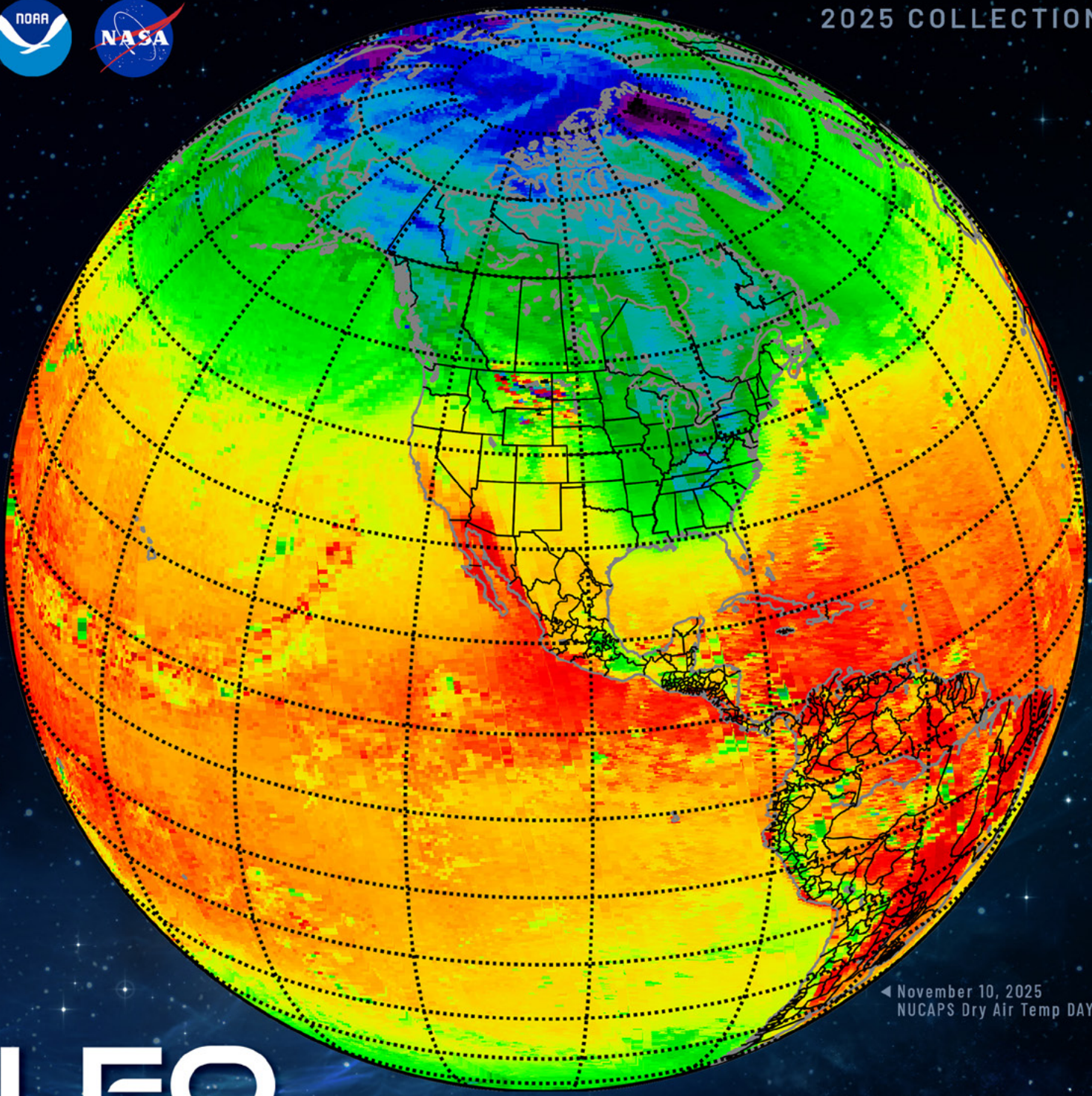
2025 COLLECTION



◀ November 10, 2025
NUCAPS Dry Air Temp DAY

LEO SCIENCE DIGEST

Exploring the impact and applications of low Earth orbit data

From the NOAA NESDIS Office of Low Earth Orbit (LEO) Observations

Welcome to the
2025 LEO Science Digest!

Learn more about the NOAA NESDIS Office of Low Earth Orbit (LEO) Observations by visiting our web page.

The image on the cover shows a polar vortex disruption that resulted in a blast of frigid Arctic air to much of the United States, causing widespread freeze alerts from Texas to the Carolinas as observed by CrIS and ATMS sensors on NOAA20 and NOAA21 satellites on November 10, 2025. Air temperatures close to Earth's surface are retrieved using the NOAA-Unique Combined Atmospheric Processing System (NUCAPS). Image processing by Dr. Likun Wang, CISESS, University of Maryland at College Park.

FEATURED IN THIS

SCIENCE DIGEST

6 Opening Messages

14 FEATURE 1
Resilience in the Last Frontier: The Role of LEO Observations in Alaska

30 FEATURE 2
A Case Study in Flooding: Insights From LEO Satellites

44 FEATURE 3
Mapping and Tracking River Ice Hazards from Low Earth Orbit

60 FEATURE 4
Designing Next-Generation Observing Systems to Support Better Weather Prediction

74 FEATURE 5
Tracking Hazards From Low Earth Orbit: The Impact of Hurricane Helene on North Carolina's Mountain Region

94 FEATURE 6
Inside the Storm: Estimating Tropical Cyclone Intensity with LEO Microwave Soundings

110 FEATURE 7
Enhancing Weather, Water, and Hazard Forecasts With Blended LEO Soil Moisture Observations

126 FEATURE 8
From Data to Decisions: The Role of a Satellite Liaison

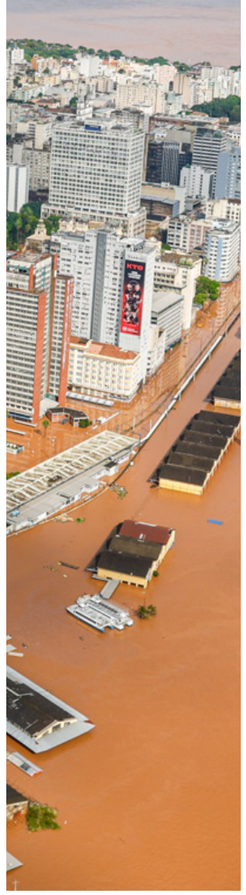
144 FEATURE 9
HARP2's Multi-Angle View: Advancing Aerosol and Cloud Measurements From Space

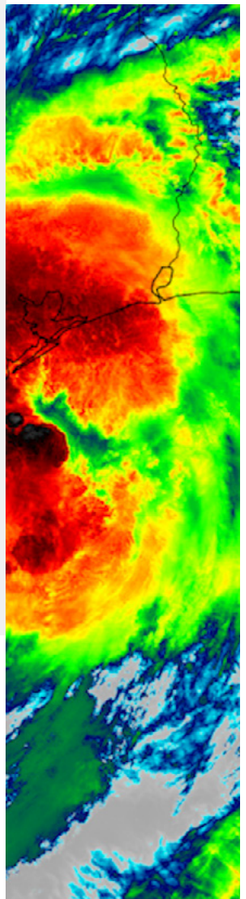
162 FEATURE 10
Cascading Impacts: LEO Insights into the Effects of Wildfires on California Agriculture

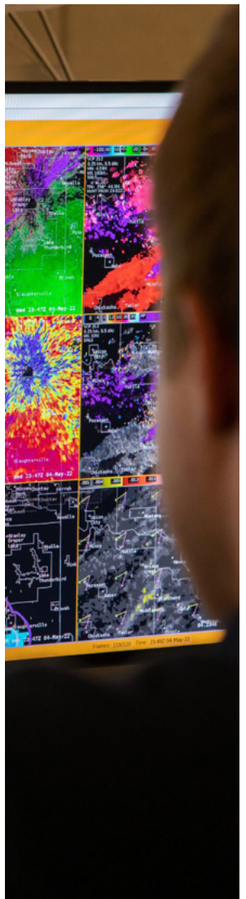
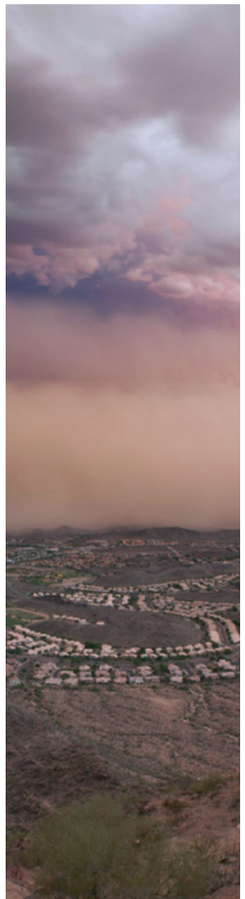
180 Highlights: Meet the LEO Summer Interns

188 Highlights: JPSS in the News

194 Highlights: LEO Web Stories from NESDIS





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Feature 5 - Tracking Hazards From Low Earth Orbit: The Impact of Hurricane Helene on North Carolina's Mountain Region
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Feature 7 - Enhancing Weather, Water, and Hazard Forecasts With Blended LEO Soil Moisture Observations
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Feature 8 - From Data to Decisions: The Role of a Satellite Liaison
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Feature 9 - HARP2's Multi-Angle View: Advancing Aerosol and Cloud Measurements From Space
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The contents of the LEO Science Digest are solely the opinions of the authors and do not constitute a statement or policy decision, or position on behalf of the Government of the United States of America, the U.S. Department of Commerce, the National Oceanic and Atmospheric Administration (NOAA), or partnering agencies and organizations.

Timothy Walsh

LEO PROGRAM DIRECTOR

Welcome to the *2025 LEO Science Digest*, the annual publication from the Office of Low Earth Orbit (LEO) Observations. Originally known as the *JPSS Science Digest*, the publication highlights the broad applications and benefits of LEO observations supported by NOAA's National Environmental Satellite, Data, and Information Service (NESDIS). The Office of LEO Observations manages two major NOAA satellite programs: the Joint Polar Satellite System (JPSS), our foundational program that will exist well into the 2030s, and the Near Earth Orbit Network (NEON), our next generation program that will implement future LEO architecture beyond JPSS.

The *LEO Science Digest* continues to showcase how LEO observations benefit society and the importance of their applications. It features content from monthly LEO Science Seminars hosted by NESDIS, where scientists, data users, and decision makers discuss how they apply LEO observations to their work to solve real-world challenges. Through its articles, the *Digest* demonstrates how LEO data benefit a wide range of economic sectors while strengthening weather forecasting, disaster response, and environmental monitoring of our oceans, land, and atmosphere.

This year, the three operational JPSS satellites continued the vital mission of providing our nation with crucial weather data every day. In November, NOAA-21, the primary satellite in the JPSS constellation, celebrated its third year in orbit, and NOAA-20 completed its eighth year in orbit. The Suomi National Polar-orbiting Partnership (Suomi-NPP) celebrated a remarkable fourteen years of operations in October, roughly double its anticipated operational lifespan. The JPSS baseline suite of instruments—the Advanced Technology Microwave Sounder (ATMS), the Cross-track Infrared Sounder (CrIS), the Visible Infrared Imaging Radiometer Suite (VIIRS), and the Ozone Mapping and Profiler Suite (OMPS)—continued to provide life-saving data and valuable products to users throughout a year marked by hurricanes, tornadoes, droughts, floods, fires, heat waves, and other severe weather.

We also achieved significant advancements for the future of the JPSS program, helping to ensure forecast data continuity for decades to come. JPSS-4, the next satellite in the series to launch, continued to successfully complete pre-launch activities in preparation for its launch readiness date in 2027. JPSS-4 completed its System Integration Review, Electromagnetic Interference and Electromagnetic Compatibility Testing, and Mechanical Environment Testing. JPSS-4 also had a successful test deployment of its solar array.

JPSS-4 now awaits integration of Libera, a NASA research and development instrument designed to measure Earth's solar radiation budget with greater accuracy than ever before. Libera is a follow-on to the Clouds and the Earth's Radiant Energy System (CERES) instrument that currently flies on Suomi-NPP and NOAA-20. It will observe and help maintain the 40-year data record of Earth's energy imbalance, allowing scientists to better understand shifts in Earth's systems. JPSS-4 was moved ahead of JPSS-3 in the launch sequence to minimize the schedule and cost risk to the satellites as Libera was integrated.

Meanwhile, the JPSS-3 satellite completed integration activities and was placed into long-term storage. Planned to launch in FY 2033, JPSS-3 will be tested annually to ensure its health and readiness for launch.

In preparing for the future beyond JPSS, the Office of LEO Observations made substantial progress this year with the NEON program, which lays the groundwork for the next generation of LEO satellites before the final JPSS launch takes place.

In March 2025, the NEON program passed Key Decision Point I, the first major decision point that marks the transition from the Formulation phase to the Implementation phase. NEON Series-1 and Series-2 projects will focus on providing microwave and infrared sounding data and weather imagery that are necessary to maintain the continuity of observations essential for weather forecasting. In April 2025, NOAA released the draft request for proposal for the NEON Series-1 microwave sounding instrument, called the Sounder for Microwave-Based Applications (SMBA). Microwave sounders will be the first NEON instruments launched, as their data has the greatest impact on weather forecast model accuracy. The SMBA instrument will be the follow-on to ATMS and serve as the backbone microwave sounder for the NEON program, with the first Series-1 launch planned in the early 2030s.

QuickSounder, NOAA's first environmental smallsat, is the NEON program's first project and will fly a refurbished ATMS instrument, similar to those currently flying on JPSS. The Southwest Research Institute completed integration of the ATMS instrument onto the spacecraft in October as it continues development for launch in 2026. Lessons learned from the QuickSounder mission will inform business and technical approaches for the NEON program to better leverage technological and market innovations in the aerospace industry.

In September 2025, NOAA entered into an Other Transaction Authority (OTA) agreement to partner with commercial industry to conduct a mission design and feasibility study for the Stratus project. The Stratus project, a pathfinding mission for NEON Series-2, is a single satellite consisting of a spacecraft and a weather imager instrument that will provide weather imagery essential to monitoring clouds, fog, smoke, sea ice, and other phenomena supporting weather forecasting, transportation, and commerce. The Stratus project leverages weather imager instrument materials and design developed by the U.S. Space Force, which will be modified to meet NOAA requirements.

With the lessons we will learn from QuickSounder and Stratus, we will define future LEO architecture through the NEON program. We envision a disaggregated set of instruments, increased orbital diversity, and faster refresh rates for critical data necessary to optimize numerical weather prediction.

The success of our LEO satellite programs, both ongoing and emerging, is a result of hard work and extensive collaborations with satellite developers, our NOAA corporate partners, and our national and international stakeholders. Our extensive stakeholder strategy and customer impact activities have helped build a strong foundation of operational applications to meet users' mission requirements. Our programs also maintain important relationships with international partners such as the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the Japan Aerospace Exploration Agency (JAXA). These relationships enable the international satellite community to make use of existing and planned capabilities from other research and operational satellite programs to deliver more observations to their service areas and stakeholders. Advances in the future of our LEO satellite constellation and our international partnerships expand the capabilities of our data and modeling, which are vitally important for ongoing weather prediction and environmental monitoring as we experience and prepare for extreme weather.

News headlines about weather continue to highlight the need for these critical partnerships and programs. One example is the satellite capabilities used during the 2025 Atlantic Hurricane Season. As of November 13, this hurricane season produced 13 named storms (winds of 39 miles per hour (mph) or greater), five of which were hurricanes (winds of 74 mph or greater), and four intensified to major hurricanes with sustained winds reaching 111 mph or greater. The Office of LEO Observations takes great pride in supporting our nation's response to these storms.

Thank you to the many contributors to the *LEO Science Digest*, and to our LEO science team and community for their contributions to the program. This edition joins the other Digests dating back to 2013 in documenting the successful research and operational applications of LEO capabilities. Thank you to Satya Kalluri, LEO Program Scientist, for his leadership. From the ongoing success of JPSS in providing essential weather observations to our efforts in defining the future of LEO missions, 2025 was a tremendous year. We look forward to 2026 as we continue the momentum of JPSS and shape the coming era with NEON.

Tim Walsh
Director
NOAA / NESDIS Office of Low Earth Orbit Observations

Satya Kalluri

LEO PROGRAM SCIENTIST

The year 2025 was a stark reminder of the planet's power, yet also a testament to our increasing capability to observe and predict it. NOAA's polar-orbiting satellites—the eyes of the Low Earth Orbit (LEO) program—provide mission-critical data and have firmly established the foundation for the next generation of Earth science. The annual LEO Science Digest highlights the extraordinary impact of LEO observations, from tactical disaster monitoring to strategic planning for continuity and enhancement.

The severe environmental events of 2025—Hurricane Melissa's devastating Category 5 landfall in Jamaica and the deadly flash flooding in Central Texas—share a common, complex scientific thread: the cascading nature of atmospheric events. The Texas disaster, caused by the confluence of Tropical Storm Barry's remnants and a mesoscale convective vortex, underscores the severe impact when heavy precipitation meets saturated soil moisture, a phenomenon explored in depth in Feature 5 of the LEO Science Digest.

Our LEO assets are at the forefront as we confront these hazards. Feature 6 details how atmospheric profiles of temperature and humidity, derived from the Joint Polar Satellite System (JPSS) Advanced Technology Microwave Sounder (ATMS) via the NESDIS Microwave Integrated Retrieval System (MIRS), are now routinely used to estimate hurricane intensity and structure. Crucially, MIRS water vapor data feeds into the Advected Layer Precipitable Water (ALPW) product, a vital tool used during forecast discussions for the July 2025 Central Texas flood event. Furthermore, Feature 2 illustrates ALPW's global utility, showing how it successfully tracked the atmospheric rivers that delivered massive, damaging rainfall to Brazil's Rio Grande do Sul state.

Conversely, too little rainfall leads to droughts, making soil moisture a key measurement in the hydrological cycle, as explored in Feature 7 about NOAA's Soil Moisture Operational Product System (SMOPS), which blends observations from several LEO microwave sensors. Our LEO satellite products are also essential for predicting, mapping, and evaluating the atmospheric and land features that contribute to how events unfold, as detailed in the analysis of the 2024 Hurricane Helene disaster in North Carolina (Feature 5).

The unique environmental hazards of Alaska and regions north of 60o latitude demand the frequent, high-spatial resolution coverage that only polar-orbiting satellites can provide. For this region, Visible Infrared Imaging Radiometer Suite (VIIRS) imagery and the VIIRS Near-Constant Contrast product ("day-night band") from the JPSS mission are Key Performance Parameters (KPPs). Following a highly productive 2024 workshop in Anchorage that identified critical unmet needs, JPSS satellites are now a major contributor to essential services in the Alaskan region (Features 1 and 3). This support includes aviation data needs, active volcano and wildfire monitoring, and tracking hazardous marine conditions. Feature 3 of this year's LEO Science Digest specifically highlights how LEO satellites deliver critical information on the highly dynamic and hazardous river ice breakup, helping the National Weather Service (NWS) Alaska-Pacific River Forecast Center mitigate flood risks for communities across the state.

As the JPSS mission nears its fourteenth year, the LEO program is actively planning the next generation of LEO observations. This future architecture requires integrating data from missions we build, like JPSS, with crucial data from partners (such as the Weather System Follow-on Microwave, WSF-M, and the JAXA-ESA EarthCARE missions) and new commercial data streams. We eagerly await data from EUMETSAT's Metop-Second Generation-A1 and the Japanese GOSAT-GW satellites, observations critical for NOAA line offices.

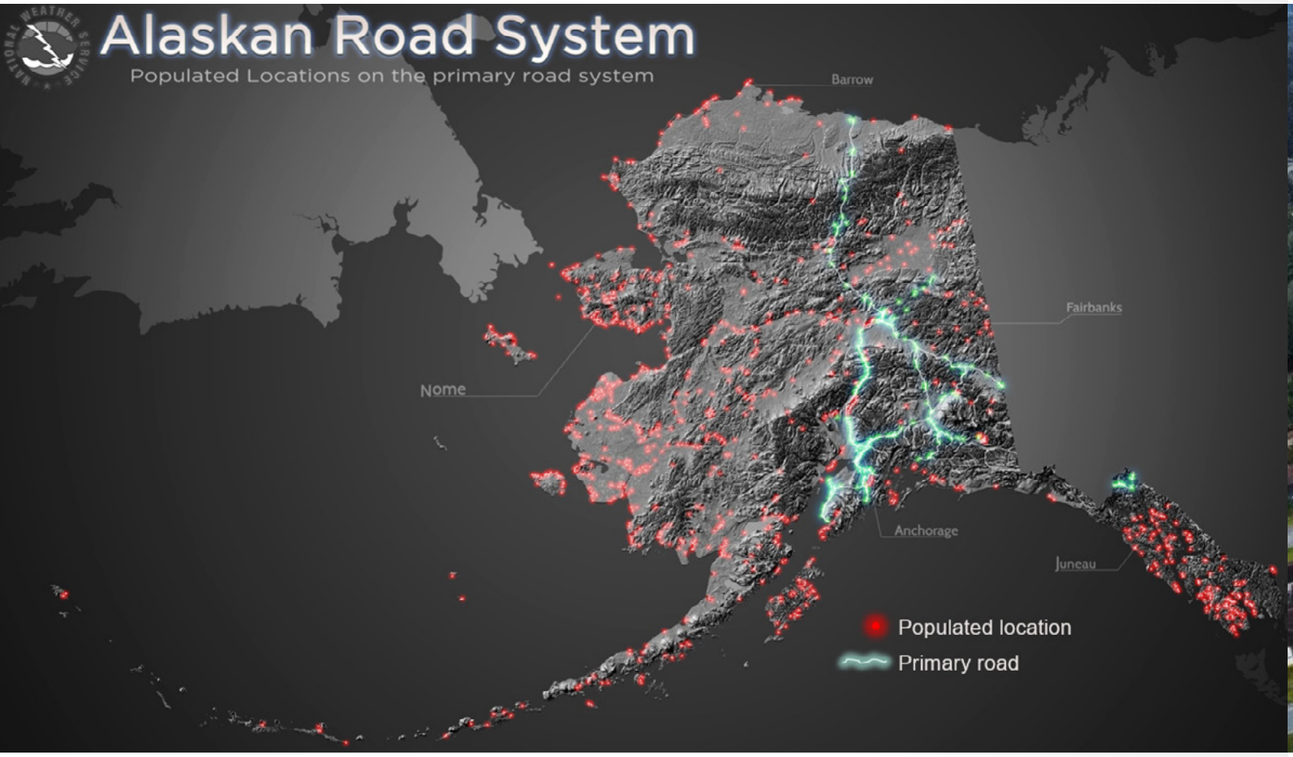
A vital part of this planning includes Observing System Simulation Experiments (OSSEs), highlighted in Feature 4, which rigorously evaluate how proposed future observations will enhance weather models. Furthermore, new scientific instruments like HARP2 (Hyper-Angular Rainbow Polarimeter #2) onboard NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, described in Feature 9, are being used to improve our understanding of aerosol size, composition, and shape, enabling us to better characterize observations from operational sensors like VIIRS. This comprehensive approach—from mission formulation through satellite data user training (Feature 8)—ensures that the LEO program will not only provide necessary continuity but will be enhanced by unique scientific observations and a clear, forward-looking strategy.

The annual LEO Science Digest is a tribute to the scientific volunteers and dedicated staff—Amy Leibrand, Josh Brady, and Michelle Birdsall—whose efforts and passion translate our monthly LEO Science Seminars into easy to "digest" articles for a vast audience. I am grateful for the scientists and speakers who share their discoveries at our meetings and seminars, and whose body of knowledge is captured here, securing the LEO program's status as a mission-critical asset for the nation and the world.

Sincerely,
Satya

Resilience in the Last Frontier: The Role of LEO Observations in Alaska

Airplanes serve as the primary means of transporting people, food, supplies, and essential services across Alaska's remote and challenging landscapes. Photo: Steve Betts via Flickr, CC BY 2.0 (cropped).



ALASKA is a land of awe-inspiring beauty and untamed wilderness, but beneath its majestic peaks and sprawling tundra lie a host of challenges that shape daily life for its 733,000 residents. From the rugged isolation of its remote communities to the thawing permafrost that threatens infrastructure, Alaskans face unique challenges that require ingenuity and adaptation. As its residents navigate icy roads, harsh weather, and a dynamic environment, the state stands as both a testament to resilience and a proving ground for innovation.

"Around 85% of Alaskans are not connected to a major road network," explained Dr. Jessica Cherry, NOAA NCEI's Regional Climate Services Director for the Alaska Region, at a recent LEO Science Seminar. This isolation makes aviation and maritime transport essential lifelines for delivering necessities like food and medical care, a need amplified by Alaska's vast expanse of 425 million acres. The state's frigid winters and unpredictable weather add complexity, increasing risks for both air and sea travel while complicating daily life. Thriving in Alaska demands careful planning and adaptability to navigate a landscape where extreme cold and sudden storms can disrupt essential activities and access to critical resources.

"The list of environmental hazards in Alaska is long," Cherry noted. The region faces a multitude of threats, including heavy rain and snowfall, which can lead to flooding, avalanches, and debris flows with tragic consequences. Flooding from river ice jams and glacial dam outbursts unrelated to precipitation hit record levels in 2023 and again in 2024, causing severe damage to residential areas in Juneau and beyond.

Pressures on ocean ecosystem health are also proving costly, with Alaska's seafood industry incurring an estimated $1.8 billion loss between 2022 and 2023, partly due to the decline of some species. Wildfires, earthquakes, drought, and volcanic activity add to the risks. Furthermore, coastal communities contend with tsunamis, typhoons, and storm surge. In addition, Alaska's high-latitude location makes the state more susceptible to the impacts of space weather, such as radio frequency interference, as compared to the Continental U.S. The wide range of hazards highlight the critical importance of low Earth orbit (LEO) observations collected by polar-orbiting satellites in providing crucial weather and environmental data.

