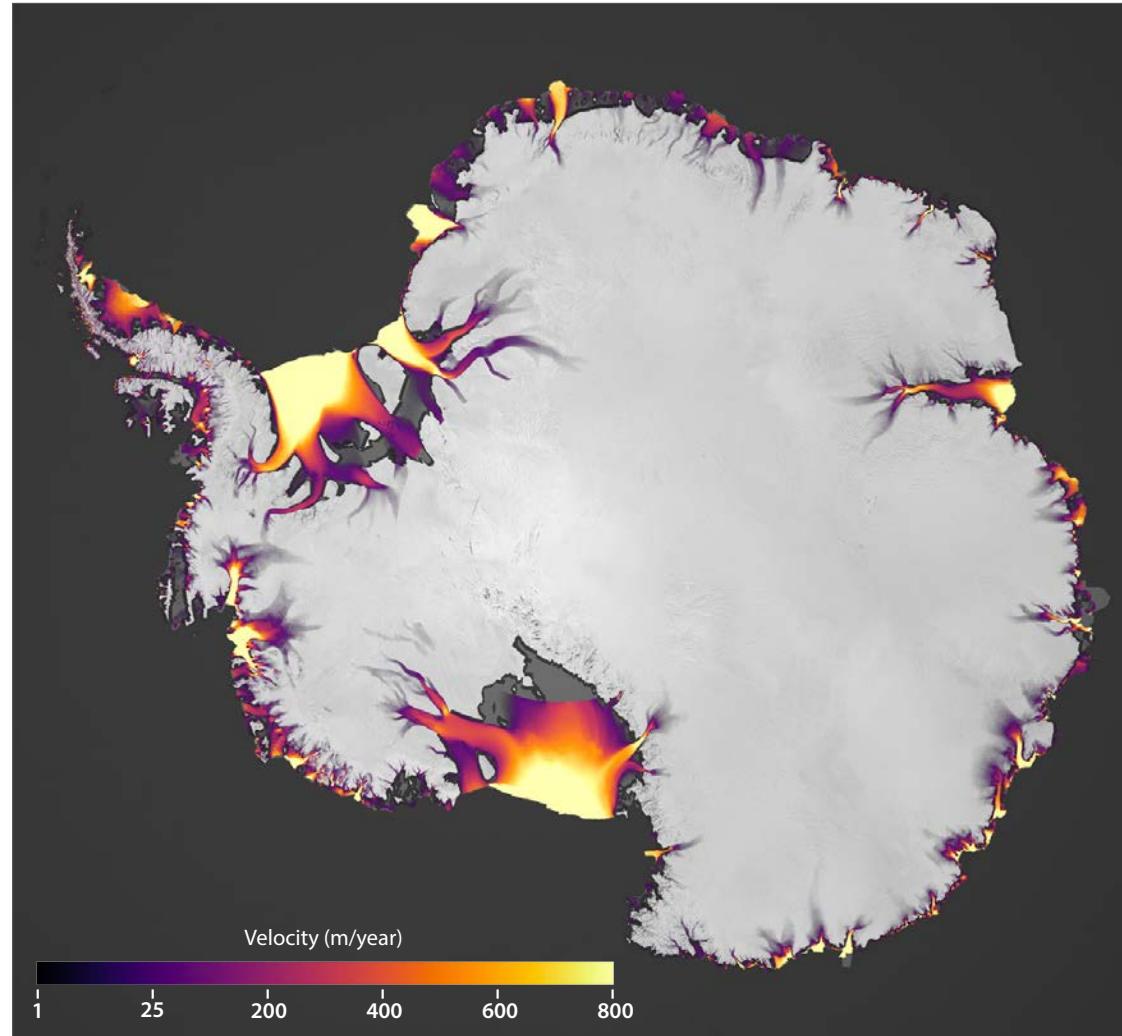


How Landsat Helps: CLIMATE

The scope of measurements researchers can make with GoLIVE continues to expand, as does the sophistication of the data processing behind it, allowing better and better monitoring of glaciers around the globe.

"It's incredible how these seemingly unchanging glacier systems come alive when we look at their changes through time—they're much more dynamic than you'd think," Gardner said. ■

This article was originally published on www.nasa.gov December 12, 2016. Updates for this publication were made in August 2018.