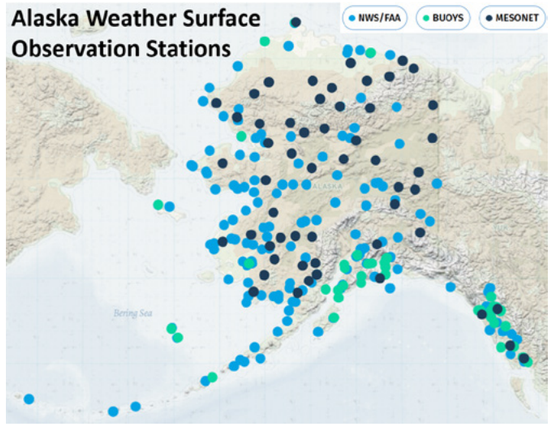
Top: Glacial outburst flood, Juneau, Alaska. Source: Alaska National Guard.

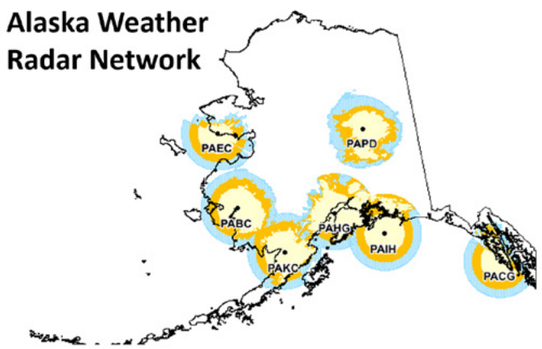
Right Top: Landslide in Haines, Alaska. Source: NWS.

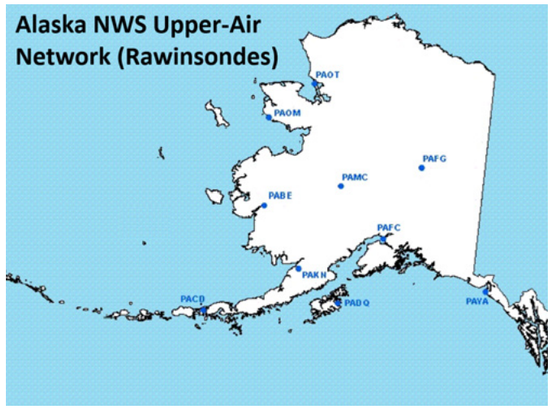
Right Bottom: Anaktuvuk River tundra fire, North Slope, Alaska. Source: BLM/AK Fire Service.

A Reliance on LEO Observations

Alaska has a limited number of surface and upper-air observations, with only seven radars to cover an area larger than Texas, California, and Montana combined, leading to substantial gaps in ground-based observational coverage. This makes satellite observations critical for weather forecasting. Cherry emphasized the vital role of polar-orbiting LEO satellites in a region where aviation is essential and environmental hazards, along with unpredictable weather, pose constant challenges: "We need our polar satellites here—they play an especially important role [in Alaska]."



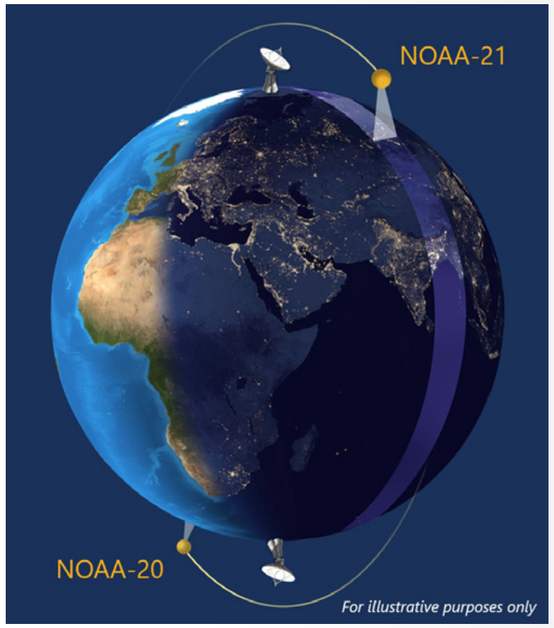




Source: https://akclimate.org/weather/

Polar-orbiting LEO satellites, such as NOAA's Joint Polar Satellite System (JPSS), pass over the poles multiple times per day, providing comprehensive coverage of these hard-to-reach areas. In contrast, geostationary satellites remain fixed above the equator, which makes it hard for them to effectively monitor extreme latitudes like Alaska.

Numerous LEO satellite data products are used operationally in Alaska to support aviation and maritime safety, disaster response, weather and flood forecasting, ocean health, and public health applications. Many products reach users in as little as 15 minutes after overpass thanks to direct broadcast operations and an advanced near real-time processing system operated by the Geographic Information Network of Alaska (GINA) with support from the NOAA NESDIS JPSS Program and the U.S. National Weather Service (NWS). This reduced latency is a key advantage in a region characterized by rapidly changing weather conditions. The following are just a few examples of the many LEO data products commonly used by forecasters, emergency managers, first responders, and other key decision makers in Alaska.



Operational JPSS satellites—NOAA-21, NOAA-20, and Suomi NPP (not shown)—orbit the Earth from pole to pole, crossing the equator about 14 times a day, providing full global coverage twice daily.

VIIRS in Action in Alaska

The Visible Infrared Imaging Radiometer Suite, or VIIRS, is a powerful instrument that provides critical observations for monitoring Earth's land, cryosphere, atmosphere, and oceans. Three VIIRS instruments are in low Earth orbit aboard each of the operational JPSS satellites, collectively providing as many as 27 passes per day over Northern Alaska and up to 12 over Southern Alaska. VIIRS data is widely used in monitoring various environmental conditions, including sea ice and snow, precipitation rates, air quality, volcanic ash, clouds and fog, and sea surface temperatures. It is also instrumental in detecting wildfires, smoke, and burn scars, which can increase the chance of landslides and flash flooding. Following is a small selection of Alaska-focused VIIRS resources, with many more accessible through GINA.

Clouds or Ice and Snow? VIIRS Knows!

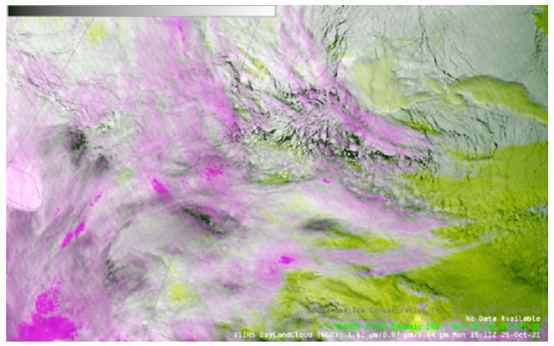
Ice and snow observations offer essential insights into the dynamics of glaciers, sea ice, and freshwater ecosystems. They also hold practical significance for Alaskans, whose safety during travel and hunting depends on understanding current ice and snow conditions.

VSCD Bands

	Band	µm	Spectrum
Daytime	M3	0.48	Visible
	M5	0.67	Visible
	M9	1.38	Shortwave IR
	M10	1.61	Shortwave IR
	M11	2.25	Shortwave IR
	M15	10.7	Longwave IR
Nighttime	DNB	0.7	Visible
	M12	3.7	Mid-wave IR
	M14	8.6	Longwave IR
	M15	10.7	Longwave IR

Differentiating between clouds and ice or snow in true color imagery can be difficult, as they often appear similar in color and texture. To overcome this challenge, the VIIRS Snow/Cloud Discriminator (VSCD) combines information from 10 different VIIRS bands—six during the day and four at night—to produce color-coded imagery that distinguishes clouds from snow and ice.

The product integrates data from the VIIRS Day/Night Band (DNB), which is highly sensitive to visible light at night, allowing for consistent data collection even in low-light conditions. Unlike other snow and ice



Click image to enlarge. *Imagery from the VIIRS Snow/Cloud Discriminator (VSCD) product on October 25, 2021, clearly distinguishes between snow and ice (white), low clouds (yellow), and high clouds (pink). This product was developed by Dr. Steve Miller and Dr. Curtis Seaman at the Cooperative Institute for Research in the Atmosphere (CIRA).*

products, VIIRS DNB can detect reflected moonlight along with artificial and natural light sources during nighttime. Delivering fast, reliable observations during Alaska's prolonged winter darkness makes the VSCD product indispensable for high-latitude monitoring, supporting critical applications such as tracking ice motion, which is essential for safe maritime operations and navigation in Alaska's ice-covered waters.

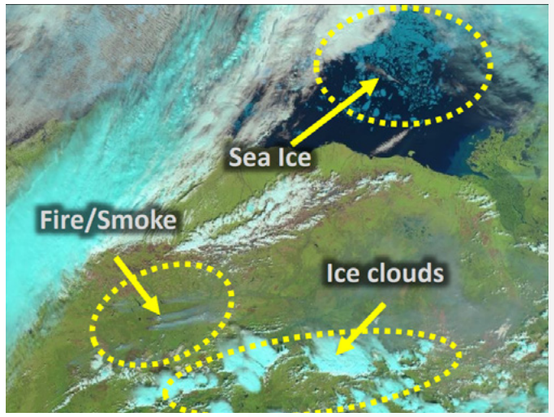
A different product, the VIIRS Day Land Cloud RGB (short for Red-Green-Blue), offers a complementary view of ice and snow conditions, as well as wildfire activity. The RGB can differentiate surface ice or snow from low clouds, distinguish between liquid and ice clouds, and detect fires, smoke, and burn scars. This is achieved by combining three VIIRS bands: a shortwave infrared (IR) "red" channel (1.61 µm, VIIRS M10) that is sensitive to ice and snow, a near IR "green" channel (0.86 µm, VIIRS M7) sensitive to vegetation health and burn scars, and a visible "blue" channel (0.64 µm, VIIRS M5) that detects smoke. With a 375-meter resolution, the VIIRS Day Land Cloud RGB product effectively captures small details like ice floes, ice leads, and localized fires, though its use is limited to daylight hours due to its band composition.

A fishing boat among sea ice on the Eastern Bering Sea. Photo: NOAA Fisheries.

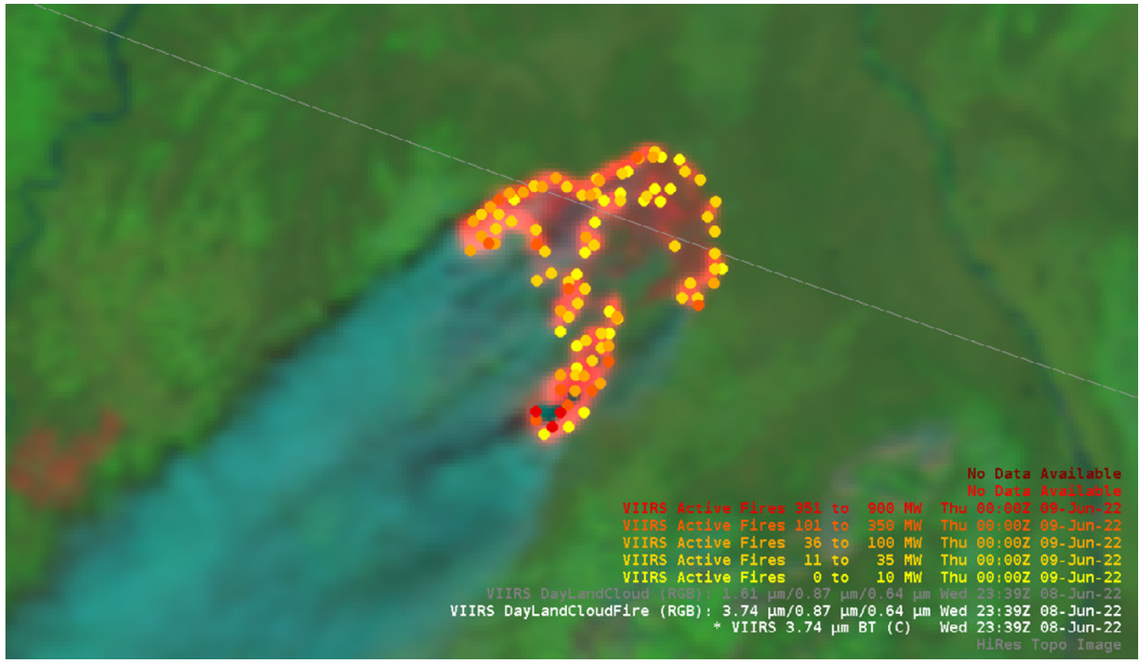
Where There's Smoke, There's Fire

Alaska's wildfire season is getting longer, with larger burns becoming more common. Alaskans have long relied on polar-orbiting LEO satellites for wildland fire management, and GINA provides a range of VIIRS fire products tailored for regional users to aid in active fire and smoke monitoring and analysis.

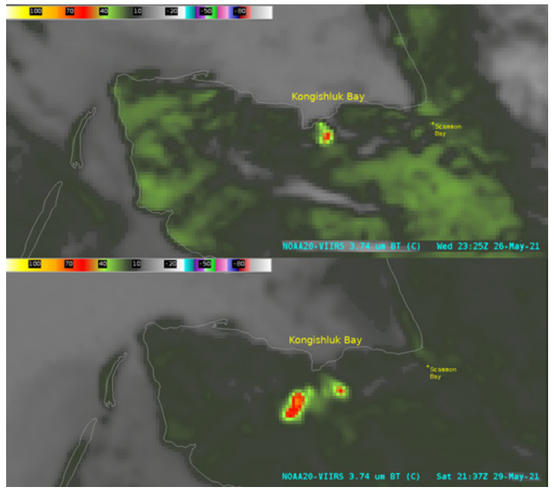
Multi-spectral VIIRS products include capabilities for estimating fire temperature and intensity, which can help inform response efforts, such as determining when and where to allocate firefighting resources or issue evacuation orders. Single-band products like the VIIRS I4 and M13 bands also provide valuable fire detection capabilities. The I4 band (3.74 µm) is particularly sensitive to fire emissions both day and night. This capability helps prevent the so-called "sunrise surprise," when wildfires grow or shift unexpectedly overnight and catch incident command teams off guard. Likewise, the M13 band (4.05 µm) has a high saturation temperature, meaning it can detect very intense fires without saturating the signal; it is used in calculating fire radiative power, a crucial metric for estimating wildfire intensity. VIIRS fire products also support operations at prescribed fires by providing site-specific information to verify ground-based observations of fire locations and intensity.



VIIRS Day Land Cloud RGB imagery over northeast Alaska on July 11, 2017, shows sea ice, ice clouds, and smoke. Image: GINA.



The images above and to the right showcase two fire events in Alaska. The first image (above), from the VIIRS Day Land Cloud Fire RGB, shows the Tatlawiksuk Fire in June 2022, overlaid with heat points (red, orange, and yellow dots) derived from the VIIRS Active Fire (VAF) algorithm, which highlight the fire's intensity expressed in megawatts (MW). The reddish hues are the fire and freshly burned ground, and a large blue-gray smoke plume extends southwest. The VAF algorithm is also a key input to the NOAA operational High-Resolution Rapid Refresh (HRRR)-Smoke model, a real-time weather model that predicts the movement and concentration of smoke from wildfires across North America.

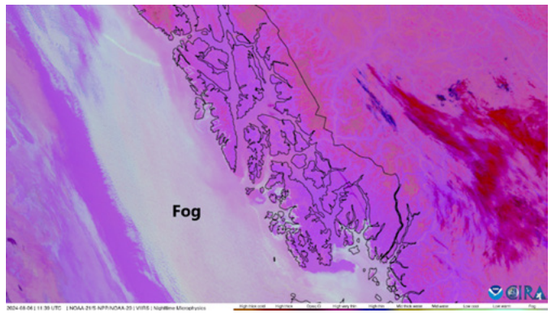


Click image to enlarge.

The second set of images (above right), derived from the VIIRS I4 Band, tracks the progression of a fire near Kongishluk Bay over three days in May 2021. The images use a colormap to display temperature in Celsius, ranging from green (coolest) to red and yellow (hottest). The images show the fire spreading southward and dividing into two distinct areas by May 29 (bottom), with yellow pixels in the fire's center indicating an increase in fire intensity. The ability to continuously track fire and smoke behavior in near real-time supports strategic planning for fire managers to protect Alaskans, while also contributing to broader environmental assessments, such as air quality analysis.

Aiding Aviation

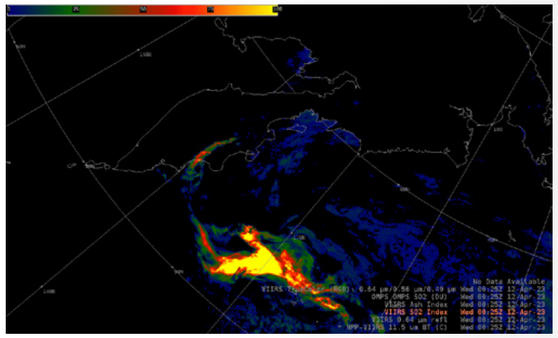
"There are 250 [Alaskan] communities that are exclusively accessed by air," remarked GINA's Director Dr. Jennifer Delamere, at the 2025 American Meteorological Society (AMS) Annual Meeting. She added, "This really factors into why LEO satellites are so important for Alaska." This reliance on aviation, coupled with brutal weather and rugged terrain, highlights the critical role of VIIRS atmospheric data in providing information on cloud, fog, and smoke or ash plume characteristics, helping pilots and meteorologists assess hazardous conditions.

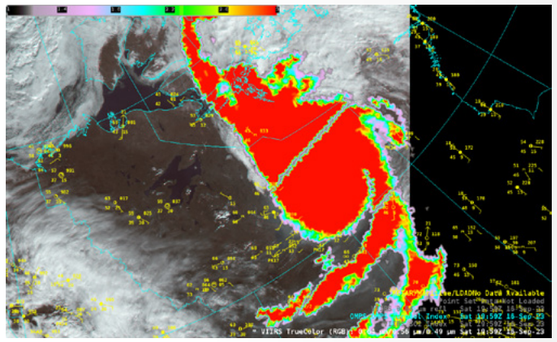


A VIIRS Nighttime Microphysics RGB image captures dense fog along the Alaska Panhandle on August 6, 2024. Image: CIRA/CSU & NOAA/NESDIS.

GINA provides an assortment of near real-time VIIRS cloud products to Alaska's aviation sector, delivering detailed data about cloud phase and structure, cloud base height, and other features (for a deeper dive, see *Feature 1—Visualizing Clouds in Three Dimensions for Aviation Weather Applications* in the 2022 JPSS Science Digest). The VIIRS Nighttime Microphysics RGB and the VIIRS Day/Night Band RGB help distinguish between fog and other cloud types—important information for assessing visibility and planning flight routes to ensure safer takeoffs and landings.

Volcanic activity presents another aviation hazard. Alaska, home to more than 130 active volcanoes, and the neighboring Kamchatka





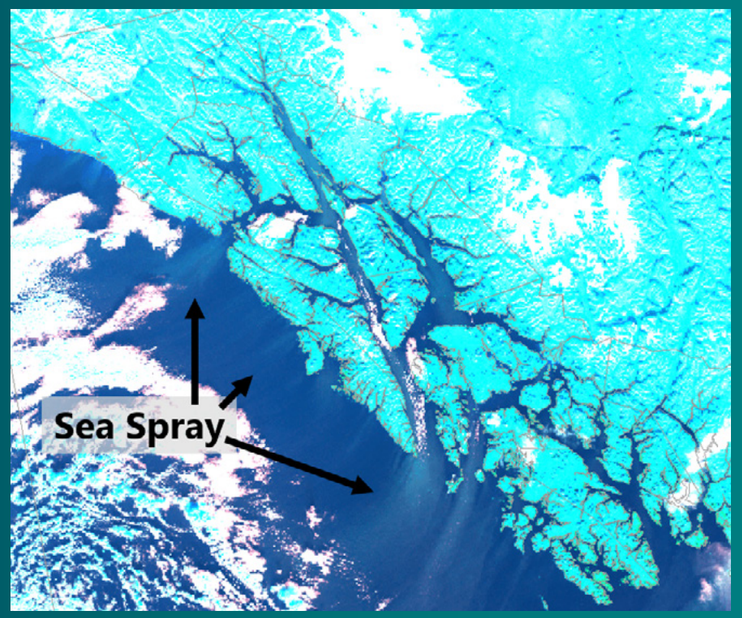
Top: The VIIRS SO_2 Index (April 12, 2023) detects elevated SO_2 (yellow) over Alaska's Aleutians from Russia's Sheveluch Volcano, which erupted April 10. Bottom: The OMPS Smoke-Ash Index (Sept. 16, 2023) highlights a dense ash plume (red) from Mount Shishaldin's Sept. 15 eruption in the Aleutians.

Peninsula with 29 active volcanoes, are regions of frequent volcanic activity. Eruptions release ash and sulfur dioxide (SO_2) into the atmosphere, posing risks to aviation such as reduced visibility, navigation challenges, in-cabin air quality issues, and potential engine damage.

To mitigate these hazards, SO_2 products from VIIRS and its companion on JPSS satellites, the Ozone Mapping and Profiler Suite (OMPS), are specifically tuned to detect SO_2. The VIIRS SO_2 Index operates day and night, using mid-to-longwave thermal radiation bands (M14, M15, M16) to measure SO_2 as a percent concentration. By comparison, the OMPS SO_2 product quantifies SO_2 as an amount (in Dobson Units) using ultraviolet (UV) solar reflectance and is therefore only available during daylight. Additionally, the VIIRS Ash Index and OMPS Ash-Smoke Index distinguish

When the Seas Spray

Sea spray is made up of tiny seawater droplets lifted into the air by waves and wind. Sea spray icing poses safety risks to marine operations by forming ice buildup that can destabilize vessels. The 375-m VIIRS Sea Spray RGB product monitors sea spray aerosols over oceans where few surface observations exist, helping to fill critical data gaps across remote Alaskan waters. By capturing sea spray in near real-time, this product enhances situational awareness for mariners navigating harsh Arctic conditions.



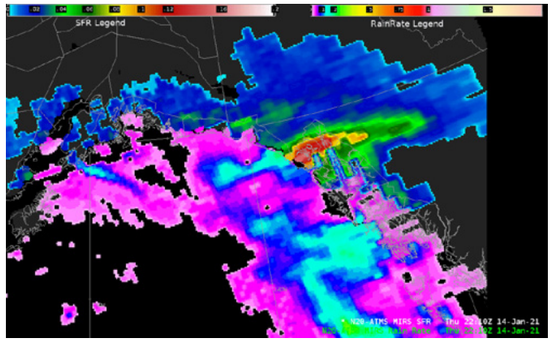
Left: In this VIIRS Sea Spray RGB image, the wispy lighter blue colors show sea spray generated by high winds over water in the narrow channels of southeast Alaska. Image: CIRA/CSU & NOAA/NESDIS. Right: Ice accumulated on a NOAA ship. Photo: NOAA Office of Marine and Aircraft Operations.

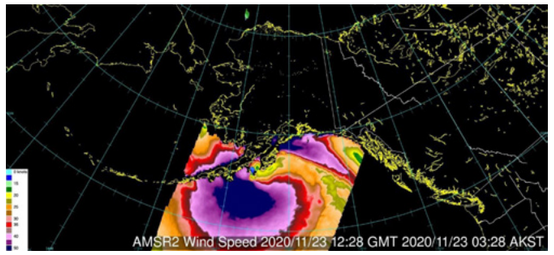
volcanic ash from other atmospheric particles, providing timely updates on the concentration, location, and spatial extent of potentially hazardous volcanic plumes.

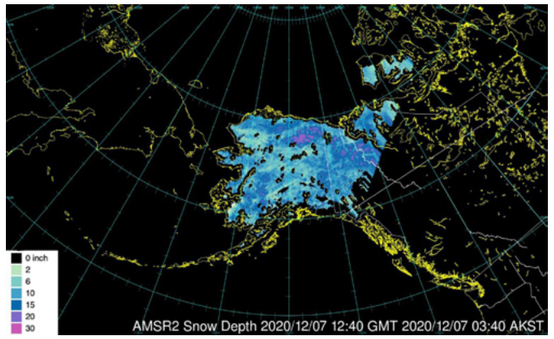
A Suite of Microwave Solutions

VIIRS is a powerful tool, capturing detailed Earth observations across visible and IR wavelengths both day and night. But no single satellite sensor can address every observational need. Visible and IR wavelengths are unable to penetrate opaque clouds, limiting the effectiveness of VIIRS in overcast or stormy weather. In contrast, microwaves, with their longer wavelengths, can pass through clouds, providing unobstructed observations in nearly all types of weather. While conditions vary, much of Alaska remains consistently cloudy throughout the year, making the ability to "see" beneath clouds essential for delivering accurate forecasts that protect the public.

Microwaves exhibit a unique sensitivity to large precipitation droplets, making them ideal for estimating rain rates. Leveraging this capability, the AMSR2 Rain Rate product, derived from the Advanced Microwave







Top: MiRS microwave imagery from January 14, 2021, shows a weather front near Southeast Alaska, with rain rates (pink-blue-cyan) in the southern panhandle and heavy snowfall (blue-green-red) near Haines, AK. Middle: The AMSR2 Wind Speed product on November 23, 2020, detected surface winds over 50 knots near the storm's center (deep purple). Bottom: The AMSR2 Snow Depth product from December 7, 2020, shows up to 30 inches of snow in Northern Alaska (purple-pink shading).

Scanning Radiometer 2 (AMSR2) onboard Japan's GCOM-W satellite, and NOAA's Microwave Integrated Retrieval System (MiRS), an advanced algorithm using microwave data from six polar-orbiting LEO satellites (including the Advanced Technology Microwave Sounder (ATMS) on JPSS), provide detailed insights into rainfall patterns. These products deliver consistent observations regardless of meteorological conditions and are especially valuable in areas with limited radar coverage, like much of Alaska, as they can reveal heavy rainfall otherwise hidden beneath high clouds.

Other Alaska-specific microwave products, including those that measure snow cover and depth, snow water equivalent, ice concentration, and wind speed, are also accessible through GINA. By providing critical data in cloud-covered regions where visible and IR sensors fall short, microwave products play an essential role in monitoring Alaska's many environmental hazards.

Aligning Science with Regional Priorities

Engaging with Alaskan communities is essential to ensure satellite data effectively meets their unique weather and environmental challenges and decision-making needs. By demonstrating the value of NOAA satellites at the regional level, these efforts enhance resilience and support effective resource management in Alaska's remote, high-latitude regions, where accurate and timely Earth observations are critical. NOAA's commitment to understand Alaska's challenges set the stage for collaborative discussions at the Alaska NextGen Satellite Workshop, aimed at addressing the state's most pressing concerns.

Held in Anchorage in September 2024, the three-day workshop brought together NESDIS leadership, data scientists, user engagement specialists, and state and regional leaders to discuss concerns and key priorities specific to Alaska. "We wanted to get [relevant stakeholders] together to better understand needs in Alaskan communities to help drive next generation product development," said Cherry. Co-hosted by NOAA's National Center for Environmental Information (NCEI) and the University of Alaska Fairbanks, the event highlighted challenges such as limited broadband access and explored strategies aligned with NOAA's service delivery model, which emphasizes continuous user engagement.

Cherry explained, "We wanted to demonstrate a vision for regional services, not just for NCEI but also for NESDIS, and show how we work with the regional team specifically to engage users in Alaska." She emphasized the importance of expanding the satellite data user community and showcasing how LEO observations can address gaps left by aging or malfunctioning surface observational networks.

Throughout the workshop, out-of-state leaders connected with Alaska-based managers, scientists, product developers, and data users to encourage collaboration and build partnerships. Visiting participants observed environmental processes such as river ice and flooding firsthand, deepening their understanding of Alaska's challenges. Sessions combined the expertise of regional specialists, data users, and product developers to address environmental hazards and explore innovative solutions, underscoring the critical role of LEO observations in tackling Alaska's unique environmental and weather concerns.

The Anchorage Museum

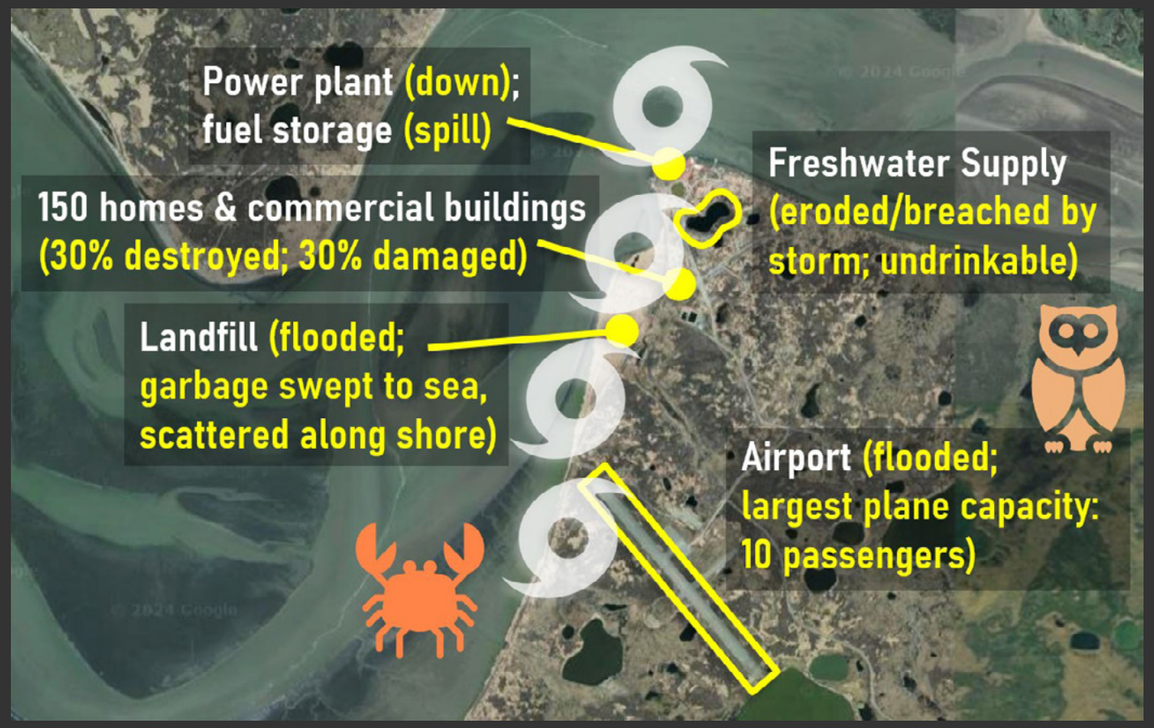
The Anchorage Museum hosted the Alaska NextGen Satellite Workshop, offering an inspiring and creative backdrop for showcasing the value of NOAA satellite products in the region.

Workshop participants connected with the local museum community through curator talks and exhibits focused on Alaska.

Workshop attendees participate in an Education and Workforce Panel. Photo: Jessica Cherry/NOAA.

The Fictional Village of Beringberg, AK: A Role-Playing Exercise

During the workshop, participants engaged in a role-playing exercise designed to simulate the impacts of a major typhoon hitting a fictional coastal Alaskan village named Beringberg. The scenario, inspired by real stories Cherry collected from across Alaska, aimed to personalize the challenges faced by village residents as they navigated survival, preparation, and the decision to stay, evacuate, or permanently relocate. The fictional village was modeled after typical coastal Alaskan communities, featuring 400 residents, 150 buildings, and a mixed economy of cash-based jobs and subsistence lifestyles. The village also grappled with challenges such as a local fishery exposed to storms, nearby federally managed lands protecting an endangered (fictional) "Sea Owl," and limited modes of transportation—planes and boats in summer, planes and snow machines in winter.



Participants were assigned one of 22 characters, each with a detailed backstory reflecting the community's range of economic backgrounds, including figures like Darren, the school principal, Crystal, a crab shack restaurant owner, and TJ, the Wildlife Refuge Area Superintendent. "This was going to set up a scenario where people in different roles were going to have challenges reacting to an event from their own character [perspective]," Cherry explained. As the typhoon unfolded, participants were asked to consider how their character would prepare for the storm, whether they would evacuate and why, and if they would return to rebuild or choose to settle elsewhere.

The exercise challenged participants to think from their assigned character's perspective, reflecting on how personal and professional perspectives influence decisions during a crisis. By immersing themselves in the fictional scenario, they gained a deeper appreciation for the complexities faced by real Alaskans and the importance of making satellite observations accessible, usable, and discoverable for different users. (*Figure courtesy of Jessica Cherry*).

Key Takeaways

The Alaska NextGen Satellite Workshop identified several user needs for improving satellite data use in Alaska. First, data users stressed the importance of low-latency solutions, such as direct broadcast capabilities, in future satellite programs to effectively meet mission requirements. Second, Alaskans, weather forecasters, and data distributors need a trusted and established source for region-specific data, products, and services. Maintaining trust requires transparency about data quality issues, ensuring users are informed about when and how to apply datasets appropriately. "We don't pretend that there's no impact [when infrastructure fails or there is an outage], Cherry explained. "When we communicate these problems, we remain a trusted source."

Co-developing data products with in-region users was seen as essential to creating practical solutions that address user needs, avoiding the disconnect that can arise when products are delivered without collaboration. "We really want to help our [NOAA] data scientists create the solutions that work [for Alaskans]," emphasized Cherry. Additionally, participants stressed the importance of accessible, easy-to-understand data, and the need to create long-term archives where data is findable, interoperable, and reusable, following best practices for data management. Lastly, Alaskans need support to enhance their capacity for using satellite data products, such as training and assistance in securing funding.

GINA's "Big Dog" X-Band receiving station, located atop the Akasofu Building at the University of Alaska Fairbanks (UAF), features a 3.6-meter dish housed within a fiberglass radome. This station captures dozens of daily passes from polar-orbiting LEO satellites, with the data processed and distributed through GINA's near real-time facilities on the UAF campus. Photo: Todd Paris/UAF.

While many of these challenges are unique to Alaska, they highlight broader lessons about the importance of tailoring solutions to the specific needs of a region. The workshop emphasized that region-specific approaches, built on collaboration and trust, are key to ensuring NOAA's satellite data delivers meaningful, actionable benefits to the people who need it most.

Looking Ahead

NOAA NESDIS is uniquely positioned to transform how Alaskans access and use LEO satellite data by aligning its user engagement strategies with the specific practices and preferences of the state. Looking ahead, the NESDIS Office of LEO Observations plans to strengthen connections with Alaskan users through follow-up meetings and collaborative initiatives, ensuring that future projects reflect the input and needs of those they serve. NESDIS is committed to a collaborative approach, ensuring that accessibility, usability, and meaningful partnerships remain central to its roadmap for addressing Alaska's distinct challenges.

Key recommendations from the workshop will guide NOAA in this endeavor, starting with the creation of a baseline plan to coordinate service delivery and avoid duplicative efforts that burden end users. Establishing a structure for formalized user engagement will further strengthen connections with Alaskans, enabling NESDIS to expand its reach and tailor existing data to support new user groups.

Investment in high-impact areas like aviation and maritime transport, which are critical to Alaska's economy and daily life, will ensure satellite products meet the state's most pressing needs.

Lastly, maintaining and enhancing direct broadcast capabilities and other low-latency solutions will be vital for delivering near real-time data that supports essential operations in Alaska's remote regions. By implementing these recommendations and continuing to refine its strategies, the NESDIS Office of LEO Observations is committed to ensuring that LEO satellite technology serves as a valuable resource for Alaskans, fostering resilience and enabling informed decision-making in the face of evolving challenges. For a deeper look at user needs, future plans, and recommendations, refer to the *2024 Alaska Next Generation Satellite Workshop Report* available on the NOAA Institutional Repository. ✦

Learn More

Learn about how GINA provides near real-time weather monitoring for Alaska and its adjacent oceans.

Hear from scientists about *Why Polar-orbiting Satellites Are So Critical for Weather Forecasting in Alaska*.

Discover real-world applications of JPSS data in Alaska through the JPSS in Your Community series.

Story Source

The information in this article is based, in part, on the December 16, 2024, LEO Science Seminar, "2024 Alaska Next Generation Satellite Workshop," presented by Dr. Jessica Cherry, NOAA NCEI Regional Climate Services Director for the Alaska Region, and Dr. Jennifer Delamere, Director of the Geographic Information Network of Alaska (GINA).

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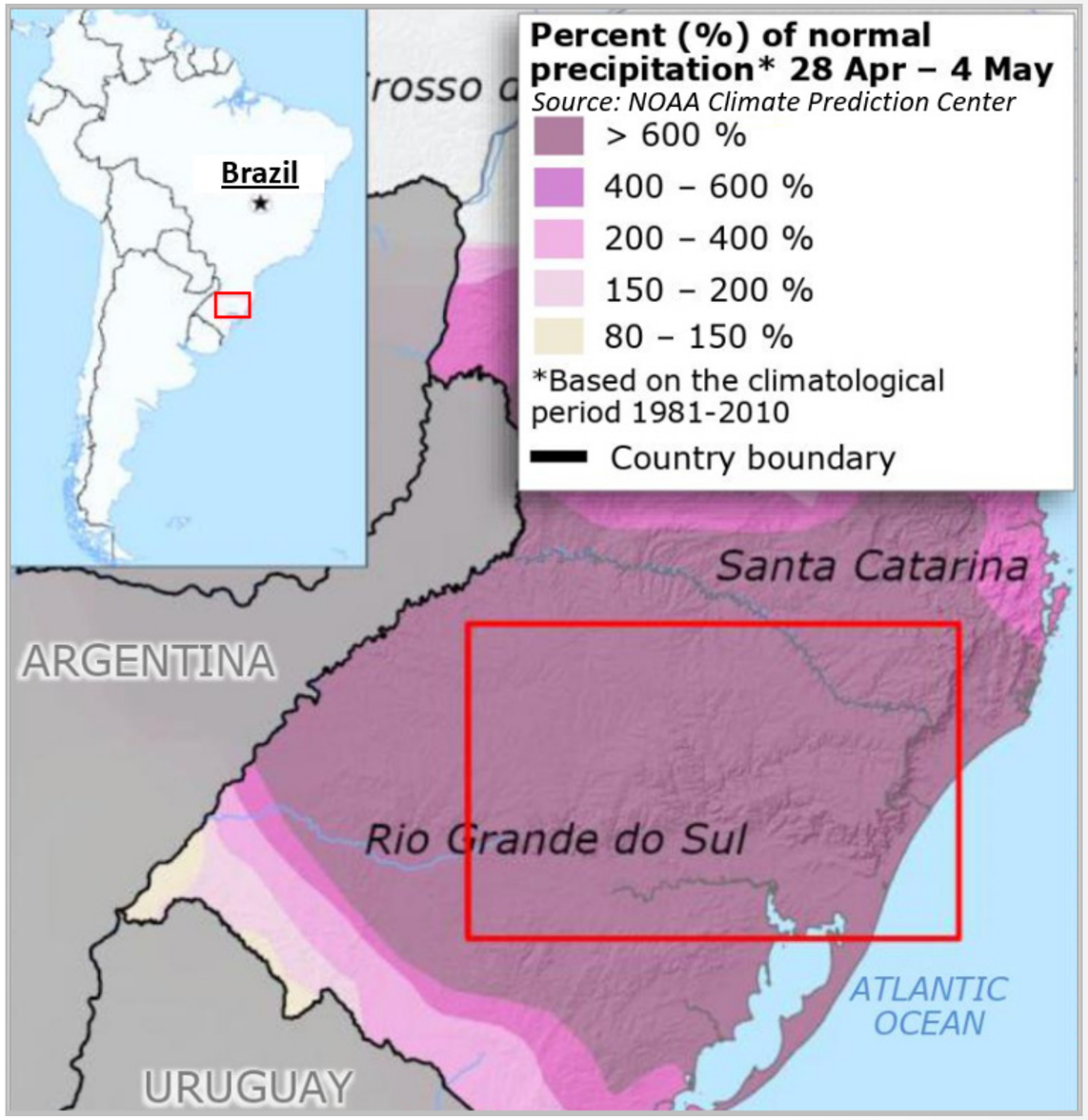
FEATURE 2

A Case Study in Flooding: *Insights From LEO Satellites*

An aerial view of Porto Alegre, Brazil on May 5, 2024, shows extensive flooding. Credit: Ricardo Stuckert/PR via Flickr. CC BY-SA 2.0 (cropped).



Percent of normal precipitation for the Rio Grande do Sul region of Brazil from April 28 to May 4, 2024.
Credit: European Commission/Copernicus.

From late April to mid-May 2024, Rio Grande do Sul, Brazil's southernmost state, endured its worst flooding since 1941, caused by weeks of relentless heavy rainfall. Porto Alegre, the state capital with a metropolitan population of around 4.3 million, recorded nearly 540 millimeters (mm) of rain, while some surrounding areas saw more than 700 mm (nearly 28 inches!)—eight times the historical average. Fueled by a confluence of factors, the torrential rains led to catastrophic flooding that washed away roads, collapsed bridges, and triggered landslides across the region.

The impact of the flooding was devastating, leaving widespread destruction and hardship in its wake. One-third of the state's population was left without clean water and hundreds of thousands faced power outages. Agricultural and livestock sectors, critical to Brazil's economy, suffered

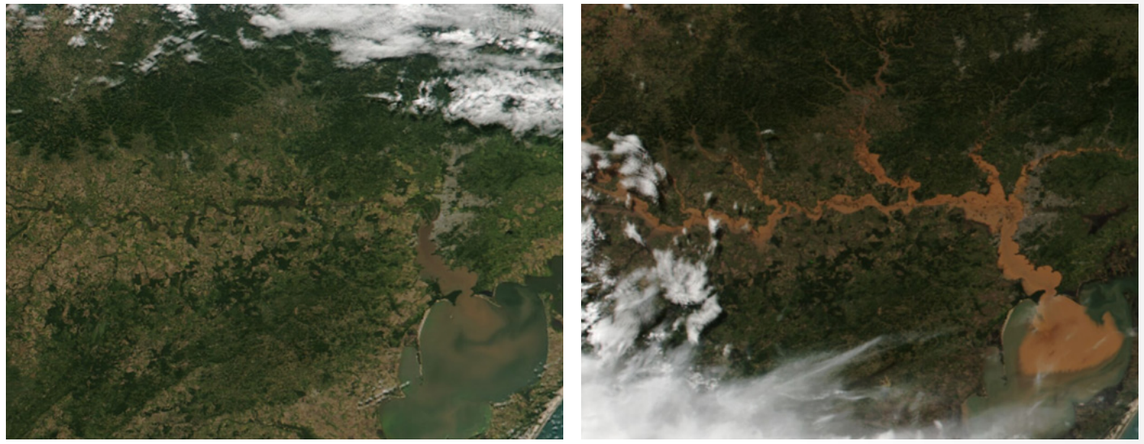
A horse was stranded on a rooftop for two days in Rio Grande do Sul before being rescued. This image is a screenshot from a Globo TV video obtained by Reuters.

devastating losses, including a loss of 2.71 million tons of soybeans, the country's top agricultural export. Overall, the disaster affected nearly 2.4 million people, claiming 183 lives, leaving 27 missing, and displacing 600,000 individuals.

Low Earth orbit (LEO) satellites played a crucial role in helping forecasters and scientists analyze the complex interplay of atmospheric and surface conditions that contributed to this significant event. Understanding these factors is important for improving flood forecasting and preparedness in the U.S., especially in regions like the Mississippi River Basin and the West Coast, where heavy rainfall, erosion, and flooding are common. By studying past events, meteorologists and other stakeholders can refine their knowledge of extreme weather, strengthening both long-term planning and rapid response efforts. This leads to earlier warnings and improved resource allocation, providing communities across the U.S. with more time and resources, supporting NOAA's mission to protect lives and property.

For the U.S. economy, understanding the causes and ripple effects of extreme weather is critical in major agricultural regions like Brazil, a major global exporter of soybeans, meat, corn, and sugar. Flooding that damages crops, livestock, and transportation networks can disrupt global supply chains and drive up commodity prices worldwide. After the Rio Grande do Sul floods devastated much of the region's unharvested soybean crop, the USDA lowered its 2023–2024 soybean forecast for Brazil by one million tons, signaling the potential for tighter supplies and market impacts. A deeper understanding of the drivers behind extreme weather can help U.S. analysts anticipate market disruptions earlier and mitigate price shocks. This is especially important in an interconnected economy where disasters abroad can directly influence domestic markets. LEO satellites, with their continuous global Earth observations, provide critical insights into the forces behind events like the Brazil flooding, strengthening our nation's ability to anticipate and respond more effectively to potential impacts to key global sectors.

Flooded farmland in Rio Grande do Sul, Brazil, due to extreme rainfall in 2024. Photo: Secretaria de Comunicação Social (SECOM) / Government of Brazil.



The Visible Infrared Imaging Radiometer Suite (VIIRS) onboard Joint Polar Satellite System (JPSS) satellites shows Greater Porto Alegre on April 25, 2024, before flooding (left), and on May 6, 2024, after flooding (right). Images: NASA Worldview.

Insights From Low Earth Orbit

LEO environmental satellites play an important role in tracking and analyzing atmospheric and surface conditions that lead to catastrophic flooding. Orbiting pole to pole, they provide high-resolution, global observations of our land, atmosphere, and oceans. NOAA's Joint Polar Satellite System (JPSS) satellites complete about 14 orbits daily, revisiting locations twice per day to deliver frequent data essential for weather forecasting, environmental monitoring, and disaster response. Complementing NOAA's efforts, polar-orbiting LEO satellites like the Metop series from European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the Global Change Observation Mission-Water (GCOM-W) satellite operated by the Japan Aerospace Exploration Agency (JAXA) contribute additional data and products.

Delving Into the Drivers

Extreme precipitation events are influenced by a combination of prevailing weather systems, atmospheric and surface conditions, and the long-term average of weather patterns. In Rio Grande do Sul, Brazil, consistent rainfall is a defining feature of the region due to its proximity to the Atlantic Ocean and the Amazon Rainforest, which both provide a steady stream of atmospheric moisture. However, the persistent and heavy rains that struck the region in early 2024 were exceptional, driven by the convergence of meteorological conditions.

A recent paper highlights three driving factors: an atmospheric block over Southern Brazil, which prevented typical rain-causing systems from moving; an atmospheric trough that led to atmospheric instability; and an Amazon moisture corridor east of the Andes that intensified precipitation. These conditions were further influenced by El Niño, which disrupted weather patterns and prolonged atmospheric instability in the region.

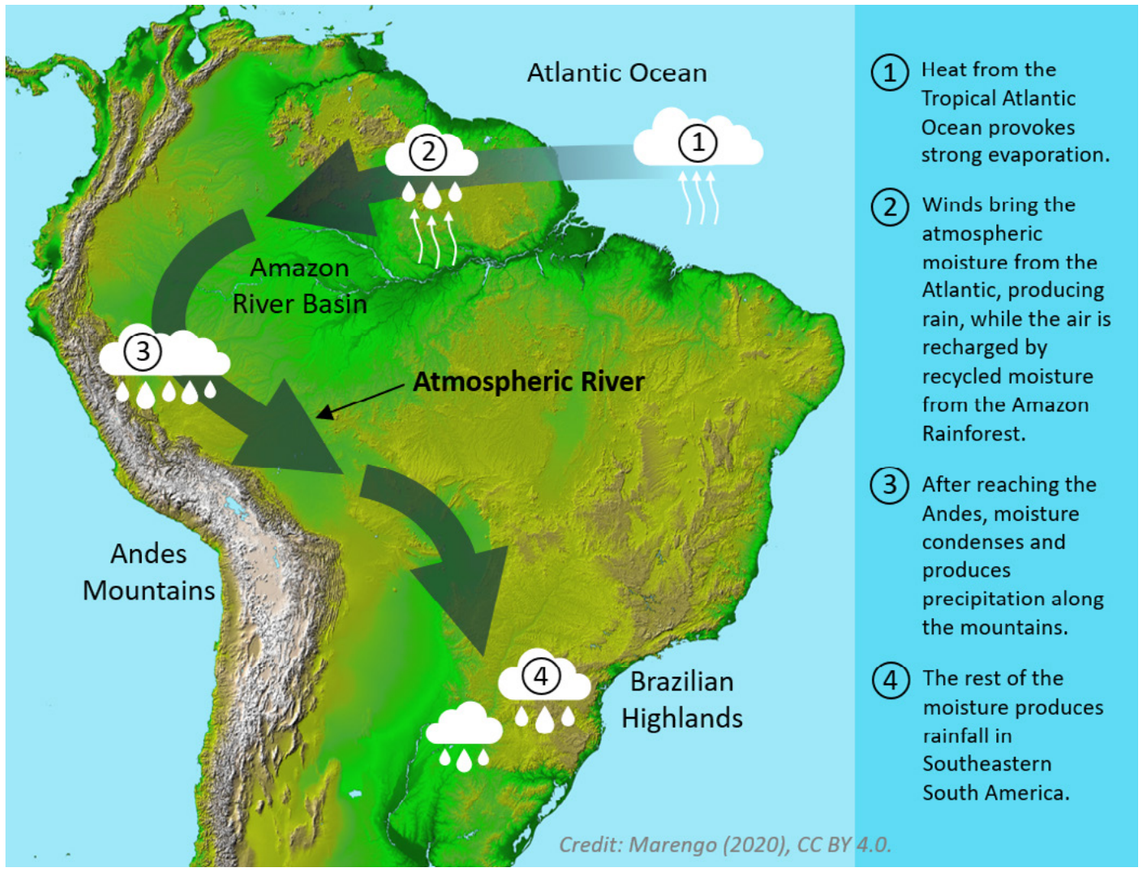
What is an atmospheric block?

An atmospheric block occurs when waviness in the jet stream obstructs the flow of synoptic disturbances. This results in long-lasting and slow-moving high-pressure systems that "block" winds in mid- to high-latitudes, causing the normal progress of weather patterns to stall.

LEO satellite data products were essential in examining the environmental factors that contributed to this event. At a LEO Science Seminar, researchers Sheldon Kusselson, Christopher Grassotti, and Pingping Xie, PhD, presented their analysis of atmospheric and surface conditions in the Rio Grande do Sul region before, during, and after the flooding. Their findings highlighted the complexity of these factors and the vital role of LEO observations in understanding the drivers behind such impactful events.