Above: Ice velocity map of Antarctica made with the GoLIVE Landsat-based ice-flow data. Image credit: Joshua Stevens, NASA Earth Observatory

Opposite: A scientist takes in the towering icescapes of Greenland during the 2017 Oceans Melting Greenland field campaign. Photo credit: NASA

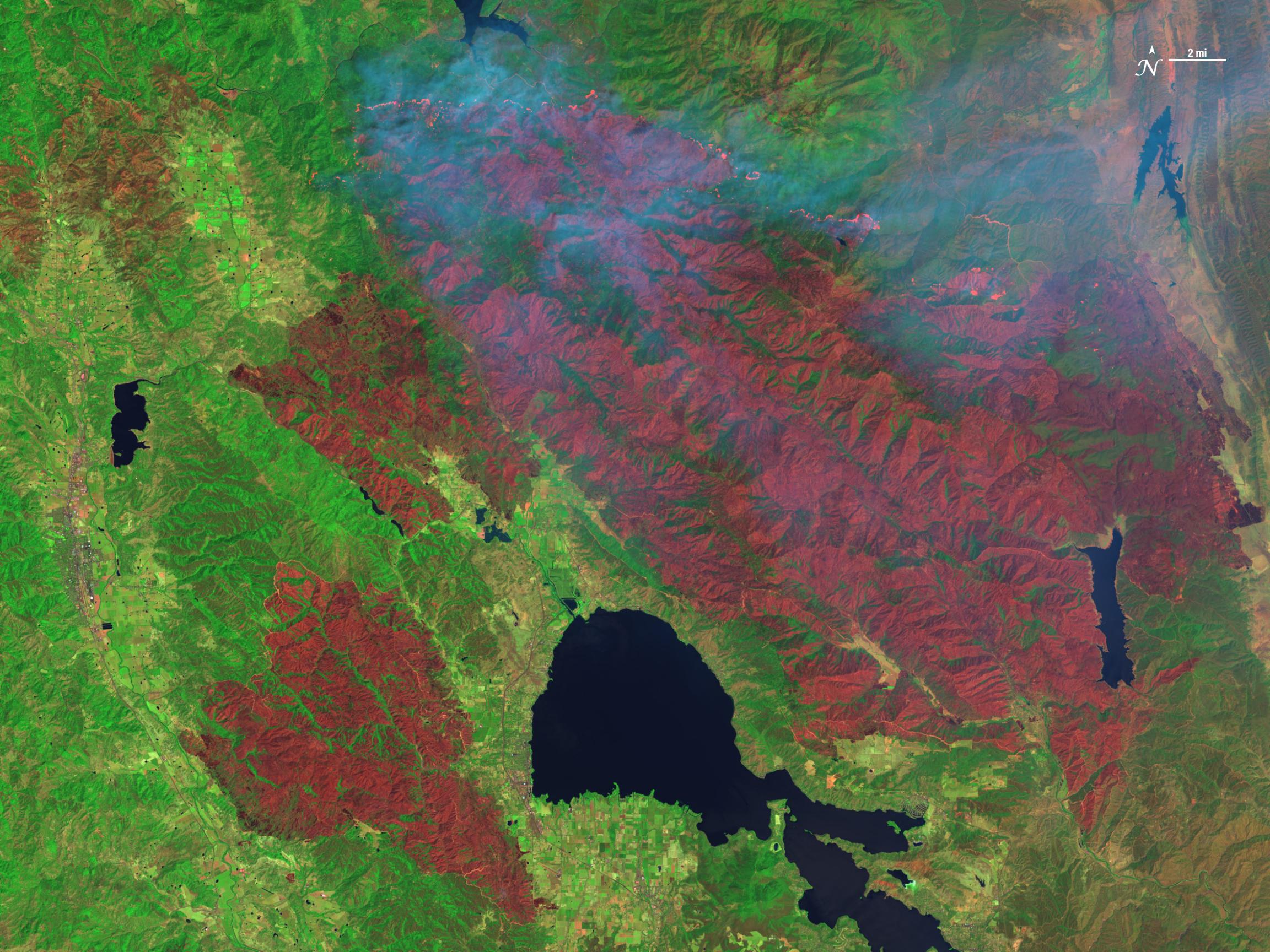
Satellite Data Requirements:

- ⌚ 16-day revisit, or better
- ▢ 15-30 m resolution
- ⚙ Vis, NIR, SWIR, Panchromatic
- ▀ Global coverage
- ⟳ Archive continuity and consistency
- ✈ Rapid delivery of free, unrestricted data
- ☒ Geolocation ≥ 15 m
- 🛠 Calibration $\geq 5\%$
- 👁 ≥ 12 -bit data digitization

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The Mendocino Complex was comprised of two fires, the River Fire and the Ranch Fire. Heavy smoke covers the Ranch Fire as it burns in the Mendocino National Forest northeast of Clear Lake in this natural-color Landsat 8 image acquired on August 11, 2018. The burn scar of the River Fire appears charcoal-gray (left). By mixing infrared with visible light, this false-color image created with the same Landsat data reveals both the extent of the burned area and the location of active fire. The freshly-burned area is red, unburned vegetation is green, active fire is orange, and heavy smoke appears blue (right). Image credit: Mike Taylor



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After the Fire: Landsat Helps Map the Way Forward

Steve Young and
Peggy Connot

When a wildfire rages across the landscape, the danger seldom ends with a final, fading ember.