Rivers Above, Rains Below

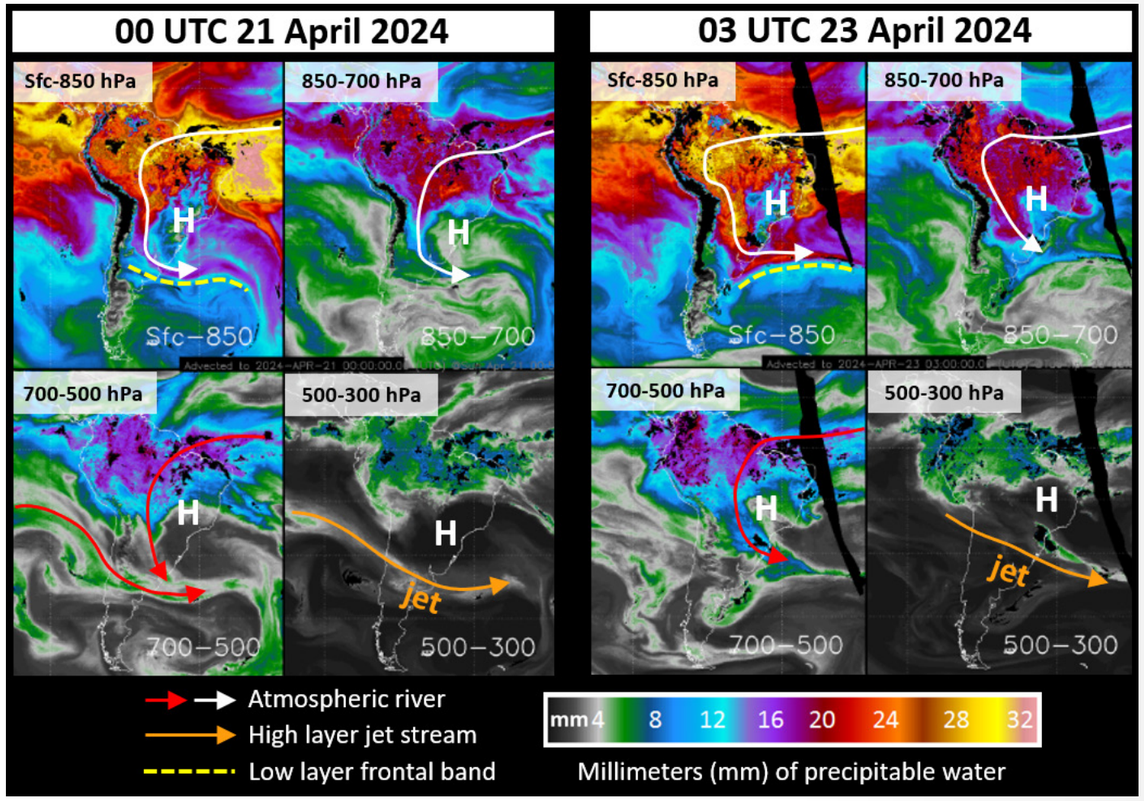
Atmospheric rivers earn their name from their resemblance to rivers on land, transporting vast amounts of water vapor through the atmosphere, measured as precipitable water. These moisture corridors, spanning thousands of miles, deliver critical precipitation to replenish water supplies while also posing risks of extreme rainfall and flooding.



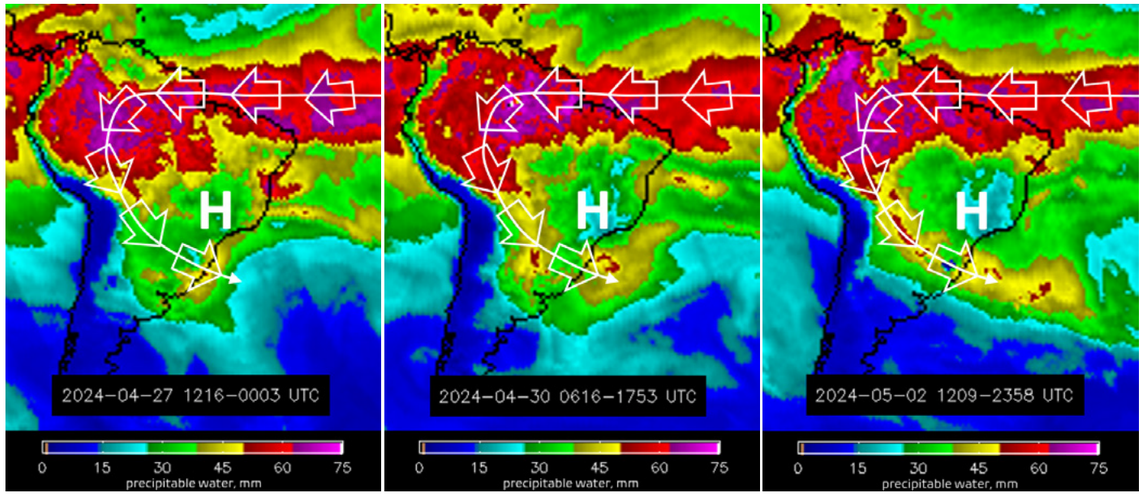
The operational Advected Layer Precipitable Water (ALPW) product, developed at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, provides a four-dimensional view of atmospheric water vapor, helping forecasters monitor these "rivers in the sky" and assess their potential impacts. The ALPW product leverages moisture profiles from the constellation of available polar-orbiting microwave sounders, typically four to seven, including the Advanced Technology Microwave Sounder (ATMS) aboard JPSS satellites.

Derived exclusively from passive microwave sounders on polar-orbiting LEO satellites, along with Global Forecast System (GFS) winds, the product uses these inputs to "separate water vapor into four distinct layers of the troposphere and advect [align] it to the time of the [satellite] image," explains Kusselson, a researcher at CIRA and one of the product's developers. Understanding the vertical distribution of precipitable water helps forecasters assess moisture depth, an indicator of potential heavy rainfall.

Before the Rio Grande do Sul flood event, the ALPW product provided clues about the impending disaster. Days before the heavy rains, an atmospheric river transported tropical moisture over Central and Southern Brazil, visible in the ALPW imagery below from April 21 and 23 (white and red arrows). The effects of this moisture were amplified by a nearly stationary high pressure system ("H")



***Click image to enlarge**. The ALPW product shows water vapor, measured in millimeters of precipitable water, at four discrete levels of the atmosphere: the surface (Sfc) to 850 hectopascals (hPa), 850 to 700 hPa, 700 to 300 hPa, and 500 to 300 hPa. These images for April 21, 2024, 00 UTC (left) and April 23, 2024, 03 UTC (right) show atmospheric rivers in three layers (Sfc-850 hPa, 850-700 hPa, and 700-500 hPa), as well as a low layer frontal band (Sfc-850 hPa), an upper layer jet stream (500-300 hPa), and a near-stationary high pressure system ("H"). This confluence of factors contributed to the persistent and heavy rains and subsequent flooding in Rio Grande do Sul in 2024. Figures courtesy of Sheldon Kusselson.*



This time series of images from the bTPW product illustrates the progression of an atmospheric river on April 27 (left), April 30 (middle), and May 2 (right), 2024. The images depict tropical moisture looping from the equatorial Atlantic Ocean into Brazil and curving around the Andes, guided by a high-pressure system (anticyclone) marked with an "H." Figures courtesy of Sheldon Kusselson.

over East Central Brazil, a strong upper level jet stream (orange arrow), and a low level frontal boundary (yellow dashed line) along Brazil's southern edge. Together, these features produced the lift and atmospheric instability needed for thunderstorms to develop.

NOAA's operational Blended Total Precipitable Water (bTPW) product, developed by CIRA, also offered insights into the unfolding events (above). The bTPW blends meteorological data from multiple LEO imagers and sounders such as JPSS ATMS, the Advanced Microwave Sounding Unit (AMSU) onboard Europe's MetOp missions, and the Advanced Microwave Scanning Radiometer 2 (AMSR2) on the JAXA/NASA collaborative GCOM-W1 mission, as well as information from surface-based Global Positioning System (GPS) measurements and the NOAA Geostationary Operational Environmental Satellites (GOES) Advanced Baseline Imager (ABI). The result is an hourly continuous global map of atmospheric moisture.

Like in the ALPW product, the bTPW revealed a persistent high pressure system over East Central Brazil, directing tropical moisture from the Atlantic toward the Amazon and southward along the Andes into Southeast Brazil, as shown by white arrows in the images above. "From my experience, it's unusual to have such a long and persistent atmospheric river of moisture do this," elaborates Kusselson, who has been researching atmospheric river events for most of his professional career. This rare event produced extraordinary amounts of rainfall, with parts of Rio Grande do Sul receiving as much as 150 mm (nearly 6 inches) in just 24 hours on April 30.

Satellite-based precipitable water products such as ALPW and bTPW are meant to complement forecast models, providing an additional layer of validation, and enhancing the reliability of predictions. "The satellite data is extremely important to use in conjunction with models to increase forecaster confidence," Kusselson emphasizes. By offering early indications of atmospheric conditions that may contribute to extreme precipitation, these products give forecasters critical lead time to prepare and respond effectively.

The Marvel of Microwaves

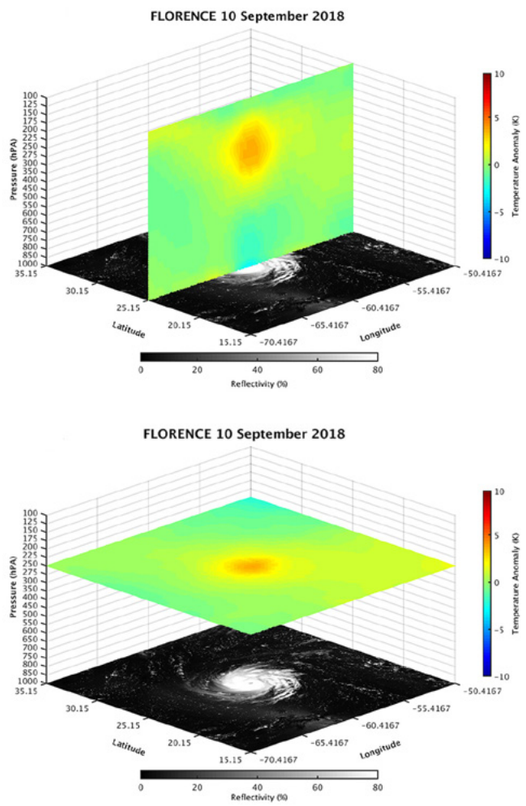
"Over the last decade I have been telling many of my media meteorologist friends that they would not be talking about atmospheric rivers of moisture and the destruction that they do if it wasn't for LEO microwave sounders," says Kusselson. ATMS and other microwave sounders on LEO satellites provide essential data for the ALPW and bTPW products. By detecting microwave radiation emitted by the Earth's atmosphere, these instruments capture detailed vertical profiles of atmospheric temperature and moisture, offering insights into how these variables vary with altitude in the troposphere.

Unlike visible or infrared radiation, microwaves can penetrate clouds, enabling microwave sounders to perform in almost all weather conditions. This ability allows forecasters to "see" beneath cloud cover, a crucial advantage for identifying moisture-rich areas, predicting heavy precipitation, and supporting early emergency planning ahead of potential flooding.

ATMS, currently operational on three JPSS satellites (Suomi National Polar-orbiting Partnership (S-NPP), NOAA-20, and NOAA-21), captures data across 22 channels with a 2,600-kilometer swath, providing full global coverage twice daily. The slight differences in each satellite's orbit enhance temporal resolution, allowing for more frequent atmospheric observations. Combined with a 12-hour revisit time, this ensures the consistent and timely delivery of atmospheric data that CIRA's precipitable water products rely on for monitoring and forecasting.

Rain, Rain, Go Away

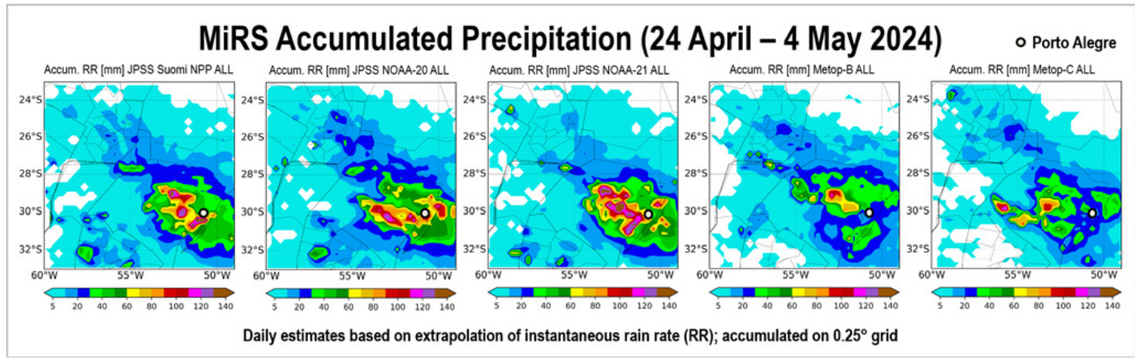
Numerous satellite-based algorithms are designed to observe rainfall characteristics using data from microwave and infrared



These two cross-sections depict ATMS-derived temperature anomalies across atmospheric layers (y-axis), highlighting the 3D warm-core structure of Hurricane Florence on September 10, 2018. From: Yan et al. (2020), Earth and Space Science, 7(8), e2019EA000961. https://doi.org/10.1029/2019EA000961

sensors onboard LEO satellites. While their resolution is coarser than land-based weather radar, these algorithms are invaluable in regions with limited surface observations, such as along coasts and over oceans. NOAA employs several operational precipitation algorithms, including MiRS and CMORPH2 highlighted here, along with many others.

For the Rio Grande do Sul flood event, "the most relevant product would be the precipitation rate," says Grassotti, Technical Lead for the Microwave Integrated Retrieval System (MiRS) at NOAA NESDIS Center for Satellite Applications and Research (STAR), and Senior



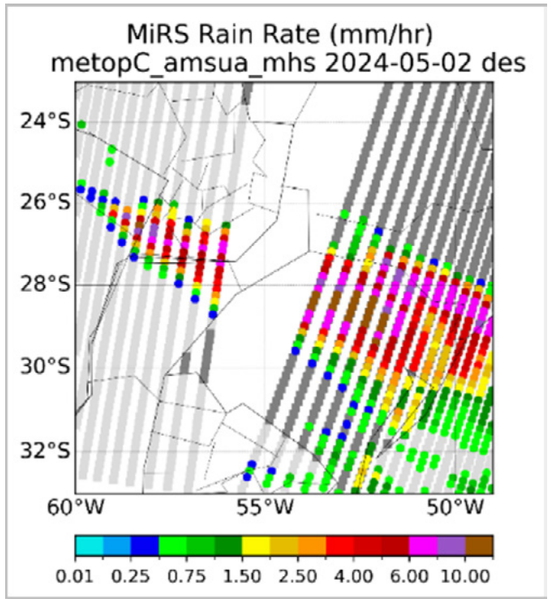
Click image to enlarge.

Faculty Specialist at the Cooperative Institute for Satellite Earth System Studies (CISESS) at the University of Maryland-College Park. MiRS is an algorithm for retrieving atmospheric profiles of temperature, water vapor, and other parameters from passive microwave sensors onboard LEO satellites, including ATMS and AMSU. It uses the one-dimensional variational retrieval (1D-Var) technique to find the best possible solution by comparing the satellite data to a computer model of the atmosphere, adjusting the model until it matches the observations as closely as possible.

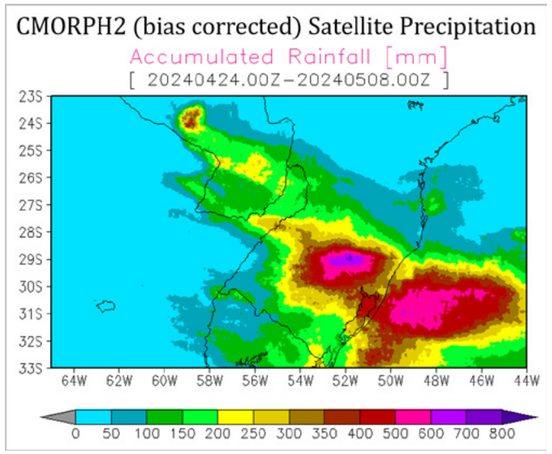
The images above display MiRS accumulated precipitation in Greater Porto Alegre from April 24 to May 4, coinciding with the flood event. Each panel shows rain rate from a different satellite, listed from left to right: Suomi NPP, NOAA-20, NOAA-21, MetOp-B, and MetOp-C. "What you see when you compare the different satellites is that they're quantitatively similar, showing fairly heavy accumulations of rain of over 100 millimeters inland of the coast," Grossotti says, emphasizing the flood's immense scale.

He also points out a common challenge with LEO observations: "The alignment of the satellite and the event may or may not be ideal." Because LEO satellites have variable spatial coverage, observational gaps can occur, as seen in the MiRS rain rate for May 2, 2024, in the figure below. These gaps can lead to missing data and increased uncertainty in precipitation estimates. One way forecasters and researchers address this limitation is by incorporating data from complementary sources. These include geostationary satellites, radar, radiosondes, and surface measurements, which together provide a more comprehensive and reliable assessment.

Another operational precipitation algorithm used at NOAA is CMORPH2. The algorithm estimates global precipitation rates in near real-time based on cloud movement. It combines passive microwave data from about



Click image to enlarge. *Figure courtesy of Christopher Grassotti.*



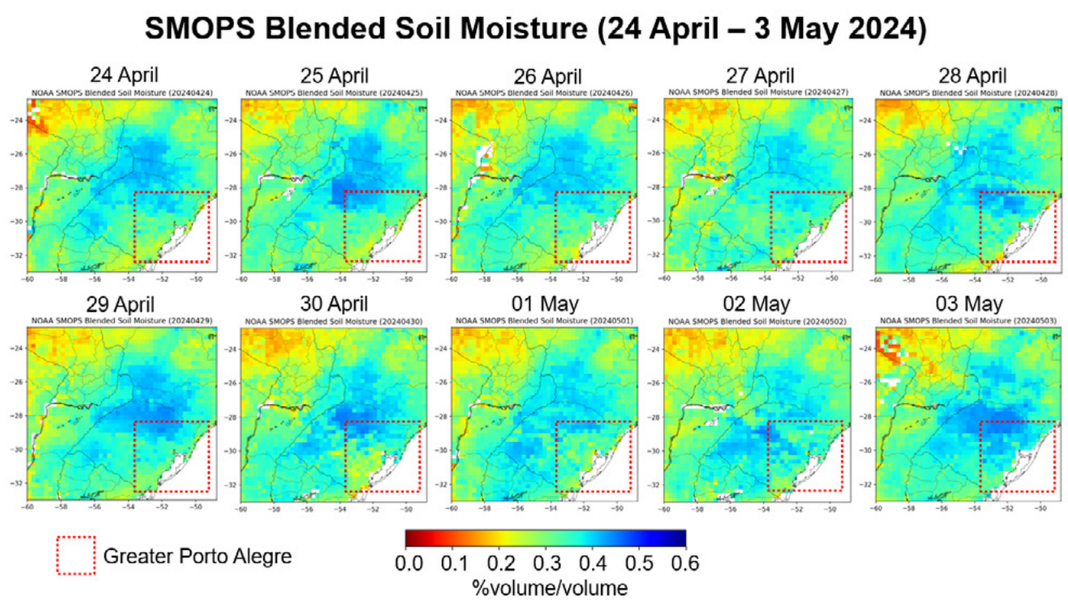
Click image to enlarge. *Figure courtesy of Pingping Xie.*

ten LEO satellites, including JPSS missions, and fills gaps in microwave observations with infrared data from both LEO and GEO platforms. "With CMORPH2 we're able to detect and quantify the precipitation associated with Brazil flooding," says Xie, Research Meteorologist at NOAA's National Centers for Environmental Prediction.

The image above shows CMORPH2 accumulated rainfall from April 24 to May 5 for the Rio Grande do Sul region. "We can see a very heavy rainfall area going from the northwest to the southeast—the same direction as in the [precipitable water] products [described above]," Xie explains. Some areas, indicated by purple hues, received as much as 800 mm of rainfall during this period. "It's very unusual," he remarks about the exceptional amount of rainfall across such a vast area in a short timeframe.

Soil Moisture: A Peek Beneath Our Feet

While atmospheric observations provide insights into weather patterns, surface conditions like soil moisture offer important information about the ground's response to precipitation. Soil moisture data provides insight into how much additional rainfall the soil can absorb. This serves as an important early warning for areas susceptible to flooding, often before atmospheric clues appear, and continues to be a crucial indicator as flooding unfolds. Numerous soil moisture products leverage data from LEO satellite sensors, including instruments like microwave sounders, scatterometers, and imagers.



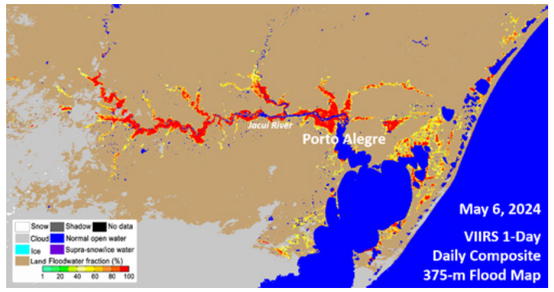
Click image to enlarge. *Figure courtesy of Christopher Grassotti.*

An example is the Soil Moisture Operational Products System (SMOPS), which blends observations from multiple LEO microwave sensors, including the Advanced Scatterometer (ASCAT) on MetOp satellites, AMSR2 on GCOM-W1, NASA's Global Precipitation Measurement (GPM) Microwave Imager (GMI), and NASA's Soil Moisture Active Passive (SMAP) mission. SMOPS displays soil moisture values (%volume/volume) for the top five centimeters of soil, reflecting the percentage of the soil's volume occupied by water.

Between April 24 and May 3, SMOPS data (shown on the previous page) captured a significant rise in soil moisture across Greater Porto Alegre as flooding worsened. "By the end of the period, the coastal areas are significantly more saturated than they were at the beginning," Grassotti explains, noting that darker blue areas indicate higher moisture levels. This increase aligns with the heavy rainfall patterns, with some areas exceeding a volume fraction of 0.5, meaning water comprises 50% of the soil's surface volume. At this level, the ground can no longer effectively absorb additional water, greatly increasing flood risk. By leveraging LEO satellite data, SMOPS provides timely insights that help forecasters identify areas most susceptible to flooding.

Waters Rise Under Satellites' Eyes

Once flooding begins, operational VIIRS Flood products, derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) on JPSS satellites, become valuable for forecasters and emergency responders. These maps depict horizontal flood extent as floodwater fractions (1–100%), showing the percentage of surface water within each 375-meter VIIRS pixel. This information is especially important where on-the-ground assessments are unsafe or impossible. For example, on May 6, 2024, VIIRS captured severe flooding across Greater Porto Alegre (below), with nearly all areas along the Jacuí River showing floodwater fractions of 90–100% (red), indicating widespread inundation and highlighting the disaster's scale.



Click image to enlarge. *VIIRS 1-day daily composite flood map showing widespread flooding near Porto Alegre and the Jacuí River on May 6, 2024. Red areas indicate severe flooding, with 90-100% surface water coverage. Image: NOAA; CIMSS/GMU.*

VIIRS Flood Products

NOAA, in collaboration with the University of Wisconsin-Madison's Cooperative Institute for Meteorological Satellite Studies (CIMSS) and George Mason University (GMU), has developed a suite of VIIRS Flood products that utilize data from the JPSS VIIRS instrument and geostationary satellite sensors. These products offer near real-time global visualizations of flood-affected areas, including flood extent maps and floodwater depth data, which enhance situational awareness for emergency responders, weather services, and impacted communities. Thanks to VIIRS's 375-m spatial resolution, 3,000-km swath, and twice-daily global coverage, these flood products provide detailed and timely insights to support timely flood response and resource allocation. Regional and global VIIRS flood maps are available daily via RealEarth™.

Perspective

The devastating flooding in Rio Grande do Sul, Brazil, serves as a stark reminder of the destructive power of extreme precipitation and the vital role satellite technology plays in mitigating its impact. LEO observations help forecasters, responders, and decision makers analyze, predict, and manage such events, ultimately improving readiness and reducing loss. Studying extreme weather abroad benefits the U.S. by identifying disruptions to major global sectors like agriculture, supply chains, and trade while providing NOAA and the National Weather Service with valuable insights that can enhance forecasting and early warnings. However, challenges remain, including observational gaps and uncertainties in rapidly evolving conditions. Addressing these issues will require more frequent satellite overpasses, continued innovation, and potentially leveraging machine learning to fill spatial and temporal gaps in satellite coverage.

Like the currently operational JPSS satellites, the next two in the series, JPSS-3 and JPSS-4, will each carry four baseline sensors: VIIRS, ATMS, the Cross-track Infrared Sounder (CrIS), and the Ozone Mapping and Profiler Suite (OMPS). These missions will strengthen our nation's LEO capabilities by providing more frequent and detailed atmospheric, land, and ocean observations, refining numerical weather prediction models. By filling observational gaps and increasing data availability, they will support more accurate and timely forecasting of extreme weather events. Maintaining the continuity of critical observations is vital to NOAA's mission of protecting lives, property, and the economy in the U.S. and beyond. ✦

Learn More

Explore advected blending, the process of aligning satellite moisture fields using model winds, as applied in the ALPW product, in this journal article: Using the Multisensor Advected Layered Precipitable Water Product in the Operational Forecast Environment.

Dive into the CMORPH2 Precipitation Rates product in this Quick Guide from CIRA.

Learn about satellite-based remote sensing of soil moisture in this YouTube tutorial.

Watch this quick VIIRS Flood Map Training Video from CIRA to explore the value and use of VIIRS flood products.

Story Source

The information in this article is based, in part, on the October 23, 2024, LEO Science Seminar, "Analysis of the 2024 Southern Brazil Heavy Rain and Flood Event from the Perspective of NOAA Satellite-Based Retrievals," presented by: Sheldon Kusselson, Cooperative Institute for Research in the Atmosphere (CIRA)/Colorado State University (CSU); Dr. Pingping Xie, NOAA NCEP CPC; and Christopher Grassotti, Earth System Science Interdisciplinary Center (ESSIC)/Cooperative Institute for Satellite Earth System Studies (CISESS)/University of Maryland-College Park. The seminar featured contributions from many, including: John Forsythe, CIRA/CSU; Dr. Stanley Kidder, CIRA/CSU; Dan Bikos, CIRA/CSU; Shaorong Wu, NOAA CPC; Dr. Shuyan Liu, CIRA/CSU; Dr. Yan Zhou, ESSIC/CISESS/University of Maryland-College Park; Dr. Veljko Petković, ESSIC/CISESS/University of Maryland-College Park; Dr. Malarvizhi Arulraj, ESSIC/CISESS/University of Maryland-College Park; Dr. Jifu Yin, ESSIC/CISESS/University of Maryland-College Park; Dr. Xiwu Zhan, NOAA NESDIS Center for Satellite Applications and Research (STAR); Dr. Quanhua Liu, NOAA NESDIS STAR; and many others.

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Mapping and Tracking River Ice Hazards from Low Earth Orbit

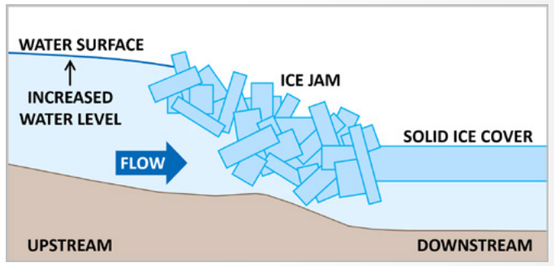
An ice jam formed on the Connecticut River in New Hampshire on February 18, 2022, causing approximately 12 feet of backwater. Credit: Todd Campbell and Max Hankard, U.S. Geological Survey (USGS) New England Water Science Center.

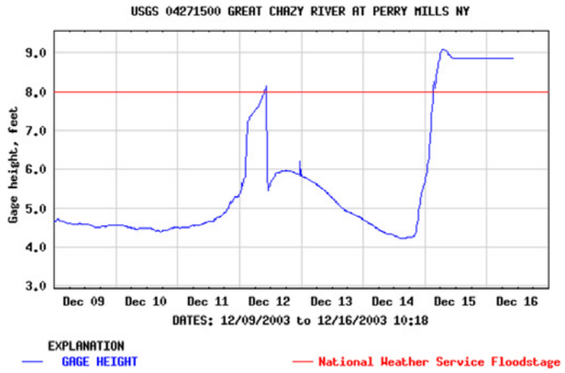
Ice jam on the Connecticut River at the East Haddam Swing Bridge, January 19, 2018. Credit: Civil Air Patrol.

Each winter, falling temperatures across the colder regions of North America cause rivers to freeze. As warmer weather returns, the ice begins to thaw. During both freezing and thawing, river ice shifts, fractures, and moves along with the flowing water. As it accumulates, ice can get stuck and build up around river bends or under bridges, forming blockages known as ice jams.

These jams restrict river flow, sometimes causing water to back up and rapidly rise behind the blockage. If the pressure is too great, the ice jam might suddenly break apart, releasing a surge of water. This rapid release can overwhelm the riverbanks, potentially flooding nearby communities. River ice breakup is a natural seasonal hazard in many northern U.S. states, including Alaska, that can occur with little warning and may quickly lead to flash flooding, leaving limited time to prepare or respond.

"Ice jams are common anywhere there's a change in river slope or any sort of morphology that restricts the flow of the river like bends, restrictions, stream intersections, reservoirs, areas with woody debris, and around infrastructure like bridges and dams," explained Blaine Morriss, a scientist with the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), during the April 2025 LEO Science Seminar. CRREL has been tracking these events through its Ice Jam Database since 1992, documenting more than 23,400 ice jams dating back to 1780—over 6,100 of which have occurred in just the past





Click image to enlarge. *This hydrograph of the Great Chazy River at Perry Mills, NY, shows two sharp spikes in river stage caused by ice jams on December 12 and 15, 2003. In both events, the water level rapidly exceeded the National Weather Service flood stage. The first jam released suddenly, allowing the river to drop back below flood stage. The second jam on December 15 caused another abrupt rise, with water levels remaining elevated afterward, signaling the potential for widespread flooding. Figure courtesy of Blaine Morriss.*

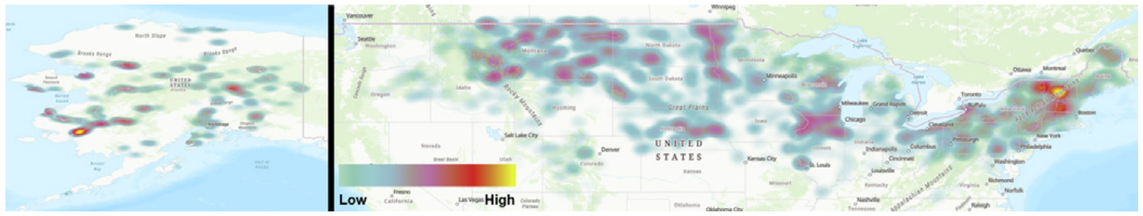
25 years. Many of these events have caused severe flooding, damaging homes, crops, roads, and bridges, and disrupting shipping routes and drinking water supplies.

There are two main types of river ice jams: freeze-up jams and break-up jams. Freeze-up jams tend to occur in early to mid-winter, when sustained cold causes ice to accumulate and obstruct the river channel. While these jams rarely lead to widespread flooding, they can still alter river flow and put pressure on infrastructure.

"The more destructive type of ice jams are break-up jams," says Morriss. These form during periods of thawing, when snowmelt or rainfall increases water flow causing the ice cover to break up into large chunks that are carried downstream with the current. "Typically, these happen in the spring, but more and more we're seeing break-up jams occur in the middle of the winter," he says. As the ice piles up and clogs the channel, water levels can rise rapidly behind the jam. "Because of how quickly they form and how totally they can obstruct flow, break-up jams are the bigger problem in terms of flooding," he adds.

CRREL's mission includes documenting and reporting river ice jams, providing data that helps emergency managers and planners understand associated risks. "A lot of what we're looking for is where ice jams are causing flooding," explains Morriss. While historical records highlight more vulnerable areas based on past patterns, near real-time information is also essential.

Ice jams can develop rapidly and release without warning, sometimes causing flooding within minutes. When conditions favor a jam, the National Weather Service (NWS) may issue a flood watch or warning, making continuous monitoring critical for timely alerts that protect lives and property. To enhance situational awareness, forecasters at NWS River Forecast Centers across the country often turn to satellite observations as a complementary way to track conditions that signal potential ice movement or flooding, especially in remote regions with limited river gauges or eyewitness reports.



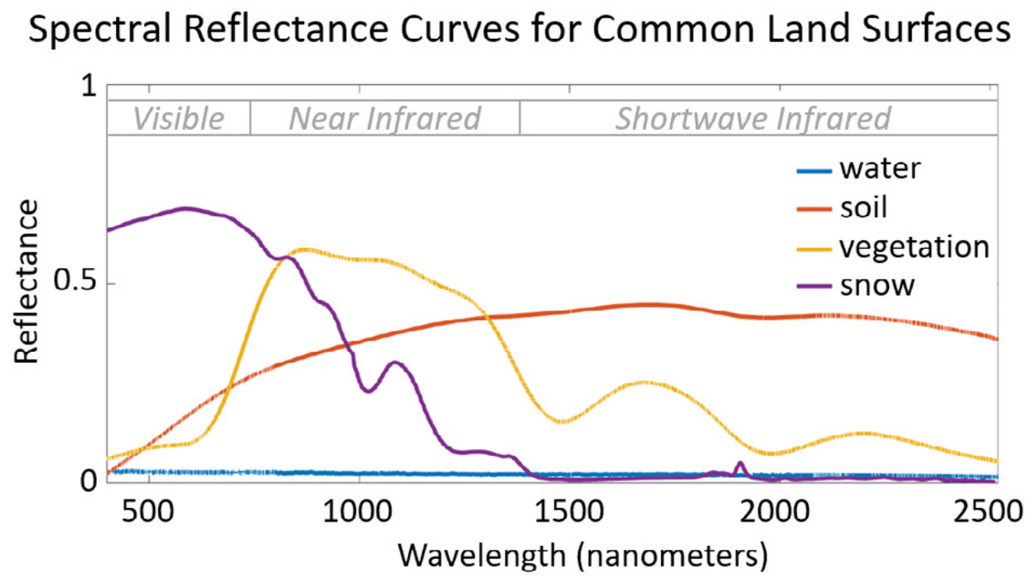
Click image to enlarge. *Heat map of ice jam occurrences from the CRREL Ice Jam Database, with yellow representing the highest concentration of events and blue-green the lowest. Data sources include the National Weather Service, NOAA's Climate Prediction Center, River Forecast Centers, river gauges and cameras, firsthand reports, and satellite imagery used to map the extent of ice jams along rivers. The map highlights regions in Alaska and the northern U.S. where ice jams are most common; however, higher concentrations in some areas may reflect increased reporting due to larger nearby populations. Figure courtesy of Blaine Morriss.*

A large ice jam formed and released within minutes on the Ausable River at Au Sable Forks, NY, on January 12, 2018. The event was driven by rapid snowmelt combined with moderate rainfall during unusually warm temperatures. The river rose 7.75 feet in just 14 minutes, peaking at 13.27 feet (bottom). This is a rise of over half a foot per minute, demonstrating how quickly an ice jam release can lead to flood conditions. Source: NOAA NWS, Au Sable Forks, NY.

Monitoring River Ice & Flood Dynamics From Low Earth Orbit

Earth-observing satellites offer an efficient way to monitor long stretches of rivers for conditions that could lead to ice jams, complementing aerial and ground-based surveillance. NOAA's low Earth orbit (LEO) Joint Polar Satellite System (JPSS) satellites circle the Earth from pole to pole 14 times per day, providing global coverage twice daily and more frequently near the poles. This is especially valuable in remote polar regions such as Alaska, where ground-based observations are sparse.

Different materials—such as water, ice, and snow—absorb, reflect, and scatter light in distinct ways across the electromagnetic spectrum, creating unique patterns that reveal details about their composition and properties. Instruments onboard JPSS satellites detect these "spectral fingerprints," enabling scientists to distinguish between different surface types and derive information about snow and ice extent, snow water equivalent, snowmelt, and other factors that influence the timing and likelihood of ice breakup. A selection of these and other LEO data products is described below.



Spectral reflectance as functions of wavelength for common land surfaces. Source: https://doi.org/10.5194/tc-17-567-2023 (© Authors 2023), CC BY 4.0.

Mapping & Tracking River Ice With NOAA's VIIRS Flood Products

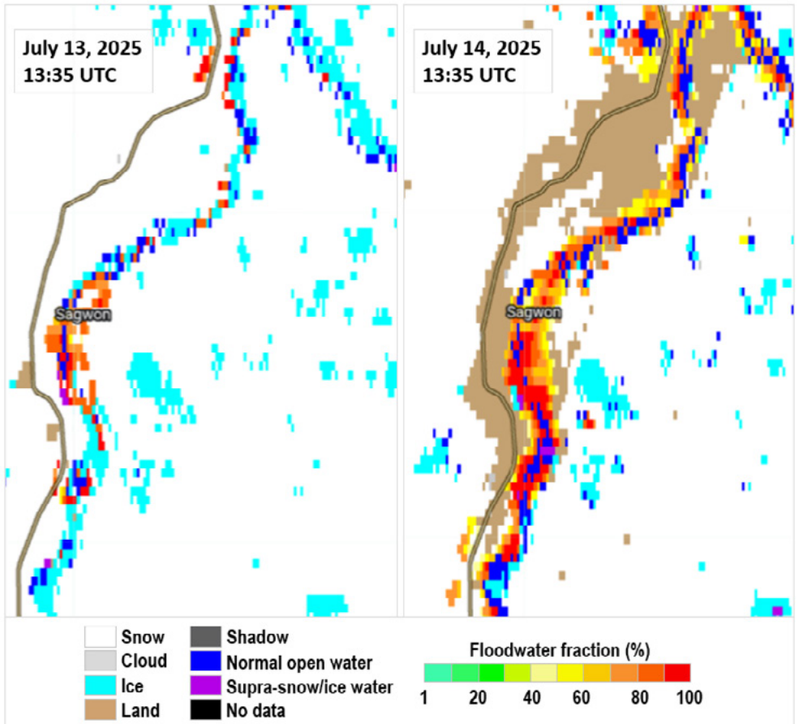
NOAA's VIIRS Flood product suite uses imagery from Visible Infrared Imaging Radiometer Suite (VIIRS) instruments onboard JPSS satellites to derive near real-time river ice and flood extent maps. Developed by researchers at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and George Mason University with support from the JPSS Program, these operational products help forecasters visualize and monitor floodwaters and ice movement along major rivers. This capability is especially useful during high-stakes seasonal transitions when conditions can change rapidly.

VIIRS's *Versatile View*

VIIRS collects global observations of Earth's land, oceans, and atmosphere in 22 channels that span visible and infrared wavelengths. Seventeen channels provide imagery at 750-meter resolution, while five scan at 375-meter resolution. Its 3,040-kilometer swath provides continuous global coverage with no gaps between passes. Overlap between consecutive orbits at higher latitudes means that many regions are observed multiple times a day, such as Alaska.

VIIRS is used for a wide range of applications, including monitoring river ice and flooding, tracking vegetation health and ocean health, detecting wildfires and nighttime lights, and much more. VIIRS is a baseline instrument on all JPSS satellites.

The flood products use VIIRS's imaging bands, known as I-bands, to distinguish between water, snow, ice, bare land, and other features. These include the visible band (I1, 0.64 µm), near-infrared (I2, 0.865 µm), shortwave infrared (I3, 1.61 µm), and longwave infrared (I5, 11.45 µm). Flood extent is represented as "floodwater fractions"—values from 1% to 100% representing the proportion of surface water present in each 375-meter (m) pixel. A unique feature of these products is their ability to detect supra-snow/ice water, where water pools on top of snow or ice. This added insight helps forecasters assess ice stress and anticipate where ice jams may form or worsen. The products also support post-flood assessments by showing how quickly waters recede, aiding emergency response and recovery.



Left: The VIIRS Flood Product 1-Day Composite captures the rapid transition from river ice to floodwater during spring thaw along the Sag River near Sagwon, Alaska. Between July 13 and July 14, 2025, the flood maps reveal rapid river ice breakup, leading to extensive flooding with red areas indicating pixels that are 100% inundated. Each spring, members of the JPSS Program Science team at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) work closely with the NWS Alaska-Pacific River Forecast Center (APRFC) to provide technical support and satellite analyses that aid in updating spring breakup maps and identifying areas of high water. Source: RealEarth™, CIMSS/University of Wisconsin.

Regional and global VIIRS Flood products are delivered to NWS forecasters via the Advanced Weather Interactive Processing System (AWIPS) and imagery is publicly available daily through RealEarth™. Because of their operational value, these products are widely used by NWS River Forecast Centers, the Federal Emergency Management Agency (FEMA), the International Charter Space and Major Disasters, and other agencies to enhance situational awareness and support decision-making during and after river ice jam and flood events.

While VIIRS Flood products are highly useful, they do have limitations: the spatial resolution is too coarse to monitor small rivers or streams, and data is limited to daylight hours and clear skies, as VIIRS I-bands cannot penetrate cloud cover. Even so, they offer valuable context when combined with aerial imagery, ground reports, and river gauges, and may be the only available observation in remote, data-sparse regions such as Alaska.

From Crisis to Capability: The Event That Shaped Innovation

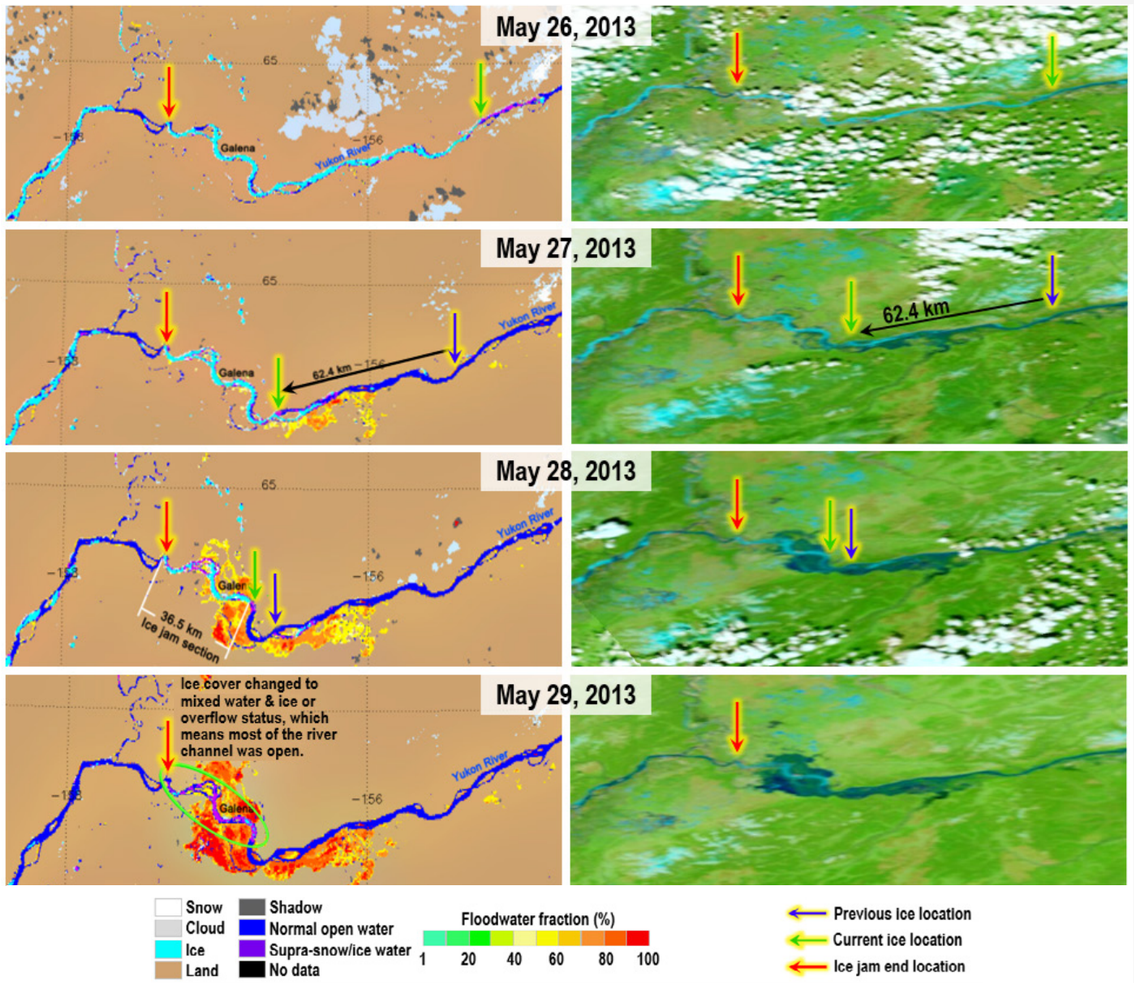
The catastrophic ice jam flood that struck Galena, Alaska in May 2013 marked a pivotal moment in the development and operational use of VIIRS Flood products, serving as a catalyst for future innovation. With much of the town submerged under as much as seven feet of water, nearly all structures destroyed, and around 470 residents displaced, the event highlighted the urgent need for better river ice and flood detection. It also revealed the limitations of relying on ground-based observations to monitor Alaska's vast river system, where fewer than 100 of the state's 12,000 rivers are equipped with gauges, many of which become unreliable when obstructed or dislodged by ice.

In support of emergency response efforts, NOAA flood experts worked closely with the NWS Alaska-Pacific River Forecast Center, providing VIIRS-derived flood data that offered

Galena, Alaska on May 29, 2013, after a river ice jam led to widespread flooding. Credit: US Army Corps of Engineers.

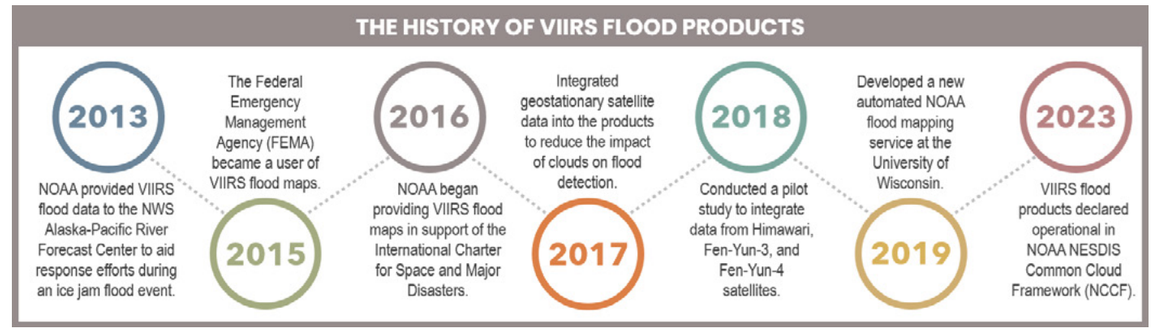
a critical and comprehensive view of flood extent and ice cover. The Center, which plays a crucial role in issuing river ice breakup and flood outlooks during Alaska's spring breakup season, used this information to closely monitor changing conditions throughout the event.

Between May 26 and 28, 2013, an ice jam persisted on the Yukon River downstream of Galena causing water to back up, river levels to rise, and surrounding areas to flood. VIIRS Flood products captured these developments, as shown in the figure below. Once the ice jam released and the river channel reopened, the flood maps helped emergency managers track the retreat of floodwaters and prioritize recovery efforts. This ability to monitor changing river conditions throughout the event supported a coordinated response, informing evacuation decisions and the allocation of critical resources during a narrow response window.



This image sequence from the VIIRS Flood daily product (left) and Suomi-NPP VIIRS False Color imagery (right) illustrates the formation and impact of an ice jam on the Yukon River near Galena, Alaska, in late May 2013. On May 26, a large section of the river was covered with ice (shown in light blue on both the flood map and in the false color imagery), and an ice jam (indicated by the red arrow) formed downstream of Galena, setting off a chain of events that led to severe flooding and evacuations. By May 27, ice breakup occurred upstream, but the ice jam persisted near Galena, causing river levels to rise and flooding to spread. Flooded areas appear as yellow, orange, and red in the flood maps (left), and as dark blue in the false color imagery (right). On May 28, the ice jam remained in place, extending approximately 36.5 kilometers, with widespread inundation clearly visible. By May 29, the jam began to release, and ice cover transitioned to a mixture of water and ice or overflow conditions, indicating that most of the river channel had reopened. Arrows mark previous ice locations (red), current ice locations (green), and the ice jam end location (blue). Sources: RealEarthTM; NASA Worldview; Goldberg et al 2020.

The effective use of VIIRS Flood products during the 2013 Galena ice jam event demonstrated the operational value of JPSS observations for monitoring river ice and flooding. This success sparked innovation, fueled product development, and accelerated adoption by other agencies. Today, VIIRS Flood products remain an important tool during spring breakup season in Alaska and other regions affected by ice jams, including New England, the Mid-Atlantic, and parts of the Midwest and Northwestern U.S.

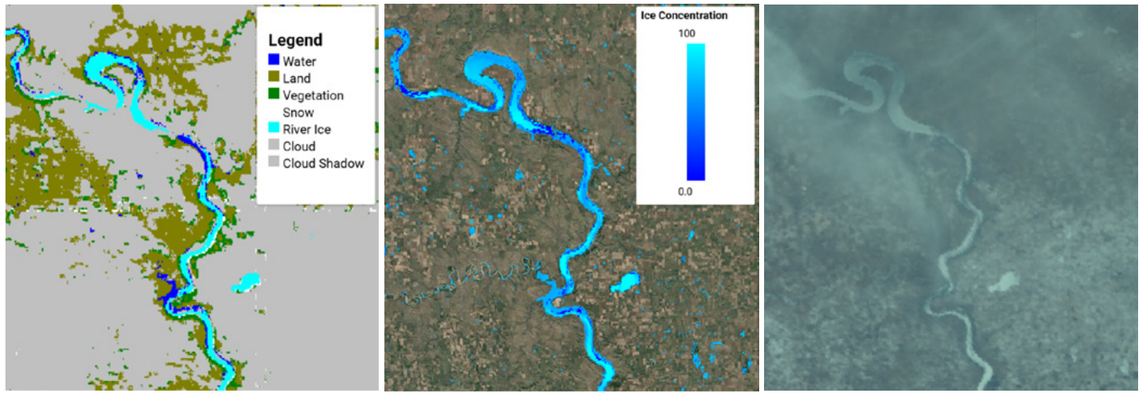


Click image to enlarge.

The Stevens River Ice Mapping System: A LEO Perspective

The Stevens River Ice Mapping System complements VIIRS Flood products in monitoring river ice conditions. Developed by researchers at Stevens Institute of Technology, this satellite-based system uses LEO observations and deep learning techniques to produce daily maps of river ice conditions across Canada and northern U.S. watersheds, including Alaska.

The system applies a U-Net deep learning algorithm to VIIRS I-band imagery, classifying each 375-m pixel as water, land, vegetation, snow, river ice, cloud, or cloud shadow. The resulting classification is used to generate maps that depict the spatial extent of each surface type. Separately, the system calculates ice concentration values as the percentage of ice within each pixel located in a waterbody, using near-infrared imagery from the 375-m VIIRS I2 band. Ice concentration is important information for shipping, navigation, and ice forecasting because changes in concentration can indicate weakening and fragmentation of the ice cover, which often precede breakups.



Maps and imagery from the Stevens River Ice Mapping System illustrate river ice conditions along the Missouri River in South Dakota on February 22, 2025. A classification map (left) highlights the extent of river ice and open water, while the middle map shows ice concentration ranging from 0% to 100% along the same stretch. A true color Sentinel-3 image (right) visually confirms ice coverage on the river, providing additional context and validation for the mapping products. Source: Stevens River Ice Mapping System, Stevens Institute of Technology.

True color imagery from European Space Agency (ESA) Sentinel satellites and NASA/USGS Landsat missions is included in the tool as a complementary feature. Since these LEO satellites observe the same regions as VIIRS but at different times of day, their combined observations can be used to infer the speed and direction, or velocity, of drifting ice sheets. Ice velocity is difficult to measure directly, yet it is essential for modeling river ice dynamics and assessing riverine flood risk. Visualizing and tracking ice movement over time helps improve situational awareness during spring thaw events.