After the fire dies, a research physical scientist like Dennis Staley with the U.S. Geological Survey's (USGS) Landslide Hazards Program in Golden, CO, needs to quickly figure out where post-fire danger potentially lurks. Where are debris flows likely to be unleashed on charred mountainsides? How much rain would send a muddy slurry of water, soil,

vegetation, and boulders careening down steep slopes? And just how massive—or deadly—might such a debris flow be?

The fact is, post-fire response teams look to Staley for answers. He, in turn, relies on the USGS' Earth Resources Observation and Science (EROS) Center and the U.S. Forest Service's Geospatial Technology and Applications Center (GTAC) for maps and projections derived from remotely sensed Landsat products to help those response teams prepare for the worst.



Because EROS burn maps primarily cover Department of Interior (DOI) lands and GTAC takes care of lands managed by the Forest Service and the Department of Agriculture, the combination of mapping products provides a complete look at an area both before and after a fire.

"There's no question," Staley said, "that the work EROS (and GTAC) does is critical to what we do." Staff at EROS and GTAC find two specific bands on Landsat especially useful to map fire damage effectively and quickly enough to be useful for post-fire mitigation efforts. These bands are combined shortwave infrared (SWIR) and near infrared (NIR), both of which help acquire information on moisture content in soil and vegetation, and on growing vegetation – two features that change substantially after a fire.

Vegetation reflects strongly in the NIR region of the electromagnetic spectrum while fire scar, which contains charred woody vegetation and bare land, reflects more strongly in the SWIR region. Combining NIR and SWIR allows a calculation of what is called a Difference Normalized Burn Ratio (dNBR). Figuring out fire damage relies on pre- and post-fire Landsat images of the burned area and capturing a range of values, which signify an uptick or decrease in greenness across the fire's footprint. "The greater the magnitude of the positive values," Staley said, "you can interpret as the more severely the fire impacted the surface cover." ▶



Above: Sandbags were placed around the historic Bandelier National Monument Visitors Center in August 2011 to protect it from rain-driven flooding after an earlier wildfire. Photo credit: National Park Service

In-page: USGS geologists from the Landslide Hazards Program and Earthquake Science Center work in Santa Barbara County, CA, to support a geohazard assessment of the Montecito Fire that burned from December 2017 to January 2018. Photo credit: USGS

Opposite: Laura Spellman, a Hot Shot firefighter, uses a drip torch to burn lower vegetation in an attempt to contain a fire in California's Mendocino National Forest. Photo credit: Cecilio Ricardo, U.S. Forest Service



Above: Landsat 8 captured an image of the Thomas fire scar on December 18, 2017. The natural-color Landsat 8 image was draped over an ASTER-derived Global Digital Elevation Model, which shows the topography of the area. The fire raged first near Ventura, then burned the hills around communities of Ojai and Oak View. Image credit: Landsat/ASTER, NASA Earth Observatory

In-page: This burn severity product was created using several inputs acquired in the days after the Los Conchas Fire at the Bandelier National Monument began on June 26, 2011. A Landsat 5 image from July 3, 2011, was used for a majority of the interior and southern portions of the burn area. A SPOT satellite image from July 5, 2011 was used for the western and far north areas, where cloud cover and newly burned areas existed.

Turning Landsat-derived Burn Ratios into Field Information

The Landsat-derived dNBR values then are categorized into four loosely defined classes: unburned, low burn severity, moderate severity, and high severity. That information is transformed into Burned Area Reflectance Classification (BARC) data that are then handed off to Burned Area Emergency Response (BAER) teams to use in the field as a guide for more in-depth field measurements and observations of fire damage.

In as little time as possible, the BAER teams turn all that information into what is called a Soil Burn Severity Map, which is then used in the effort to stabilize landscapes where needed and hopefully prevent further damage to life, communities, property, or natural resources.

That's important for several reasons. Hillside soils, vegetation, and rocks no longer anchored by forested mountainsides pose erosion and runoff risks to water quality in the area, said Birgit Peterson, a USGS geographer at EROS. That in turn can impact fish and other habitat. To try to prevent that, post-fire mitigation efforts can include activities such as quickly

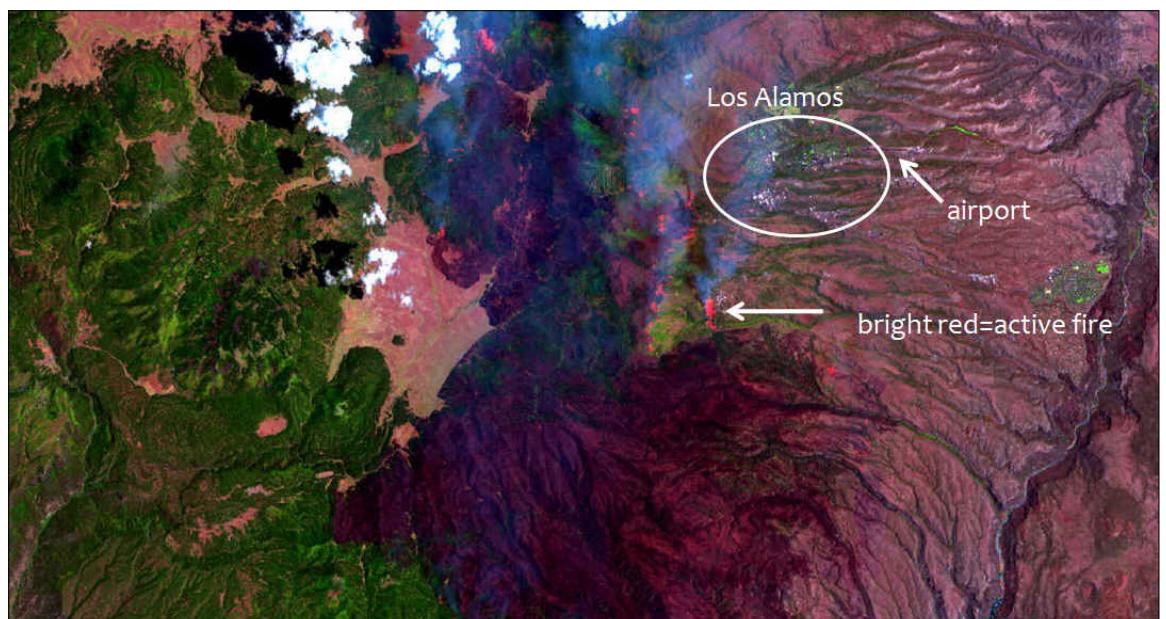
reseeding or putting up barriers to redirect potential mud and debris flows.

"Even if we're not worried about homes or other structures being destroyed because of huge volumes of earth being displaced, it's still going to be enough to have impacts down the line," Peterson said. "Those are the kinds of things the BAER teams are on the ground assessing."

In a year's time, Staley and his colleagues in the Landslide Hazards Program modeled hazards for 91 different fire events across the United States as of early 2018. Among the most significant was

the Thomas Fire in Southern California. The second largest wildfire in modern California history, that monster blaze burned more than 280,000 acres in just over a month—from December 4, 2017, to its full containment on January 12, 2018—in Ventura and Santa Barbara counties.

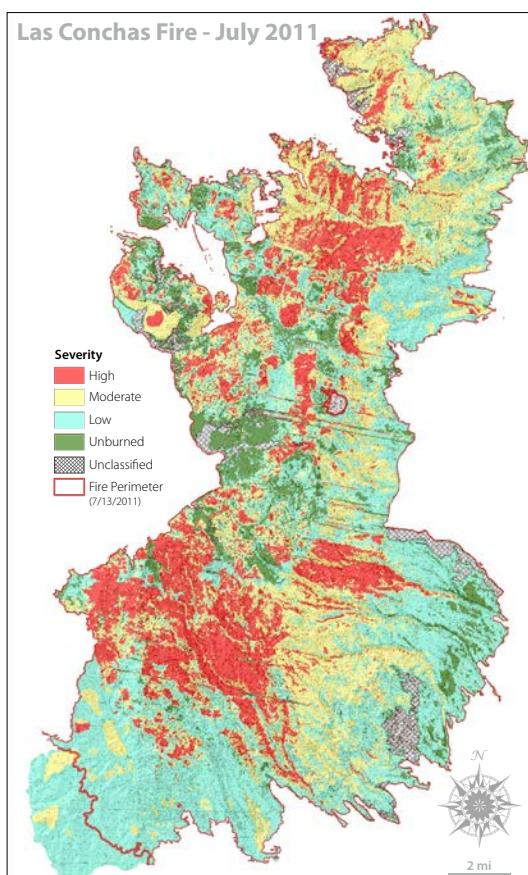
Strong, persistent Santa Ana winds drove Thomas as it destroyed at least 1,063 structures—including 500 in one night in the city of Ventura—and damaged 280 more. As the flames died, heavy rains fell in January on the scorched hills above the town of Montecito. ▶



How Landsat Helps: FIRE

The rapid erosion, mud flows, and debris flows that followed caused catastrophic damage in Montecito Creek and San Ysidro Creek. All told, 21 fatalities, 129 destroyed residences, and 307 damaged residences were attributed to the debris flows in Santa Barbara County.