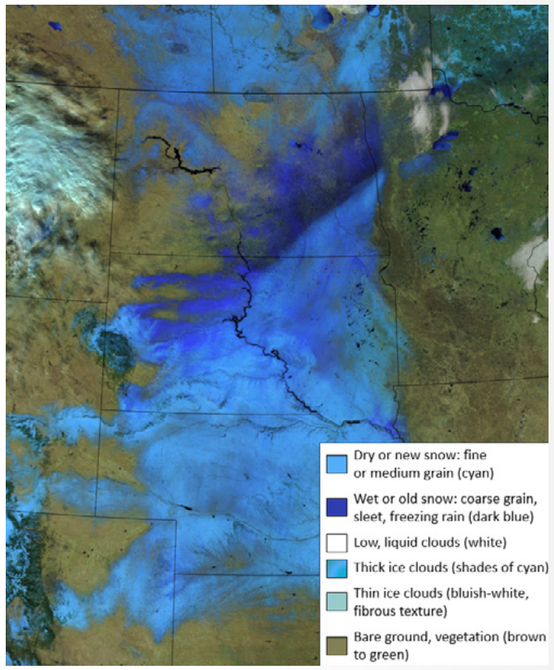
The tool enables users to examine river conditions using side-by-side image comparisons, multi-day GIF animations, and customizable time series charts. With its versatile features and intuitive design, the Stevens River Ice Mapping System supports a broad range of users in monitoring near real-time conditions and analyzing historical trends to better understand ice breakup dynamics.

The Issue of Snowmelt

Snowmelt is a key factor in mechanical breakups, the most hazardous form of ice breakup due to their tendency to cause ice jams. These events are typically initiated by rapid runoff from melting snow cover or rain, resulting in a sudden surge in water flow that breaks apart river ice cover and carries it downstream. "With snowmelt, there's both the problem of how much Snow Water Equivalent is available...and also the timing of when the snowmelt reaches the river," says Morriss.

The VIIRS Snowmelt RGB product provides valuable insight into snowpack conditions by distinguishing between fresh, dry snow (bright blue) and older, melting, or crusted snow (darker blue). It combines three VIIRS M-bands — M10 (red at 1.6 µm), M8 (green at 1.24 µm), and M5 (blue at 0.64 µm)—to capture differences in snow properties and distinguish snow and ice from clouds. The M8 band, in particular, is sensitive to snow grain size and relative wetness, helping forecasters identify early signs of melting before runoff reaches river systems.

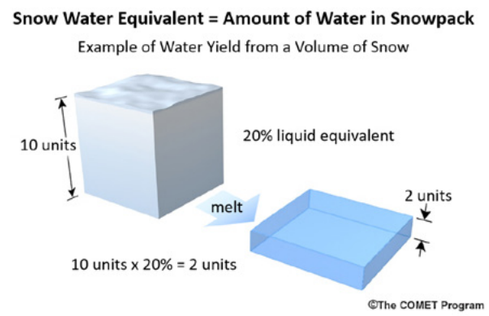
Wet or old snow upstream of rivers can indicate the potential for increased meltwater runoff, which may impact river ice conditions and lead to ice breakup or localized flooding. Although the product's 750-m resolution may miss localized snowmelt affecting small tributaries, VIIRS Snowmelt RGB imagery remains valuable for regional monitoring and for anticipating when and where increased river flow from snowmelt is more likely to begin.



Click image to enlarge. *NOAA-21 VIIRS Snowmelt RGB imagery from December 29, 2023, highlights variations in snow cover across the central U.S. Dark blue areas indicate older, crusted, or melting snow, while bright blue tones represent fresher snow cover. The Missouri River appears as a winding blue-black feature running through the center of the image. This information helps forecasters acknowledge the type and age of snow cover, supporting forecast verification and evaluating the potential for snowmelt that may be a precursor to increased runoff and flood potential. Credit: Bill Line, NOAA NESDIS/STAR, satelliteliaisonblog.wordpress.com.*

Snowpack Storage: How Much Water Does It Hold?

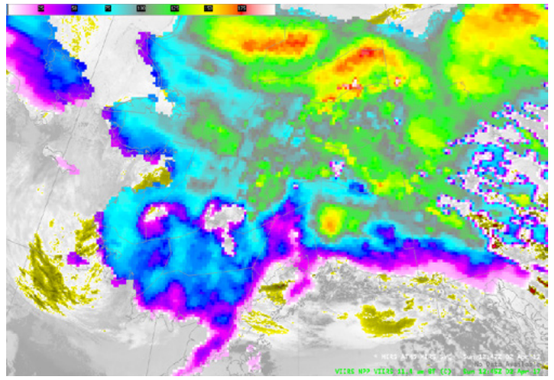
Understanding how much water would be released if the snowpack melted completely is also important for evaluating potential downstream impacts. Snow Water Equivalent (SWE) is a measure of the amount of water stored in the snowpack and can be estimated using passive microwave sensors on LEO satellites. Higher SWE values mean more stored water, which generally results in increased runoff into rivers and streams during snowmelt events.



The NOAA/NESDIS Center for Satellite Applications and Research (STAR) generates several SWE products with data from LEO passive microwave sensors. One example is the MiRS Snow Water Equivalent product from the Microwave Integrated Retrieval System (MiRS), NOAA's operational microwave retrieval platform. The MiRS SWE product uses data from several LEO microwave sensors, including the Advanced Technology Microwave Sounder (ATMS) aboard JPSS satellites, to estimate the potential water content of the snowpack at the time of the satellite overpass.

Liquid water in melting snowpack emits more microwave radiation than dry, frozen snow. This increase in microwave emissivity is a key principle behind how microwave sensors like ATMS detect and monitor freeze-thaw events from low Earth orbit. As snow shifts between frozen and melting states, these phase changes cause large variations in microwave brightness temperatures, representing the intensity of radiation at specific frequencies. LEO microwave sensors detect these variations, which are used to estimate Snow Water Equivalent values, reported as the depth of water that would result from a column of melted snow at a given point.

The MiRS ATMS SWE product has a relatively coarse spatial resolution of about 15 kilometers, which limits its ability to capture small-scale variations. For this reason, it



Click image to enlarge. *MiRS ATMS Snow Water Equivalent (SWE) imagery shows estimates of SWE in centimeters (cm) across Alaska and surrounding regions on April 2, 2017, using data from the ATMS sensor aboard the Suomi NPP satellite. Cooler colors (blue to purple) indicate lower SWE values, while warmer colors (green to red) represent moderate to high SWE, with values exceeding 150 cm in areas.*

ATMS: Measuring Microwave Energy

ATMS measures the microwave radiation emitted by the Earth's atmosphere, allowing scientists to derive temperature and moisture profiles. Because clouds are mostly transparent at microwave frequencies, microwave instruments can penetrate cloud cover, unlike visible and infrared sensors, allowing observations in nearly all weather conditions. This capability allows ATMS to provide continuous day and night monitoring of atmospheric conditions.

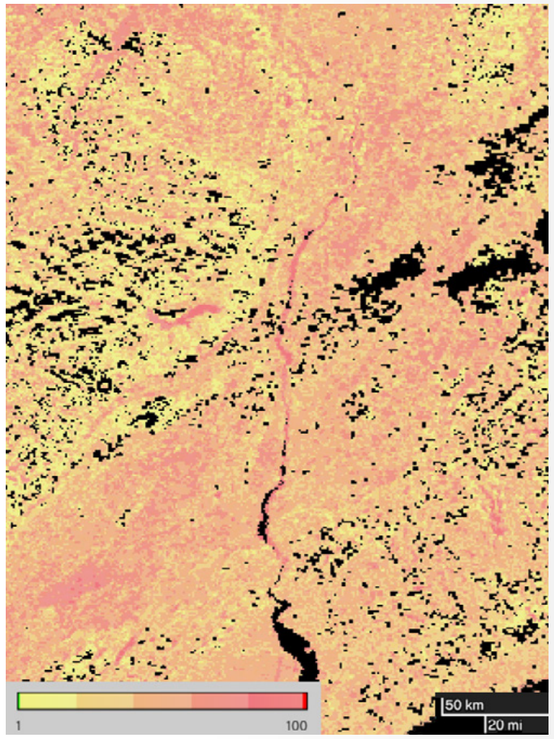
is best used alongside other data to help interpret surface conditions more accurately. Despite this limitation, the product remains valuable for enhancing regional situational awareness, providing insight into the potential for snowmelt-driven runoff, particularly in remote regions where ground-based observations may be limited.

What Snow Cover Tells Us

Snow cover is also an important factor in assessing the potential impact of snow on river ice breakup. Reduced snow cover results in less spring melt runoff, which can lead to lower river flow rates and a decreased likelihood of mechanical ice breakup. Conversely, extensive snow cover can increase runoff and raise the risk of ice-related flooding. By monitoring snow cover along with Snow Water Equivalent and other environmental conditions, forecasters can better anticipate the volume of meltwater that may contribute to rising river levels and ice breakup during thaw events.

The VIIRS Snow Cover product maps the extent of snow on the ground at a 375-m spatial resolution. It uses the Normalized Difference Snow Index (NDSI) algorithm to detect snow cover, which takes advantage of snow's unique spectral signature: high reflectance in the visible (VIS) range and low reflectance in the shortwave infrared (SWIR). The NDSI is calculated as the ratio of the difference between VIS and SWIR reflectance to their sum. The resulting values range from 0 (no snow coverage) to 100 (total snow coverage).

Complementing other snow measurements, the VIIRS Snow Cover product helps fill observational gaps and supports more accurate assessments of changing surface conditions in snow-covered areas. Its



Click image to enlarge. *This imagery from the VIIRS Snow Cover 375m product shows snow cover across the Hudson River Valley on January 23, 2025. The Normalized Difference Snow Index (NDSI) ranges from 1 (no snow) to 100 (total snow cover) and is color-coded from yellow to red. The Hudson River runs vertically through the center of the image, with surrounding areas exhibiting widespread moderate to high snow cover, reflected in NDSI values generally between 40 and 80. Source: NASA Worldview.*

global coverage also enables regional-scale comparisons that would be difficult to achieve with ground observations alone.

A Look To the Future

The U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) draws on a wide range of data sources to populate and maintain its Ice Jam Database. "The biggest source we pull from is the NWS API [Web Service] to retrieve flood warnings and advisories and [river] gauge warnings," says Morriss. Additional information comes from NOAA Climate Prediction Center forecasts, stream cameras, news reports, social media posts, and firsthand accounts. Satellite imagery, particularly from ESA's Sentinel-1 and -2 missions, provides high spatial resolution observations ranging from 5 to 40 meters, which helps CRREL pinpoint jam locations and assess the timing of breakups and releases. However, the 12-day revisit time of Sentinel satellites limits their usefulness for near real-time monitoring. To fill these observational gaps, CRREL is exploring the potential of incorporating NOAA's VIIRS Flood products into their monitoring efforts.

Morriss is in ongoing discussions with members of the JPSS Program Science team at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) to learn more about the capabilities and accessibility of VIIRS Flood products for ice jam detection. These conversations may lead to broader collaboration, including presentations and technical exchanges to introduce additional LEO data products into CRREL's operational workflows. Such efforts could improve the ability to detect developing ice jams, track flood risks, interpret river conditions, and improve temporal coverage, especially in remote or data-sparse areas.

"We're interested in improving our predictive capabilities and providing better ideas of risk in terms of being able to map risk across the country, instead of being purely reactive and cataloguing events, which is how we're operating now," notes Morriss. Reaching that goal means moving beyond post-event documentation to proactive risk assessment and early warning tools that help communities prepare in advance. Continued collaboration between CRREL and JPSS/CIMSS can support this transition by providing timely LEO satellite data and practical guidance for applying these products to real-world flood monitoring and response. ✦

Learn More

Locate ice jam events dating back to the 1700s by exploring CRREL's Ice Jam Database.

Explore the CIMSS Satellite Blog for use cases that demonstrate how VIIRS Flood products help monitor river flooding and ice jam conditions.

Read this journal article to learn about the deep learning-based technique behind the Stevens River Ice Mapping System.

Story Source

The information in this article is based, in part, on the April 21, 2025, LEO Science Seminar, "Cold Regions Research and Engineering Laboratory (CRREL) River Ice Mission," presented by Blaine Morriss and Chandler Engel, PE, of the U.S. Army Corps of Engineer (USACE) Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) Ice Engineering Group.

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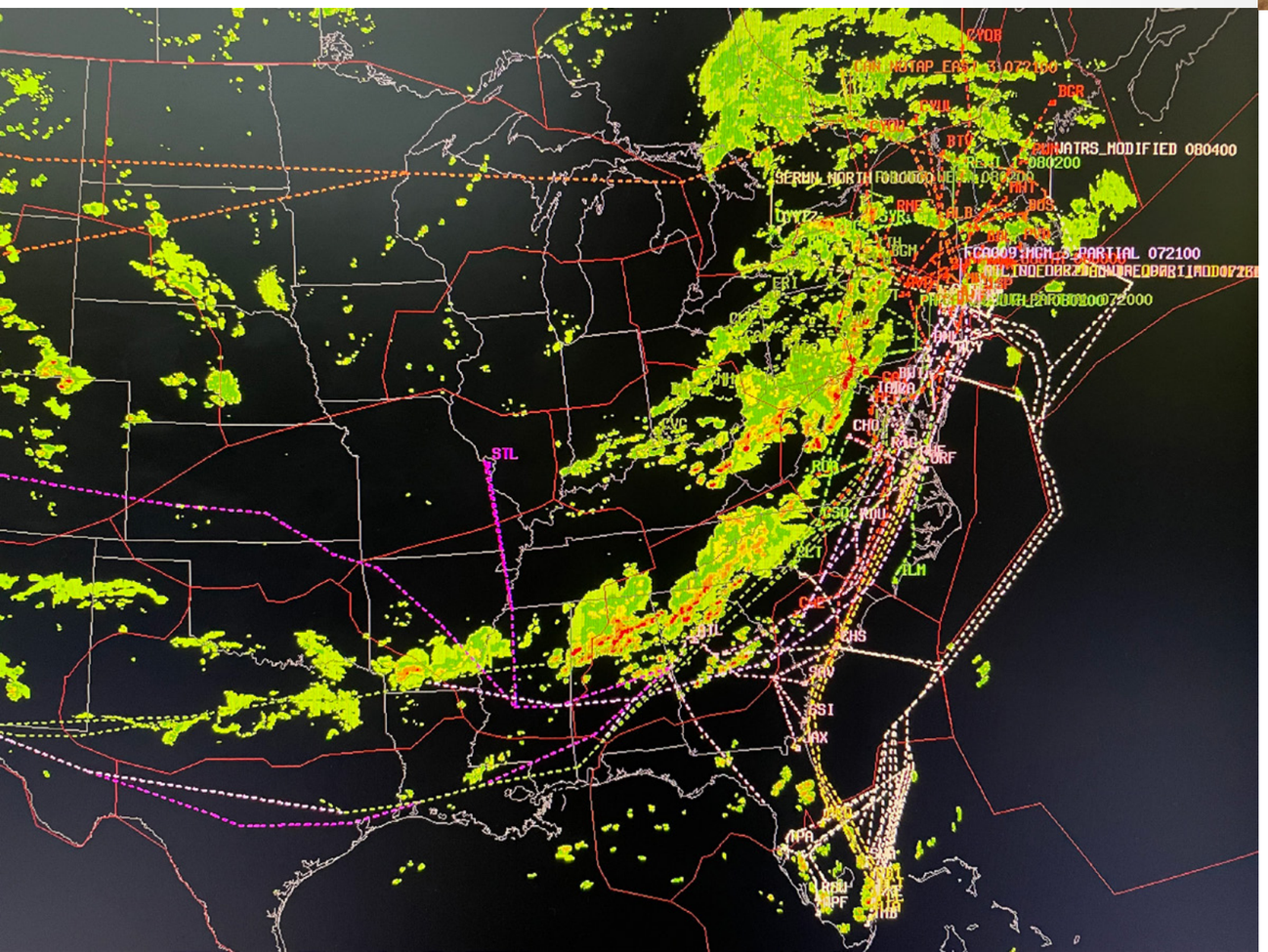
Designing *Next-Generation Observing Systems* to Support Better **Weather Prediction**

A powerful Arizona thunderstorm lights up the sky. (Image credit: iStock/mdesigner125).

Weather forecasts are part of daily life for Americans, informing both personal and economic decisions. They help people plan their commutes, dress appropriately, and organize activities, providing benefits to U.S. households valued at nearly $125 billion[1] annually. On a broader scale, NOAA's weather data supports key sectors of the U.S. economy, contributing an estimated $17 billion[2] in economic value. This information helps industries plan and operate more efficiently, from scheduling crop planting and rerouting flights to managing energy demand and aligning retail supply with consumer needs.

Forecasts, alerts, and warnings are also vital for protecting lives and property. A recent study shows that issuing winter weather advisories sooner helps prevent traffic accidents, resulting in $190 million in annual economic savings from avoided crashes in the Midwest and Northeast. Looking at hurricanes, another study estimates that improved accuracy in National Hurricane Center forecasts has saved roughly $5 billion per major storm[3] making U.S. landfall since 2007 through reduced emergency response costs and avoided damages, demonstrating the significant economic and life-saving benefits of reducing forecast uncertainty. Furthermore, NOAA satellites provide essential data for forecasting models that empower our Armed Forces to stay mission-ready, safeguard our service members, and operate with confidence in the face of weather-related threats.



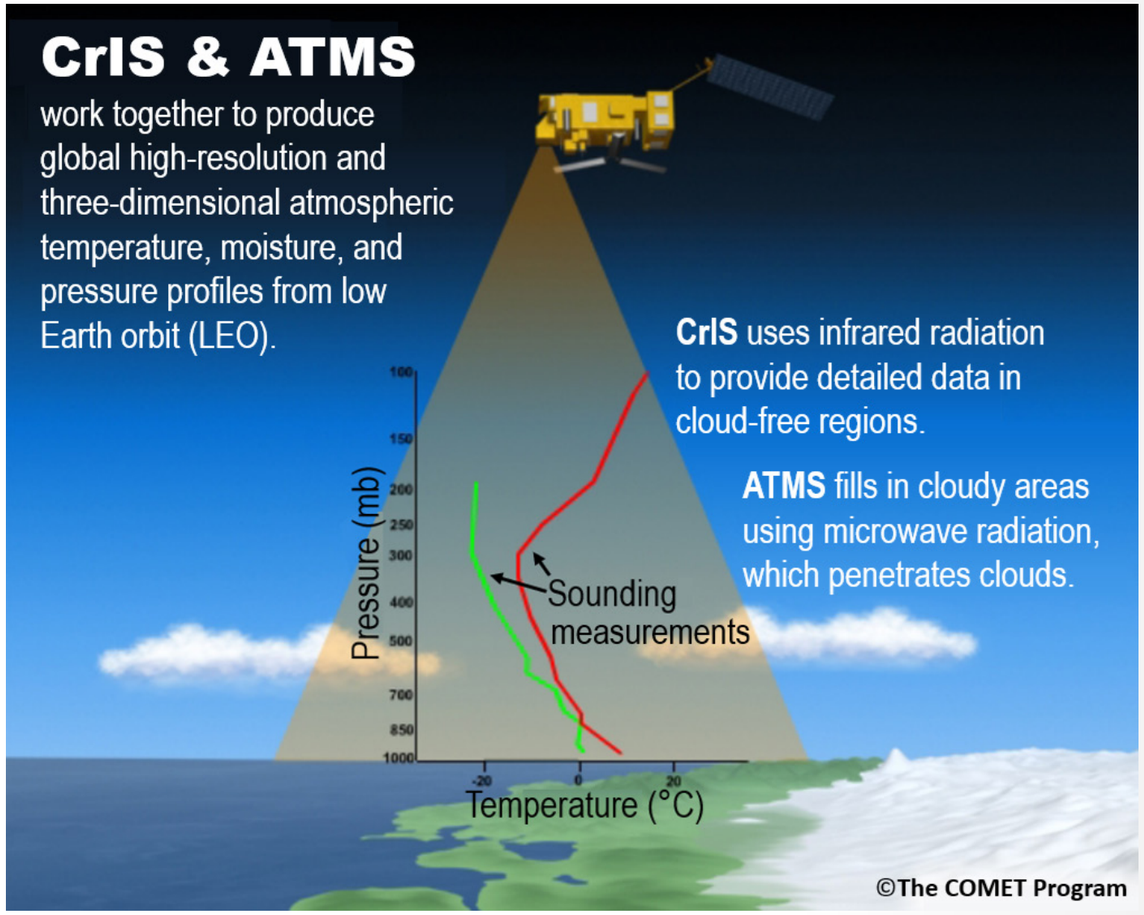
◀ *Left: The Federal Aviation Administration (FAA) relies on weather data to reroute aircraft around severe storms. In this image, dotted lines show adjusted flight paths across the Eastern U.S., while radar highlights the extent of severe weather. (Source: FAA)*

Above Left: A farmer checked on the status of his corn April 23, 2020, in Winston County, Mississippi. He was able to get his corn planted in brief windows between rains. (Photo by MSU Extension Service/Kevin Hudson)

Above Right: Accurate weather data is critical to U.S. military operations. For example, wind, precipitation, and fog can create dangerous conditions for helicopter takeoffs and landings. (Photo by Mass Communication Specialist 3rd Chris Cavagnaro, U.S. Navy/Released)

Numerical weather prediction models provide the foundation for reliable forecasts by modeling atmospheric processes like wind, precipitation, humidity, and temperature. Each model run begins with current observations from sources like weather balloons, surface stations, and satellites. These observations define the initial state of the atmosphere, giving the model a realistic starting point for predicting future conditions. Operational NWS forecasters refine numerical weather prediction model output using their expertise and additional data to deliver the trusted forecasts and warnings that Americans rely on.

Polar-orbiting low Earth orbit (LEO) satellites, including the Joint Polar Satellite System (JPSS), supply more than 80% of the numerical weather prediction model data used for 3- to 7-day forecasts. Some of the most impactful data come from atmospheric sounders, including the Cross-track Infrared Sounder (CrIS) and the Advanced Technology Microwave Sounder (ATMS) onboard JPSS satellites. Sounders like CrIS and ATMS measure the intensity of radiation within a column of the atmosphere. Their contribution to numerical weather prediction lies in providing detailed information about the vertical structure of atmospheric temperature and moisture—two essential variables for understanding and predicting storm development.

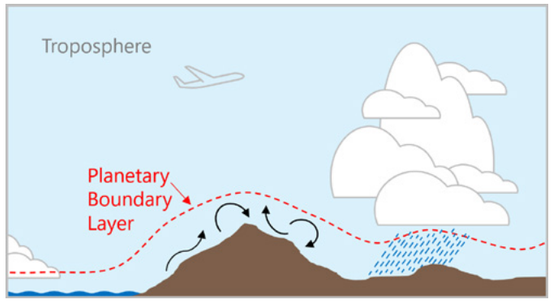


As demand grows for earlier warnings, more accurate forecasts, and higher-resolution observations, NOAA and NASA are turning their attention to the next generation of satellite systems. While ATMS and CrIS will provide data well into the 2030s, planning is already underway for future LEO missions aimed at advancing weather prediction capabilities. One important area of focus is improving observations within the planetary boundary layer (PBL), an under-observed part of the atmosphere that greatly affects the formation of severe weather.

From Ground to Cloud: Understanding the PBL

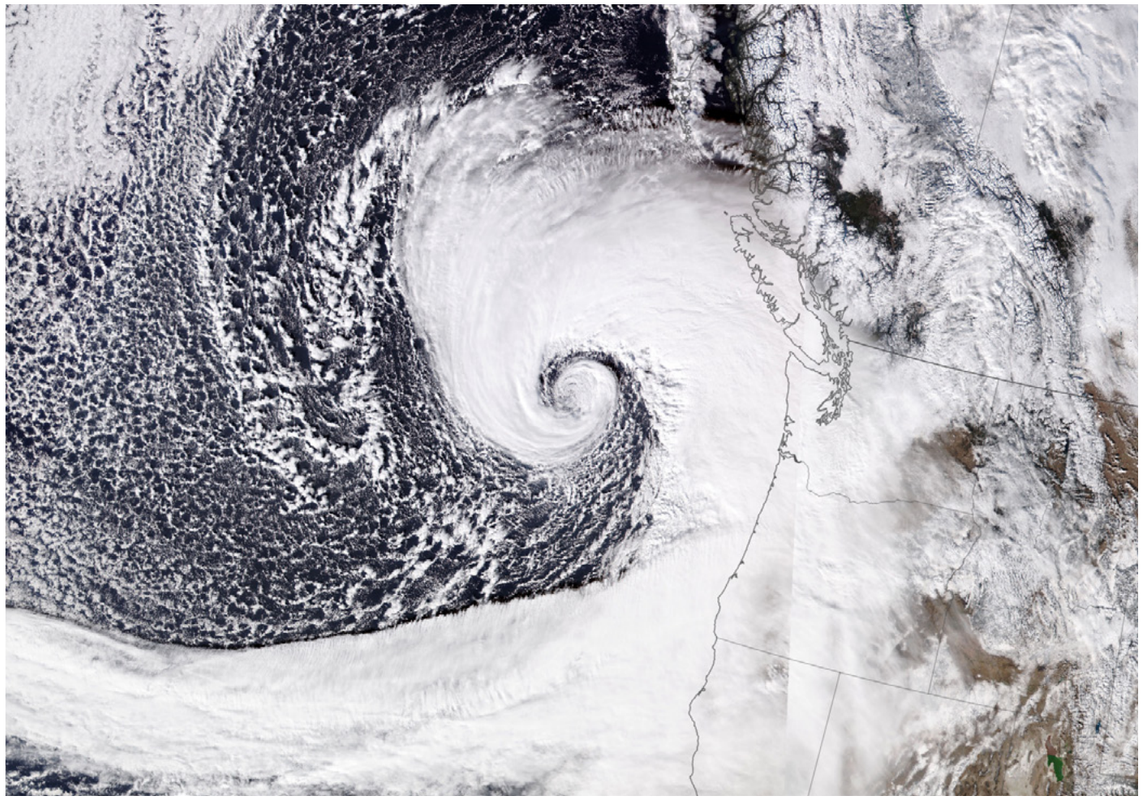
The PBL is the lowest part of the troposphere, where the atmosphere directly interacts with the Earth's surface. It's where we live and where most weather takes place. Extending from the ground up to several kilometers, the height and structure of the PBL is highly variable, influenced by dynamic surface and atmospheric conditions.