While the BAER team could not prevent the damage that occurred in Montecito, the Landslide Hazards Program engaged in a forensic analysis. Using mapping in and around the area affected by the deadly mudslide, they helped local officials and emergency responders identify and understand the mudslide hazards and additional areas of immediate risk.



The forensic analysis also looked to the future to improve understanding of data and its use in the prediction of post-fire landslide and inundation.

Unfortunately, BAER teams working with burn maps in the field aren't always able to stave off the post-fire destruction of Mother Nature. But their quick actions can and often do help save lives and structures. A good example of that occurred after the Las Conchas fire just west of Bandelier National Monument in New Mexico that began on June 26, 2011.

That wildfire started with a tree falling onto a power line. There were sparks, then very quickly a wilderness ablaze. In its first 13 hours, the Las Conchas Fire spread at a rate of an acre per second. By the time the last embers died weeks later, it had grown into what then was the largest wildfire in New Mexico history.

Assessing Las Conchas Fire Damage Relied on Landsat Burn Maps

In the smoldering aftermath, a BAER team of hydrologists, soil scientists, engineers, biologists, archeologists, and more stepped in to assess the damage armed with burn maps from EROS.

"Fires will burn in a mosaic. Not every patch is going to be equal as far as the burn severity," said Rich Schwab, the post-fire program director for the National Park Service. Still, with BARC data in hand after the Las Conchas Fire, the BAER team was able to assess those places where a loss of vegetation would most likely expose soil to erosion and other risks.

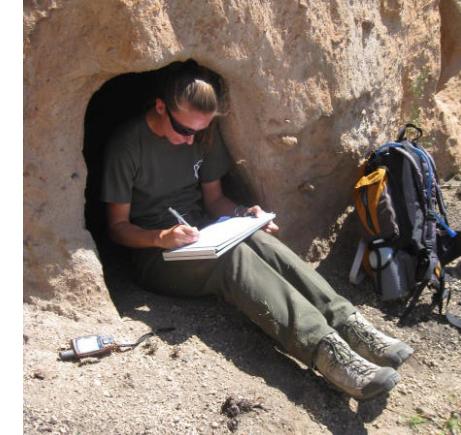
All the major watersheds within Bandelier National Monument were heavily impacted by the fire, including Frijoles Canyon, where the historic Visitors Center and the main archeological sites are located. Over 75 percent of Frijoles Canyon lay within the fire's footprint, much of it burned with high severity. Using burn severity maps and flood models, the BAER team developed a solid understanding of what potential dangers existed should the skies open up.

As it turned out, heavy rain did in fact begin falling that following August, sending huge torrents of water rampaging through the watershed and toward the Visitors Center at the bottom of the canyon. Based on the burn maps and ground assessments, the BAER team knew that there hadn't been time for seed to germinate on the slopes and slow any potential flooding. Nor would using fallen trees to channel floodwaters work in this situation.

So, after relying heavily on the burn maps and studying the burned areas, researchers "came back and said, 'Your best bet is evacuation and point protection,'" Schwab said.

They put down modular concrete Jersey barriers to divert any potential floodwater away from the Visitors Center and parking lot. They also put sandbags out by the corner of the Visitors Center to help protect it as well. It worked, and the Visitors Center was saved.

That's the goal every time, EROS' Peterson explains. "The maps we produce really are meant for them to use to help dictate where responses need to be made." ▶



Above: A Burned Area Emergency Response team member makes field notes related to soil burn severity at the Bandelier National Monument in New Mexico after the Los Conchas Fire. Photo credit: National Park Service

In-Page: The National Interagency BAER Team created this soil burn severity map after the June 2011 Las Conchas Fire in Bandelier National Monument using satellite imagery, ground mapping, and aerial mapping.



The 2011 Las Conchas Fire. Smoke billows into the town of Los Alamos on the evening of June 26th. Photo was taken from the parking lot of Los Alamos High School. Photo credit: Kristen Honig

"What mitigation activities do they need to undergo to keep worse things from happening? Our maps help to get them to that point."

The fact is, GTAC and EROS burn mapping products have been used heavily across federally managed lands through the years. For example, from 2001 through 2016, 609 wildfires on DOI-managed lands were mapped, accounting for almost 25 million acres.

"The maps are an important part of what we do, what the BAER teams do," Schwab said. "We need to assess the risks that exist after a fire as quickly as we can. Those maps help us do that."

Using Landsat to Locate Areas Susceptible to Future Flooding

While there is an immediate need to identify burn severity so local officials and emergency responders can rapidly understand where hazardous areas exist should heavy rainfall occur, there is a longer-term goal as well to post-fire hazard modeling. Staley said he and his colleagues would like to use remotely sensed data acquired after wildfires to estimate locations that may be susceptible to inundation much farther out in the future.

That's an idea he and EROS staff have discussed. While the immediate analysis that comes with pre- and post-fire Landsat images and the dNBR index will always be important, Staley said



Geologists measure the diameter of a boulder displaced by the Montecito, CA, debris flow, which will be used to understand the power of the flow. Photo credit: USGS

the idea of monitoring hazard sites long term using Landsat images would allow them to tie the dNBR index values to vegetation, soil, and hydrologic recovery.

"This is something that would be a huge advancement in the science from our perspective in terms of the hazards assessment and early warning that we do," Staley said. "One of the most frequent questions we get from folks on the ground that live below places that produce debris flows is, 'How long will this hazard last?' We have data based on our monitoring that says, 'Oh, it could be anywhere from, say, two to five years.'

With the help of Landsat, EROS and GTAC are trying to save lives and protect communities and natural resources long after the last ember has cooled.

The Thomas Fire proved it to him. "I think 20 fatalities is 20 too many," Staley says. "But I definitely think the teams we communicated and worked with, the BAER and WERT teams, succeeded in making a difference. I think those teams were responsible for saving multiple lives." ■

Previously published as two stories on the EROS website (eros.usgs.gov) on June 6, 2018, and May 7, 2018.

Satellite Data Requirements:

- 8-day revisit (w/ L7)
- ≤ 30 m resolution
- Vis, NIR, SWIR, TIR
- Continuous spatial coverage
- Archive continuity & consistency
- Rapid delivery of free, unrestricted data
- Geolocation ≤ 0.5 pix
- ≤ 5% radiance calibration
- 8-bit data digitization

Approaching a Half Century of Data

Linda Owen, Michelle Bouchard,
and Chris Barnes

"The Landsat program is one of the world's greatest open data success stories.

Landsat satellites have been orbiting the Earth for decades, creating an irreplaceable archive for studying questions ranging from the retreat of the Aral Sea to water quality in Iowa."

— Tom Lee, Policy Lead for MapBox, Aug 9, 2018

In-page: A path/row density map of the over 8 million Landsat acquisitions from July 25, 1972 through September 1, 2018 that are available in the USGS Earth Resources and Observation

Science Center's Landsat archive. Visualization credit:

Matt Radcliff with data provided by the USGS EROS Center.

Open Data Policy

On April 21, 2008, the USGS officially announced a schedule to provide users with no-charge electronic access to any Landsat scene held in the USGS-managed archive. The Landsat archive, dating back to 1972, was reprocessed to standard parameters (i.e., UTM projection, WGS84 datum, cubic convolution resampling, and GeoTIFF data format) and by January 2009 all Landsat 1-7 data held in the USGS archive became available for download at no charge. This access allowed scientists and land managers to use the archive for new applications at unprecedented spatial scales and led to a four order-of-magnitude increase in Landsat data downloads. As of Sept 1, 2018, users have downloaded more than 87 million Landsat scenes from the USGS archive.

The Landsat Archive Continues to Grow

Once NASA launches a Landsat satellite and verifies its operation, the USGS collects, archives, and distributes the data. These data are used to create images essential for understanding a changing Earth. With approximately three petabytes (+7.8 million scenes) of data archived to date, the Landsat archive grows by nearly 700 gigabytes each day with new Landsat 7 and Landsat 8 acquisitions. Landsat 9 will continue to add to the archive volume by imaging all global landmasses and near-shore coastal regions, including islands at a solar elevation greater than 5 degrees that have not been routinely collected on previous Landsat missions.

Landsat Global Archive Consolidation

In addition to current missions, the USGS continues to add historical data that were previously held only by International Ground Stations via the Landsat Global Archive Consolidation (LGAC) effort established in 2010. Early Landsat missions lacked onboard storage capabilities; instead, data were downlinked to International Ground Stations spread across the world. The goal of LGAC is to 'bring home' all unique data originally stored only by International Ground Stations. There have been some challenges in retrieving the data due to varying storage formats and due to the age and condition of the media devices used. However, over 3.6