Airflow in the PBL is turbulent, constantly shifting and behaving in unpredictable ways. This turbulence produces eddies—the swirling motion of air created by surface friction as wind moves over rough or uneven terrain. Eddies drive vertical mixing, lifting heat and moisture upward. Together with wind shear and surface heat, they contribute to atmospheric instability and significantly influence the development and intensity of storms.



"Boundary layer temperature and humidity exert a really strong control on the outcomes of weather systems, from isolated convection [thunderstorms] all the way to extratropical cyclones," explains Derek Posselt, PhD, a research scientist with the Atmospheric Physics and Weather group in the Earth Science Section at NASA Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech). These powerful weather systems can produce severe hail, thunderstorms, blizzards, and tornadoes. Posselt adds that the influence of the PBL extends beyond storm development, affecting hazards on the ground as well. "The properties of the boundary layer are critically important for things that affect the surface [such as] freezing rain, icing of roads, and fog — all forms of hazardous weather that are directly related to PBL properties."

Given its central role in weather formation, accurate representation of the PBL in forecast models is critical, yet observations remain limited. Its complex structure, high variability, and proximity to Earth's surface make the PBL hard to measure. "It's notoriously difficult to observe, especially from space," noted Derek Posselt at the March 2025 LEO Science Seminar.



NOAA-20's Visible Infrared Imaging Radiometer Suite (VIIRS) captured an extratropical cyclone impacting the Pacific Northwest on November 19, 2024, bringing strong winds and heavy rain that left nearly 600,000 people in Washington state without power. The storm's intensity was fueled by the PBL, where the exchange of heat, moisture, and momentum between the surface and atmosphere provided critical energy for its development.

Although LEO sounders have a significant positive impact on weather forecasting, their vertical resolution is insufficient to accurately capture small-scale variations in near-surface temperature and water vapor. Surface features like emissivity, vegetation, and land temperature further complicate observations by distorting atmospheric signals that introduce errors. This reduced accuracy in observations near the surface often results in misrepresentation of the PBL in weather models, contributing to forecast uncertainty, especially for storms.

Improving space-based observations of the PBL is a priority for the Earth science community, as more accurate measurements in this layer could substantially improve severe weather forecasts. "So, the question becomes, how do we determine in advance which measurements are going to be useful in addressing PBL science?" asks Posselt. To answer questions like this, researchers often turn to Observing System Simulation Experiments (OSSEs), one of several valuable tools for assessing the impact of new observations before they are collected.

The OSSE: A Planning Tool for Quantifying Impact

OSSEs are advanced computer simulations that quantify the impact of new observing systems and their effectiveness in meeting scientific objectives. Using synthetic observations, OSSEs allow scientists to evaluate the benefits of new or additional observations without the need to build and launch physical satellites and instruments, providing a cost-effective way to prioritize spending. This helps save taxpayer dollars, ensuring that public funds are spent on satellite technologies that deliver measurable improvements in forecast accuracy and public safety. OSSEs are routinely used by many agencies and organizations, including NOAA, NASA, the National Laboratories, academic institutions, and private industry, to optimize observing systems and guide strategic investments.

The Forecast OSSE

Forecast OSSEs are the traditional and most widely used type of OSSE. They rely on three core components: a "Nature Run," synthetic observations, and a data assimilation system. The Nature Run is a model simulation that represents the real atmosphere. Synthetic observations are generated from the Nature Run, with simulated measurement errors added, to mimic how different observing systems would produce data. The synthetic observations are then assimilated into a model, often a numerical weather prediction model, to produce forecasts. The results are compared to the "truth" from the Nature Run, allowing scientists to evaluate how well different observing systems would improve forecast skill. "It's a process that has to be done carefully [to limit errors], but once you've done it, it's extremely powerful," Posselt says.

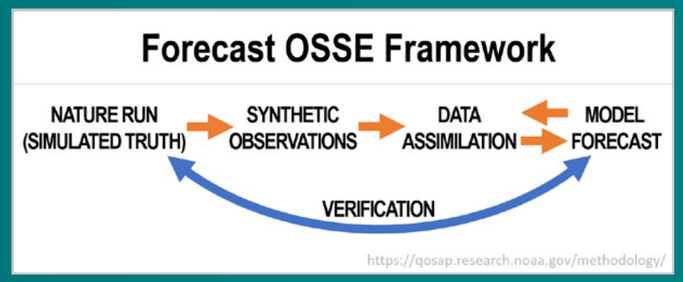


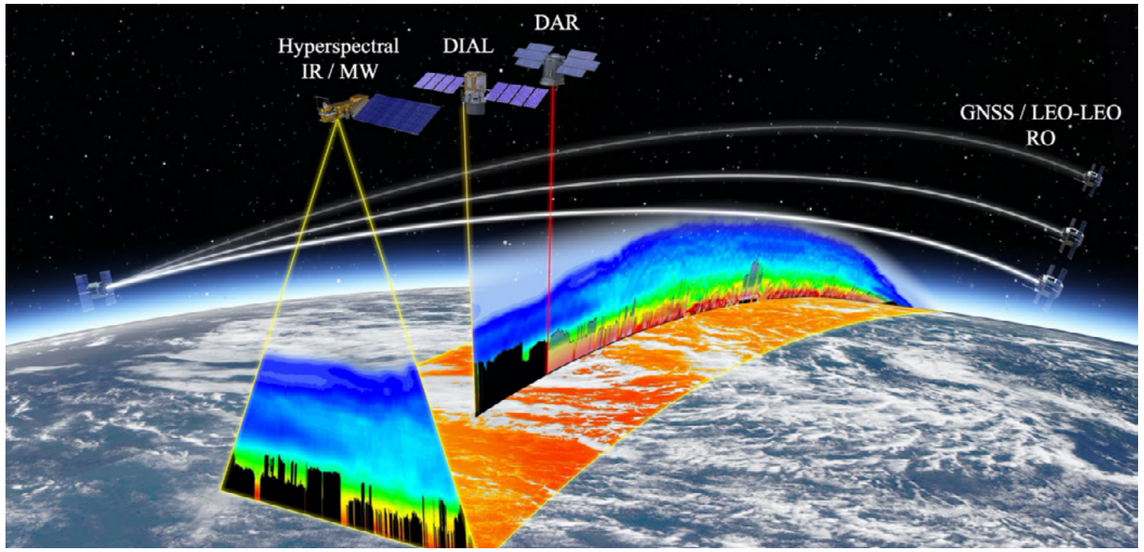
Figure: This is a simplified representation of a forecast OSSE framework for evaluating the impact of satellite observations on forecast model skill. OSSE design varies based on scientific goals, with components like the data assimilation scheme, observation types, and forecast model tailored to specific objectives and domains.

No one OSSE fits all applications. Each is tailored to a specific use, such as ocean surface monitoring or forecasting air quality, and is designed to meet objectives like improving forecast skill, enhancing retrieval accuracy, or evaluating sampling effectiveness. Forecast OSSEs—the most traditional approach—evaluate how proposed observing capabilities might affect forecast accuracy. Retrieval OSSEs quantify an instrument's ability to accurately measure specific geophysical variables. Sampling OSSEs determine whether an instrument has the spatial and temporal resolution needed to capture key features with sufficient detail and frequency. OSSEs can also be designed to support other objectives, such as assessing a particular atmospheric or physical process to improve modeling. Despite their different frameworks, all OSSEs serve as strategic tools for mission planning by quantifying the value of new or additional observations and informing the prioritization of instruments and architectures before major investments are made.

The PBL Challenge: Designing a New OSSE System

"One of the things that makes [observing the PBL] complicated is that there's no single observation that is going to get us the information that we need," remarks Posselt. LEO sounders provide global coverage of temperature and water vapor but lack the resolution to capture details near the surface. GNSS-RO, or Global Navigation Satellite System Radio Occultation, provides extremely fine vertical information, yet its horizontal resolution is coarse, ranging from tens to hundreds of kilometers. Differential Absorption Lidar (DIAL) and Differential Absorption Radar (DAR) provide very accurate measurements of water vapor content but only along narrow swaths.

The reality is this: no single instrument can currently observe the PBL with the spatial and temporal resolution needed to characterize its complex thermodynamic structure. A global PBL observing system will require multiple



A conceptual global PBL observing system demonstrates the observational synergy between different sounding technologies. These include hyperspectral infrared (IR) and microwave (MW) sounders; Differential Absorption Lidar (DIAL) and Differential Absorption Radar (DAR); and Global Navigation Satellite System (GNSS) and LEO-LEO Radio Occultation (RO). Together, these instruments provide full sky coverage of key PBL variables—water vapor, temperature, and PBL height—at varying spatial and vertical resolutions, enabling the global characterization of the PBL's thermodynamic structure and improving the understanding of its role in extreme weather, surface fluxes, cloud formation, and related processes. Source: The NASA PBL Incubation Study Team Report (Teixeira et al., 2021).

Essential PBL Science Goals

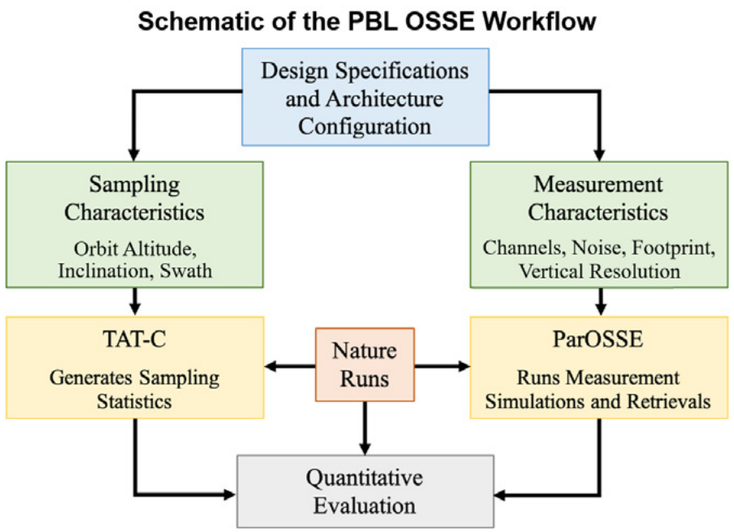
The 2017-2027 Decadal Survey for Earth Science and Applications from Space highlighted a top priority for the Earth science community: understanding how key planetary boundary layer processes influence weather, hydrological, and air quality forecasts across different timescales.

Guiding progress toward this goal, NASA scientists have outlined a vision for PBL science focused on four interconnected goals:

- Understanding the role of the PBL in convection and extreme weather events,
- Characterizing the structure and behavior of the cloudy PBL,
- Examining interactions between the PBL and the surface, and
- Exploring the links between PBL modeling, mixing and transport, and air quality.

complementary missions, varying instrument and orbit configurations, and innovative approaches to measurement and modeling. Testing every possible mission concept in the real world would be prohibitively expensive. By applying an OSSE framework, scientists can simulate the impact of different system architectures and identify the most effective measurement combinations to meet PBL science goals in a cost-efficient and scalable way. Scientists at the Jet Propulsion Laboratory have designed an OSSE system tailored for the PBL to explore options for a future PBL-observing mission (see schematic to the right).

The workflow begins by defining mission requirements and essential sampling and measurement characteristics, such as orbit inclination and spatial resolution. Two analysis tools, developed with support from NASA's Advanced Information Systems Technology (AIST) Program, are then used to assess various observing strategies and system configurations. The Tradespace Analysis Toolkit for Constellations (TAT-C), a sampling OSSE, simulates satellite orbits to quantify what can be observed with different orbit parameters and scene widths. The Parallel Observing System Simulation Experiments (ParOSSE) tool, a retrieval OSSE, evaluates the information content of each observation type to determine those best suited for capturing the PBL's small-scale processes.



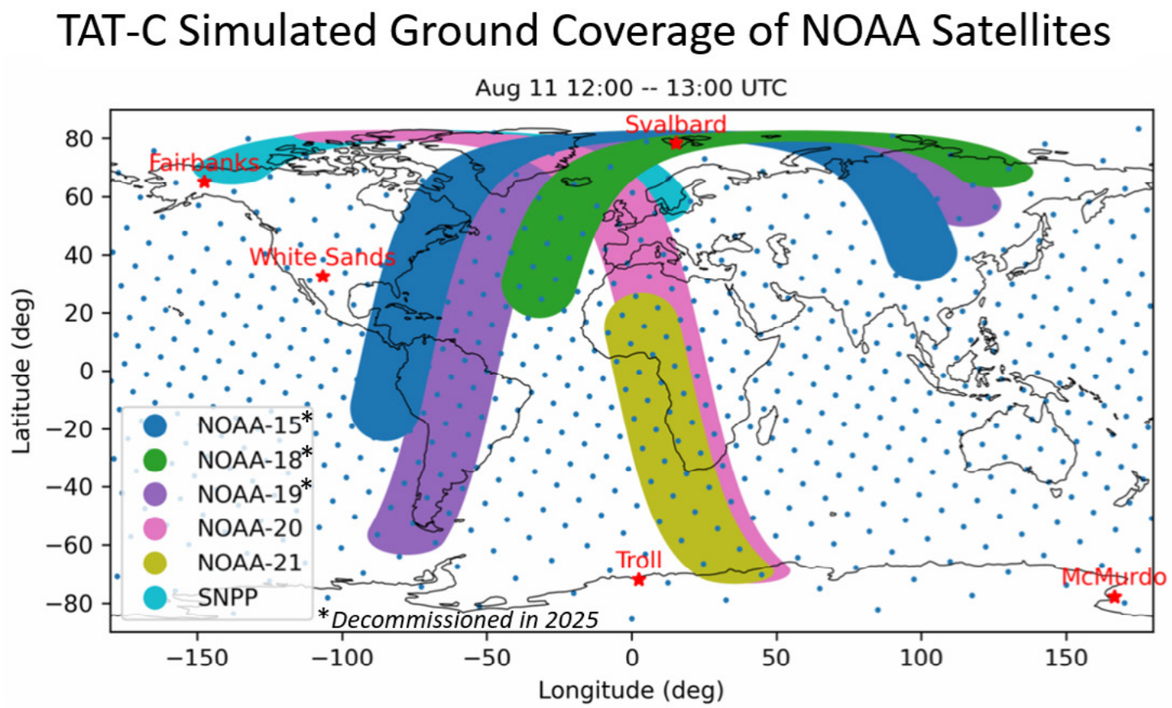
Click image to enlarge. *Figure courtesy of Derek Posselt.*

Results from both tools are compared against a "Nature Run" simulation that represents the true state of the environment, serving as a baseline for evaluating how well each system configuration performs under realistic atmospheric conditions.

The Synergy of TAT-C and ParOSSE

TAT-C and ParOSSE provide a synergistic approach for evaluating many different aspects of observing systems and their applications. TAT-C allows scientists to design and test hypothetical instruments, examining how variables like swath width or orbit timing influence coverage and performance. For example, researchers can quantify how doubling a sensor's swath affects the quality of measurements. ParOSSE builds on this by simulating the measurements those sensors would generate, enabling fine-tuning of instrument specifications for optimal performance. Using these OSSEs in parallel helps researchers weigh trade-offs between design choices and observational accuracy.

According to Posselt, the Jet Propulsion Laboratory has been partnering with NOAA, sharing TAT-C and ParOSSE to support concept studies for future geostationary microwave and infrared sounders. More broadly, these tools enable comprehensive OSSEs that inform decisions across a wide range of new and existing observing systems, helping ensure they keep pace with the evolving needs of weather prediction and environmental monitoring.



Shown above is an example of simulated ground coverage from NOAA LEO satellites generated by TAT-C. The points represent the orbital motion of the satellite during the mission. Tools like TAT-C allow scientists to explore how changes to orbit parameters, such as altitude, inclination, or timing, affect observational coverage. For instance, TAT-C can be used to evaluate how repositioning a tertiary satellite closer to a primary satellite could enable more closely timed observations. TAT-C also helps assess how adding or removing instruments impacts coverage, providing insight into when and where observations would be available under different mission designs. (Image courtesy of Dr. Paul Grogan, Arizona State University / Dr. Derek Posselt, Jet Propulsion Laboratory).

OSSE Insights for Next-Generation LEO Mission Planning

While NASA continues to refine mission concepts for observing the PBL, NOAA is leveraging OSSEs to guide the development of next-generation LEO sounders. Two currently operational JPSS instruments—ATMS, a passive microwave sounder, and CrIS, a hyperspectral infrared sounder—provide essential atmospheric data to numerical weather prediction models, enhancing our ability to predict and prepare for severe weather events. Recognizing their importance, NOAA is planning the next generation of LEO sounders to ensure continuity of critical global observations, fill coverage gaps, improve data quality, and strengthen support for the National Weather Service's mission to protect lives and property and enhance the economy.

OSSEs at NOAA

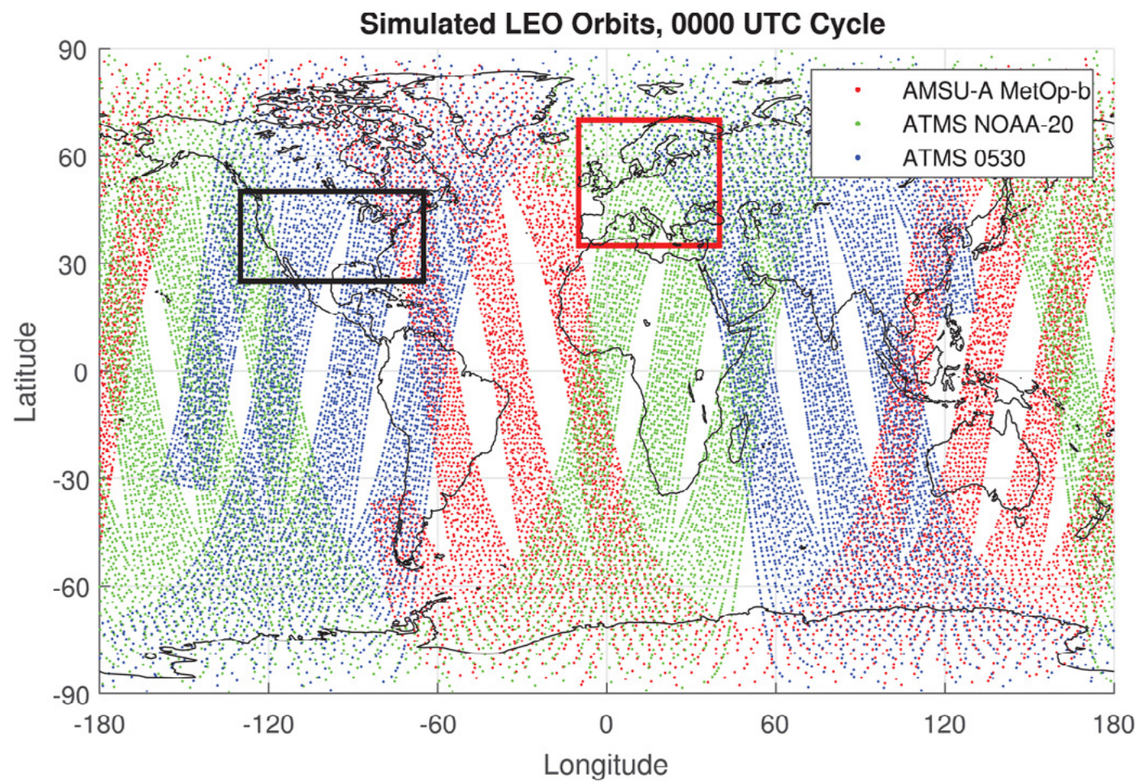
Established in 2014, NOAA's Quantitative Observing System Assessment Program (QOSAP) is dedicated to improving Earth observation systems through rigorous, data-driven evaluations. Using OSSEs and other simulation tools, QOSAP assesses the impact of current and proposed in-situ and satellite observational technologies on numerical weather prediction. These insights inform strategic decisions, allowing NOAA to invest in the most effective, cost-efficient solutions. This leads to more reliable forecasts that help save lives, protect property, and deliver economic benefits, all in support of NOAA's mission of science, stewardship, and service.

As part of this effort, the NOAA NESDIS Office of LEO Observations sponsored several OSSEs, including one designed to examine the forecast benefits of a new LEO orbit, described below.

Using an OSSE framework developed by NASA's Global Modeling and Assimilation Office (GMAO), scientists evaluated the impact of adding ATMS- and CrIS-like instruments to a new early morning orbit. This orbit was selected to fill a gap in LEO coverage in a conceptual global observing network that included only mid-morning and early afternoon passes. The goal was to assess how microwave and hyperspectral infrared observations from a third LEO orbit could enhance numerical weather prediction.

The OSSE experiments showed that assimilating sounder data from an early morning orbit into an operational numerical weather prediction model led to measurable improvements in global weather forecasts. The simulated microwave instrument in this new orbit improved medium-range forecast accuracy for up to 4 to 7 days, while a simulated infrared instrument contributed to improvements for up to 3 to 5 days. The blue dots in the figure on the next page represent the additional coverage provided by the simulated ATMS instrument in a early morning orbit.

This example illustrates the value of OSSEs in satellite mission planning and investment decisions by quantifying the forecast improvements new observing systems can offer before they are built and deployed. By simulating different scenarios, OSSEs help agencies evaluate potential returns on investment and prioritize technologies that deliver tangible benefits to the public. For a detailed analysis of the LEO orbit OSSE workflow, results, and limitations, refer to the full study published in 2024.



This diagram shows coverage of three simulated microwave instruments on LEO platforms between 2100 UTC to 0300 UTC. Blue dots represent the new early morning orbit simulated in the OSSE (ATMS 0530 LTAN), filling the gap between the NOAA-20 orbit in green (1330 LTAN) and the MetOp-B orbit in red (2130 LTAN). Together, these three orbits provide nearly complete coverage of the globe. Source: Privé, et al (2024), CC BY 4.0 (no changes).

Final Thoughts

Insights from OSSEs allow NOAA, NASA, and others to assess the cost-effectiveness and benefits of new observing systems early in the design process, helping ensure that investments are directed toward missions that deliver the greatest value to Americans. These simulations provide a proactive approach to satellite mission planning, allowing scientists and engineers to test new concepts and evaluate system configurations well before they reach orbit. This level of analysis is especially important for observing complex regions like the planetary boundary layer, where more accurate, high-resolution data could significantly improve our ability to forecast severe weather and storm development.

The coming years present exciting opportunities for NOAA and NASA to enhance Earth observation capabilities through informed, data-driven planning. OSSEs are central to this effort, offering a rigorous framework to evaluate new instruments and orbits and identify which have the greatest positive impact on numerical weather prediction models. By guiding decision-making, OSSEs empower agencies to build smarter, more agile observing networks that expand coverage, improve model performance, and deliver more impactful support to forecasters and communities that depend on timely, reliable weather information. ✦

Learn More

Explore a journal article detailing the PBL retrieval OSSE framework developed at the Jet Propulsion Laboratory.

Discover how NOAA's Quantitative Observing System Assessment Program (QOSAP) uses OSSEs and other experiments to quantitatively assess and prioritize observing system designs for improved weather forecasting.

Learn more about JPL's vision for a future global PBL observing system in the NASA PBL Incubation Study Team Report.

Story Source

The information in this article is based, in part, on the March 17, 2025, LEO Science Seminar, "Observations and Data Assimilation to Improve the Planetary Boundary Layer," presented by Dr. Derek Posselt, Research Scientist, NASA Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech), Pasadena, CA. Contributors include: Dr. Paul Grogan (Arizona State University), Dr. Hai Nguyen (JPL), Dr. Masashi Minamide (University of Tokyo), Dr. Kay Suselj (JPL), Dr. Longtao Wu (JPL), Dr. Marcin Kurowski (JPL), Dr. Matt Lebsock (JPL), Dr. Amin Nehrir (NASA Langley Research Center), Dr. Rory Barton-Grimley (NASA Langley Research Center), Dr. Luis Millán (JPL), Dr. Vijay Natraj (JPL), Dr. Mary Morris (JPL), Dr. Eric Wang (JPL), and Dr. Chris Wilson (JPL). Government sponsorship acknowledged.

Footnotes

[1] Adjusted for inflation

[2] If fully monetized; adjusted for inflation

[3] Category 3 or above, or generated at least $20 billion in damage

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TRACKING *HAZARDS* FROM LOW EARTH ORBIT:

The Impact of Hurricane Helene on North Carolina's Mountain Region

Homes, vehicles, and debris lie in scattered heaps throughout the Garren Creek community in Fairview, Buncombe County, North Carolina, on October 6, 2024. Severe flooding from extreme rainfall brought by Hurricane Helene surged down the mountainsides, destroying structures, causing landslides, and collapsing roads. Photo: FEMA Photo by Madeleine Cook/Released.

Farmland in Andrews Valley, North Carolina in the foothills of the Great Smoky Mountains. Photo: Blue Ridge National Heritage Area.

Covering roughly 35.8 million square kilometers (km²), mountains account for about a quarter of Earth's land surface. Beyond their natural beauty, mountain landscapes are essential for life, serving as the world's "water towers" by supplying 60-80% of our planet's freshwater and up to 75% of water in the Western U.S. for drinking, industry, and food and energy production. Mountainous regions also provide a vital source of income for hundreds of millions of people worldwide through agriculture, forestry, and tourism. In the U.S., farming and ranching along the Blue Ridge Mountains generate more than $38 billion a year, significantly contributing to the nation's economy. Visitor activity in U.S. mountain parks is another driving force, with spending topping $11 billion and supporting more than 163,000 jobs annually. Yet for the roughly one billion people around the world who call the mountains home, the persistent threats posed by geomorphic hazards puts lives, livelihoods, and infrastructure in jeopardy.