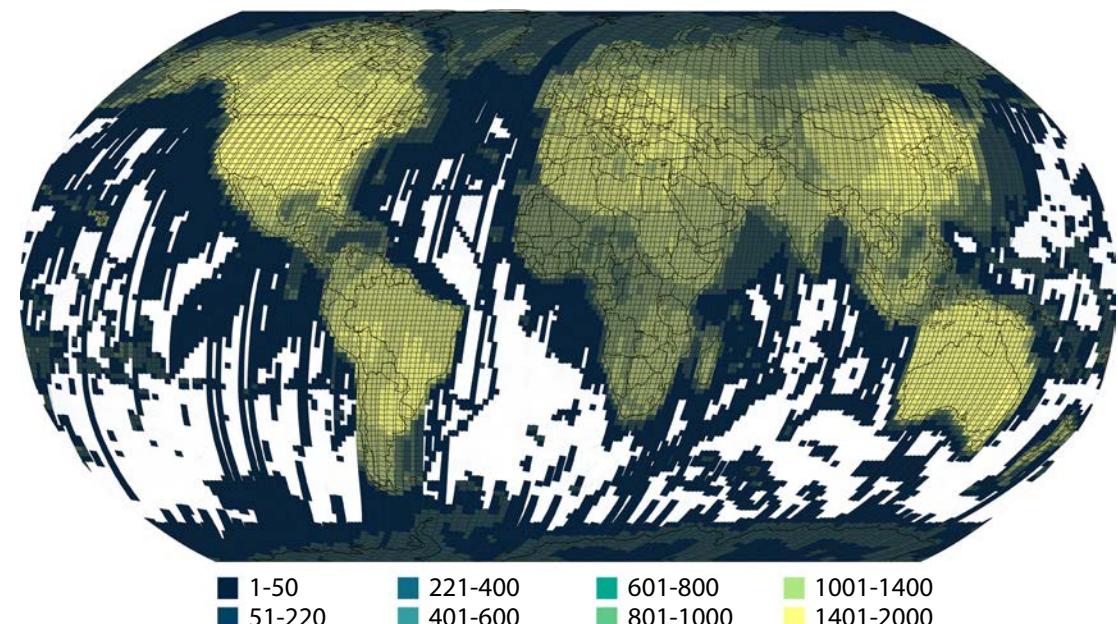
million of these unique scenes have been successfully made available for download in the USGS archive. To date, over 46 percent of the Landsat archive are from data acquired through the LGAC initiative, thus enriching the Landsat archive and furthering our ability to understand past changes on the Earth.

Landsat Global Archive Consolidation:
<https://landsat.usgs.gov/landsat-global-archive-consolidation-lgac>

Landsat International Ground Stations:
<https://landsat.usgs.gov/igs-network>

Landsat Data Archive
Landsat data are available to download at no charge from EarthExplorer:
<https://earthexplorer.usgs.gov>

Landsat Global Acquisitions



Glossary of Requirements & Landsat Spectral Bands

Revisit Time

The time that elapses between two consecutive overpasses of a location. Because of cloud cover, the period between clear observations for an application may be longer than the revisit time. To get seasonal observations, the satellite must acquire several images during the season to increase the likelihood that the area will be cloud free during at least one overpass per season.

Spatial Resolution

Spatial resolution refers to the amount of detail shown in the image or the size of a pixel on the ground. For most Landsat 8 and Landsat 9 observations, each pixel on the ground is 30 x 30 meters, about the size of a baseball diamond. The 100 x 100 meter thermal infrared observations are resampled to 30-meters during product generation.

Spectral Coverage

Most applications require observations in specific wavelength regions of light. Spectral coverage refers to the range of wavelengths observed by a sensor. In the table, Vis refers to visible light, NIR refers to near infrared, SWIR refers to short wave infrared, and TIR is thermal infrared. Landsat 8 collects data for multiple spectral bands within each region.

Geolocation

Geolocation is the accuracy with which each pixel in a satellite image is mapped to the Earth's surface. Pixels within Landat 8 and Landsat 9 images are referenced to within 12 meters of their actual location. Coregistration from scene to scene acquired on different dates is important so that users can compare scenes and know that they show the same location on the ground.

Radiance Calibration

Landsat pixel values record the absolute intensity of light received by the sensor. Radiance calibration refers to the accuracy with which the sensor records that intensity. Five percent radiance calibration required by most applications is the uncertainty relative to the actual intensity.

Data Digitization

The number of bits used to represent each pixel value in an image. The number of bits reflects the sensitivity of the data to the intensity of light received by a sensor. As an analogy, six-bit data, providing integer values between zero and 63, are required to record the range of measurements available from a foot-long ruler marked every quarter inch (48 gradations). Eight-bit data, zero to 255, are necessary to record the range of measurements available from a one-foot ruler marked every sixteenth inch (192 gradations).

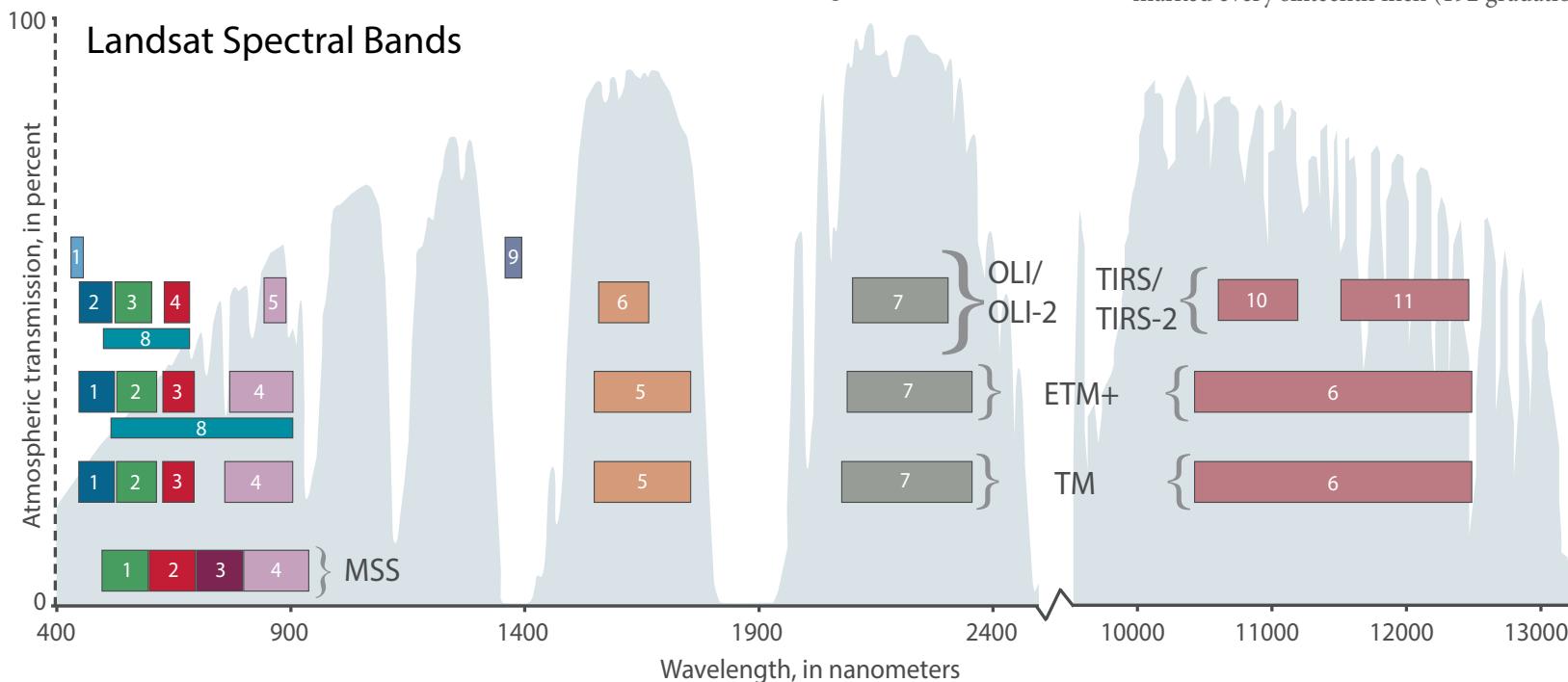
"The Landsat archive and other remote sensing systems provide the means to map and measure disturbance rates of the last 40 years."

— Jeff Masek, Landsat 9 Project Scientist, Watching A Quarter Century of North American Forest Dynamics with Landsat, Apr 27, 2018

In-page: The Multispectral Scanner System (MSS) aboard Landsats 1–5 had four bands. The Thematic Mapper (TM) aboard Landsats 4 & 5 had seven bands. Landsat 7's Enhanced Thematic Mapper Plus (ETM+) has 8 bands and the OLI and TIRS (1&2) onboard Landsats 8 & 9 have 11 bands. Image credit: Laura Rocchio and Julia Barsi

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Landsat represents the world's longest continuously acquired collection of space-based moderate-resolution land remote sensing data. Nearly five decades of imagery provides a unique resource for those who work in agriculture, geology, forestry, regional planning, education, mapping, and global change research.

As a joint initiative between the U.S. Geological Survey (USGS) and NASA, the Landsat Project and the data it collects support government, commercial, industrial, civilian, military, and educational communities throughout the United States and worldwide.

Landsat 9 will start adding data to the Landsat archive in 2021 following its launch and on-orbit checkout period. The mission will extend the Landsat data record past the half-century mark. Landsat 9 data will meet both NASA and USGS scientific and operational requirements for observing land use and land change.