Nature's Force & Fury

A geomorphic hazard is a natural process or event originating from the Earth's surface that can harm humans, damage infrastructure, disrupt activities, or impact the environment. Examples include landslides, debris flows, avalanches, floods, erosion, volcanic eruptions, sinkholes, and river channel changes, all of which can have significant impacts when they intersect with human settlements.

Geomorphic hazards are amplified by the very characteristics that define mountainous areas. Steep, often unstable slopes, rugged terrain, and dynamic weather systems make these regions especially prone to landslides, debris flows, and flash flooding. When such hazards intersect with human activity, the impacts on downslope communities can be severe, as evidenced in 2024, when Hurricane Helene caused historic flooding and more than 2,000 landslides, devastating mountain communities across large parts of Appalachia. While high-impact events like Helene tend to draw immediate attention, slower-moving geomorphic processes such as soil erosion and river channel migration can also have far-reaching, long-lasting effects on both humans and natural systems.

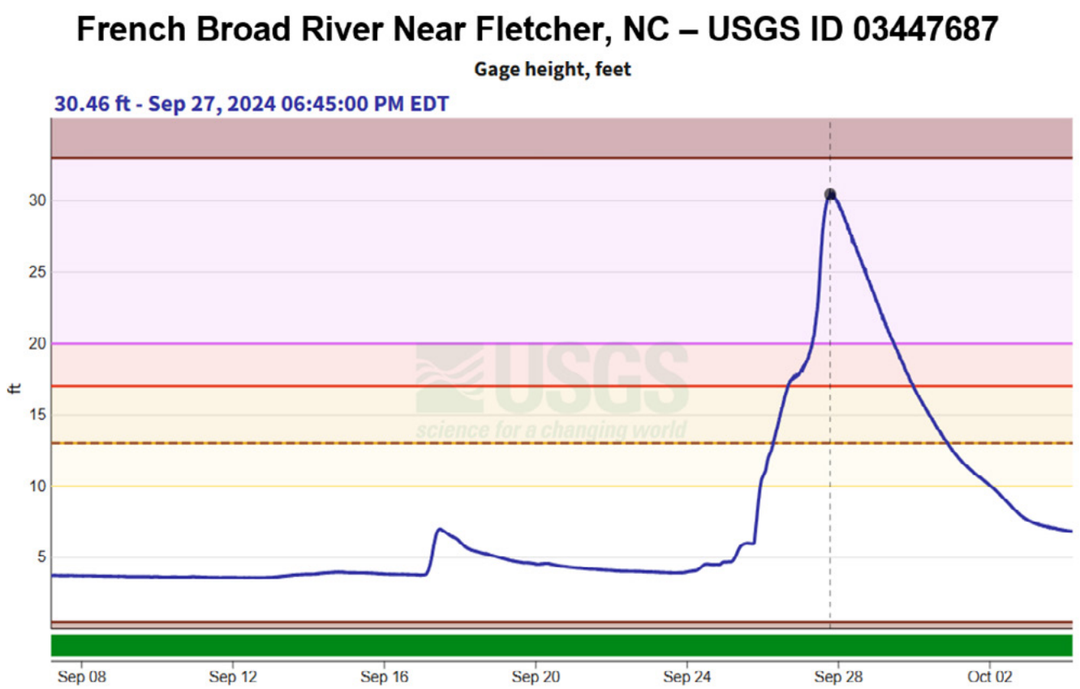
Safeguarding mountain communities from geomorphic hazards begins with understanding the factors that drive them. The NOAA/NESDIS Office of Low Earth Orbit (LEO) Observations supports this effort by providing satellite data that feeds into models and products used to monitor and forecast environmental conditions that influence the likelihood of such events. While geomorphic hazards take many forms, the impact of Hurricane Helene across the Southeastern U.S. demonstrated how the timing and intensity of weather variables like precipitation can result in destructive flash floods and landslides. In mountainous regions especially, understanding the drivers behind extreme weather is crucial for improving disaster preparedness, emergency response, and long-term resilience planning.

Cascading Hazards: What LEO Satellites Revealed

When Jenny Dissen, Engagement and Partnerships Lead at the North Carolina Institute for Climate Studies (NCICS), left her Asheville office on Wednesday, September 25, 2024, she had little idea of the devastation

A landslide from Helene collapsed a road along the Blue Ridge Parkway. Photo: National Park Service.

Hurricane Helene would soon unleash on her community. In the days that followed, relentless rainfall saturated the ground and overwhelmed rivers, causing catastrophic flooding, landslides, and debris flows that claimed more than 100 lives and damaged or destroyed thousands of homes, businesses, and critical infrastructure in the region. In a powerful account shared during a LEO Science Seminar, Dissen reflected on witnessing the storm's impacts firsthand and emphasized the importance of LEO data in forecast operations.



Top: Catastrophic flooding in Asheville's River Arts District, adjacent to the French Broad River, on Friday, September 27, 2024. Image courtesy of Jenny Dissen.

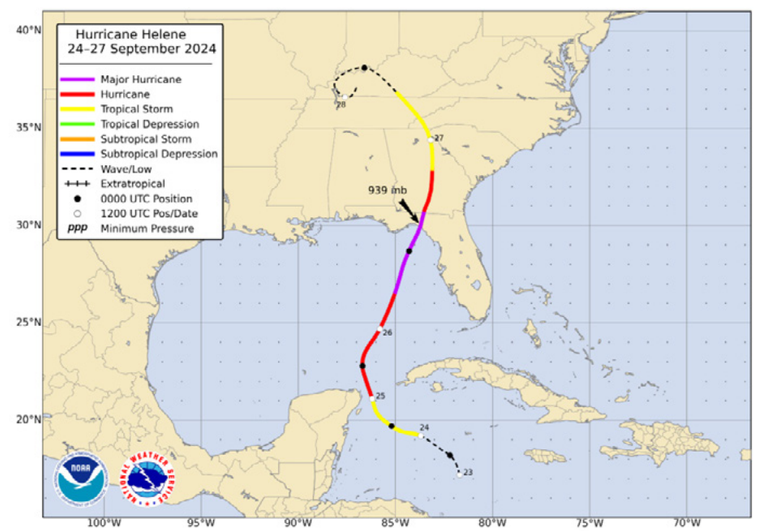
Bottom: A USGS streamgage hydrograph shows the French Broad River at Old Fanning Bridge Road in Asheville, where the above photo was taken, cresting at a record 30.46 feet that same day. Credit: U.S. Geological Survey (USGS).

Her connection to the disaster goes beyond lived experience. At NCICS, Dissen leads efforts to demonstrate the societal and economic value of satellite observations and their applications for understanding real-world impacts, which is crucial for analyzing events like Hurricane Helene. Much of her work involves engaging with community leaders and businesses that depend on forecasts and insights from LEO data to make critical decisions before, during, and after severe weather.

Grounded in both lived experience and professional expertise, Dissen offers a unique perspective on the challenges her region faces. Asheville and its neighboring communities, situated in a mountain valley where the French Broad and Swannanoa Rivers meet, face frequent geomorphic hazards due to steep terrain, complex geology, and variable weather. The area has endured landslides, floods, and severe storms before, but nothing matched the intensity of Helene. "We had almost 2,000 landslides in this mountainous region," Dissen recalls, noting widespread damage to roads, rivers, and structures. In Asheville alone, more than 10 inches of rain fell during the event, with far greater amounts in the surrounding mountains where flooding was so severe it destabilized entire hillsides.

Helene's impact in Western North Carolina was intensified by several days of heavy rainfall across Southern Appalachia that saturated soils and elevated river levels before the storm arrived. Observations from LEO satellites provide a valuable perspective for understanding the geophysical and meteorological conditions that amplified the disaster, enhancing the ability to anticipate, issue warnings, and respond to similar events.

A Look At Rainfall From Low Earth Orbit



Click image to enlarge. *The path of Hurricane Helene from September 24-27, 2024, as it moved over the U.S. and entered the post-tropical stage. Source: NOAA National Hurricane Center Tropical Cyclone Report—Hurricane Helene (AL092024).*

By the evening of Wednesday, September 25, 2024, Hurricane Helene was still more than 500 miles from Asheville, with its center just north of Cancun, Mexico. Although landfall in Florida was more than a day away, its influence was already being felt in the mountains of North Carolina. Tropical moisture moving northward fueled several days of persistent, heavy rainfall along a stalled cold front stretching from Atlanta to Asheville. As of midnight on Thursday, September 26, the Asheville Airport had already recorded more than four inches of rain. Although Helene remained several hours away, soils in the Asheville area were becoming saturated, and

***Click image to enlarge**. 3D terrain map of Buncombe County, NC, with Asheville encircled by the mountain ranges of the southern Appalachian region. Credit: ©Maphill/CC BY-ND/www.maphill.com.*

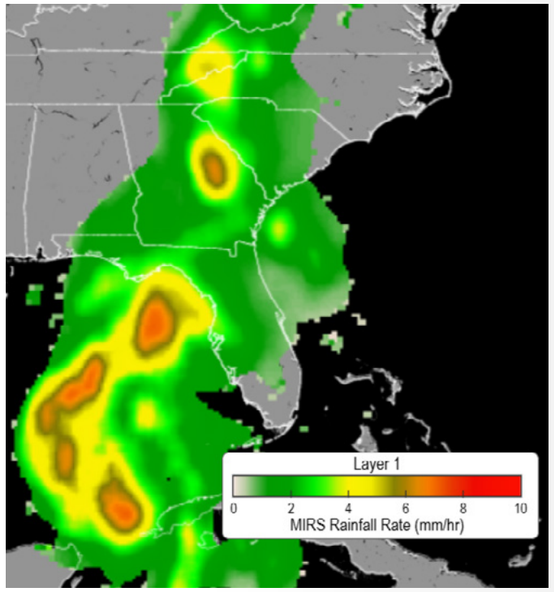
the French Broad River that flows through the heart of the city had risen to minor flood stage, leaving little capacity for additional rainfall.

"Asheville sits in a bowl between two very high peaks," explains Dissen. "The two highest elevation points, Mount Mitchell and Mount Pisgah, are the highest east of the Mississippi [River]…when precipitation arrives at the peaks, it all just gushes down [the mountainsides]." When Hurricane Helene finally reached Western North Carolina on Friday, September 27, it brought several more inches of rain, intensifying already dangerous conditions. "We had record rainfall—30+ inches up in the mountains [surrounding Asheville]," Dissen says. "In this case, all of this precipitation was 30 to 50 percent more than an average hurricane." These extreme conditions greatly enhanced the risk of landslides and flash floods across the region's already saturated, mountainous terrain.

LEO satellites equipped with passive microwave sensors, such as the Advanced Technology Microwave Sounder (ATMS) onboard Joint Polar Satellite System (JPSS) missions, provide a valuable means of monitoring extreme precipitation events. Atmospheric data from ATMS feeds into powerful satellite-based algorithms that provide estimates of precipitation rate and accumulation, making them useful for analyzing storm intensity and temporal trends.

One such algorithm is NOAA's operational Microwave Integrated Retrieval System (MiRS), which processes microwave radiances from ATMS, the Advanced Microwave Sounding Unit (AMSU) and Microwave Humidity Sounder onboard EUMETSAT's MetOp series, and NASA's GPM Microwave Imager (GMI), to generate advanced near real-time surface and precipitation products. It applies a one-dimensional variational retrieval (1D-Var) technique that compares the satellite data with a computer model of the atmosphere, adjusting the model until it aligns with the data. MiRS is primarily used to produce atmospheric temperature and moisture profiles, retrieve rain rates, support water vapor products, and generate snow and sea ice data for global monitoring.

On September 26, 2024, the MiRS Rainfall Rate product derived from ATMS data (below) revealed widespread moderate to heavy precipitation across the Southeastern U.S. The rainfall was associated with Hurricane Helene, which was nearing Florida's Big Bend as a powerful Category 4 storm, producing torrential rain and maximum sustained winds exceeding 140 miles per hour.



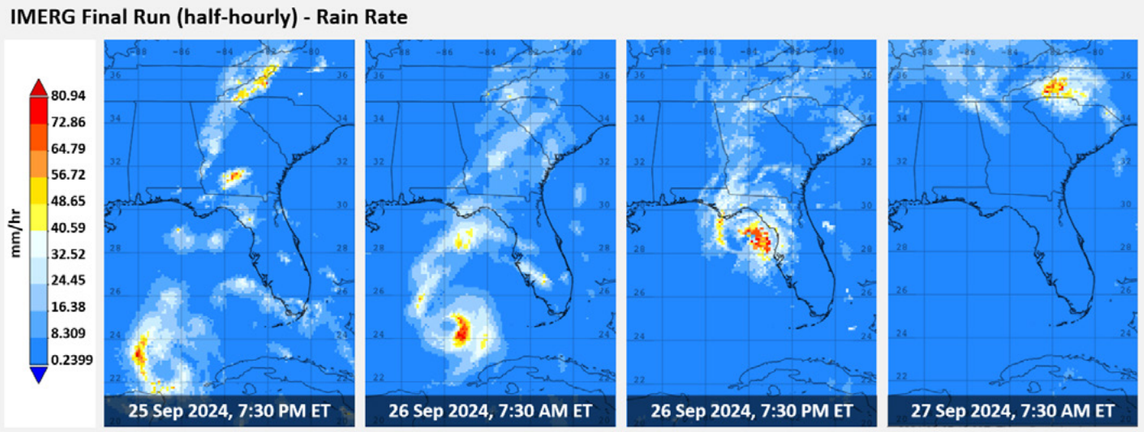
MiRS Rainfall Rate from NOAA-20 ATMS on September 26, 2024, at approximately 3:00 AM ET, reveals widespread rainfall across the Southeast U.S. as Hurricane Helene moves toward Florida's coast. Source: JSTAR Mapper.

Complementing MiRS datasets are precipitation estimates from NASA's Integrated Multi-satellitE Retrievals for GPM (IMERG) product. IMERG largely relies on microwave and infrared data from NASA's Global Precipitation Measurement (GPM) mission, which incorporates measurements from multiple LEO and geostationary satellite sensors, including ATMS and the Cross-track Infrared Sounder (CrIS) onboard JPSS satellites. The IMERG algorithm produces observed estimates of global precipitation at 0.1° spatial resolution (about 10 km at the equator) every half-hour. Below, the IMERG V07 Final Run half-hourly research-level product captured rainfall intensity in the days leading up to Hurricane Helene's arrival in Western North Carolina, between September 25 and 27, 2024.

With precipitation products derived from LEO satellite sensors, forecasters, emergency managers, and others can better assess the potential for floods, landslides, and debris flows, particularly in regions with complex terrain or limited ground observations. Such observations provide important insights for early warning, improving geomorphic hazard management and response efforts.

Inside the Storm: The Power of ATMS

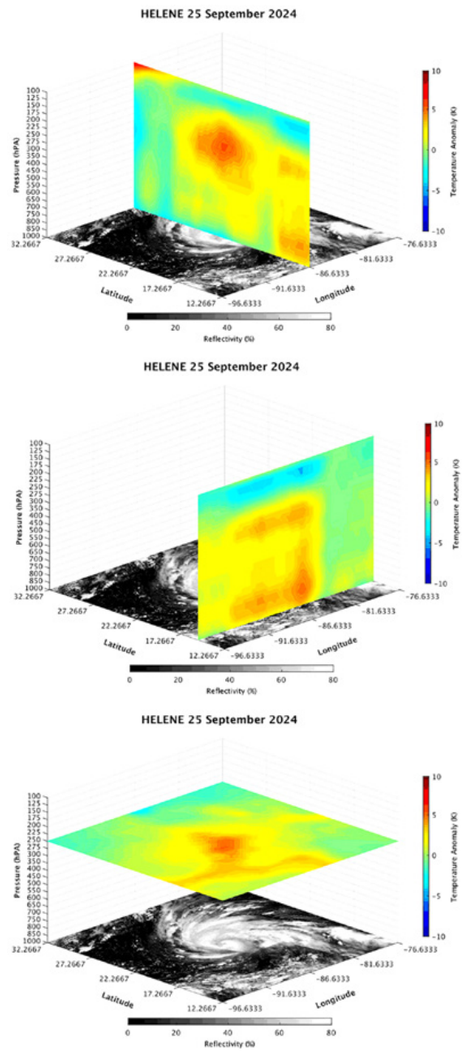
ATMS onboard JPSS satellites observes Earth in the microwave region of the electromagnetic spectrum. Microwaves have longer wavelengths than visible, infrared, and ultraviolet radiation, making them less susceptible to the atmospheric scattering that affects shorter optical wavelengths. This allows microwaves to pass through the water droplets and ice crystals that make up clouds with minimal interference, enabling ATMS to collect atmospheric data in nearly all weather conditions. These data feed into numerical weather prediction (NWP) models, helping to improve forecasts by ensuring the current state of the atmosphere is accurately represented in the models.



***Click image to enlarge.** Time series imagery from the IMERG Final Run half-hourly product shows rainfall rates (in millimeters per hour, mm/hr) as Hurricane Helene advances inland. Intense rainfall exceeding 48 mm/hr (nearly 2 inches per hour) in Western North Carolina began late on September 25, well ahead of the storm's arrival. When Helene reached the region on September 27, rainfall rates exceeded 800 mm/hr (equivalent to about 31 inches per hour) throughout Asheville and surrounding areas. Source: NASA GIOVANNI.*

ATMS's ability to "see" inside and beneath clouds is especially valuable for analyzing storms, including hurricanes. The instrument provides detailed vertical information on atmospheric temperature and moisture, allowing scientists to create three-dimensional profiles that reveal the vertical structure of the hurricane, including temperature anomalies in the eyewall and rainbands.

In the example on the right, ATMS-derived cross-sections capture Hurricane Helene's warm core on September 25, 2024, at different levels of the atmosphere. This region of warmer temperatures near the center of the storm, depicted in red and orange shading, signals a strong, organized system. The presence of a warm core is a key indicator of hurricane intensity and serves as an important metric for meteorologists tracking the storm's development and potential for rapid intensification. Surrounding this central region, cold temperature anomalies appear in the spiral rainbands along the storm's edges, shown as turquoise blue. For context, a pressure level of 100 hPa corresponds to an altitude of approximately 52,000 feet, while 1000 hPa represents sea level.



Click images to enlarge.

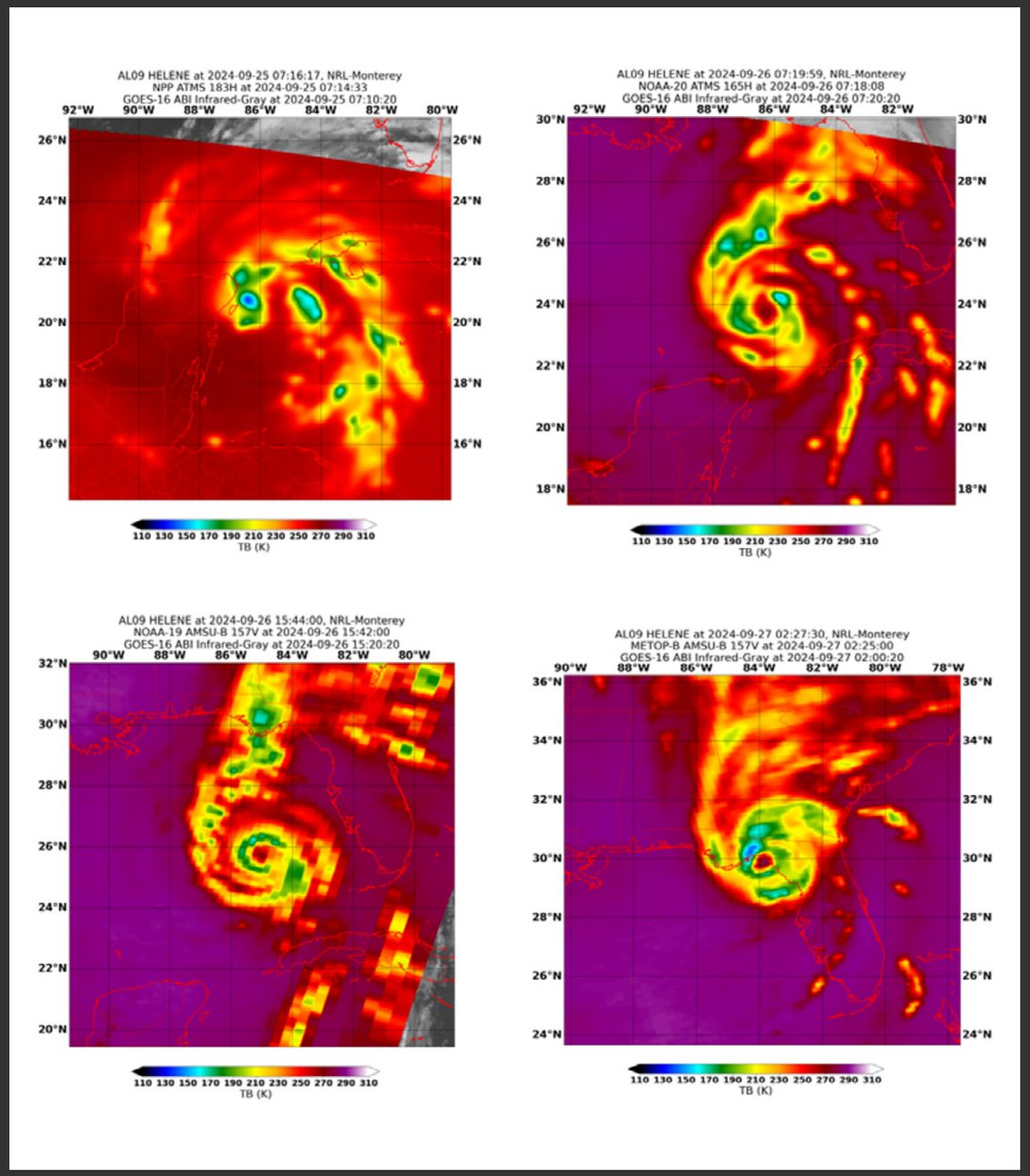
CrIS: ATMS's Infrared Counterpart

The Cross-track Infrared Sounder (CrIS) is a hyperspectral instrument onboard all JPSS missions that measures infrared radiation in 2,211 spectral channels. Like ATMS, CrIS provides detailed vertical profiles of atmospheric temperature and moisture that show how these variables change with altitude. This high-resolution, three-dimensional data is vital for improving weather forecast accuracy, particularly for short-term "nowcasting" and longer-term forecasting.

As an infrared sensor, CrIS performs best in clear to partly cloudy conditions because infrared radiation cannot penetrate thick clouds, unlike the microwave signals used by ATMS that pass through most cloud cover. Even so, CrIS offers a far richer view of the atmosphere thanks to its thousands of channels compared to ATMS's 22. For these reasons, CrIS and ATMS are often used together, combining their contrasting strengths to provide complementary data that greatly enhances the accuracy of numerical weather prediction models.

Multiple LEO Orbits Means Frequent Updates

With more than 15 microwave and infrared sensors onboard LEO satellites operated by NOAA and its partners—NASA, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and the Japan Aerospace Exploration Agency (JAXA)—frequent updates are possible. This collaborative effort helps fill gaps in global weather coverage, keeping forecasters informed of current and emerging conditions, such as Hurricane Helene's structure and intensity in the imagery below from ATMS and AMSU.



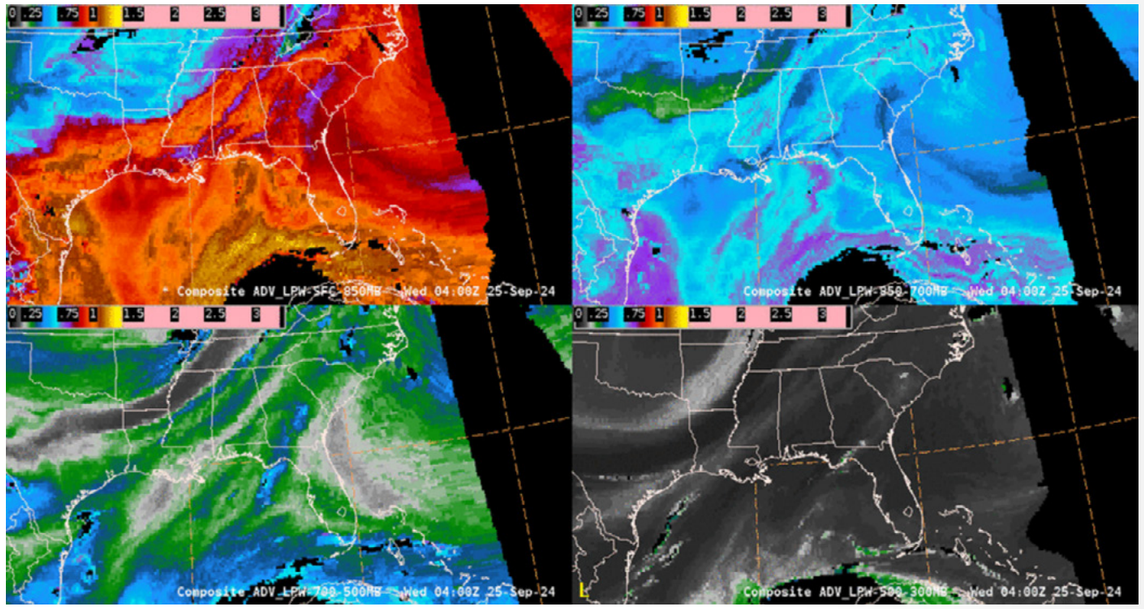
ATMS, currently onboard the Suomi NPP, NOAA-20, and NOAA-21 satellites with two additional JPSS missions planned, collects data in 22 channels with a 2,600-kilometer swath, enabling full global coverage twice daily. Slight differences in each satellite's orbit improve temporal resolution, ensuring a continuous flow of timely data that supports precipitation products and enhances weather forecasting. Beyond storm analysis and numerical weather prediction, ATMS data also benefits flight planning, maritime navigation, agricultural operations, and many other applications.

Estimating the Atmosphere's Precipitation Potential

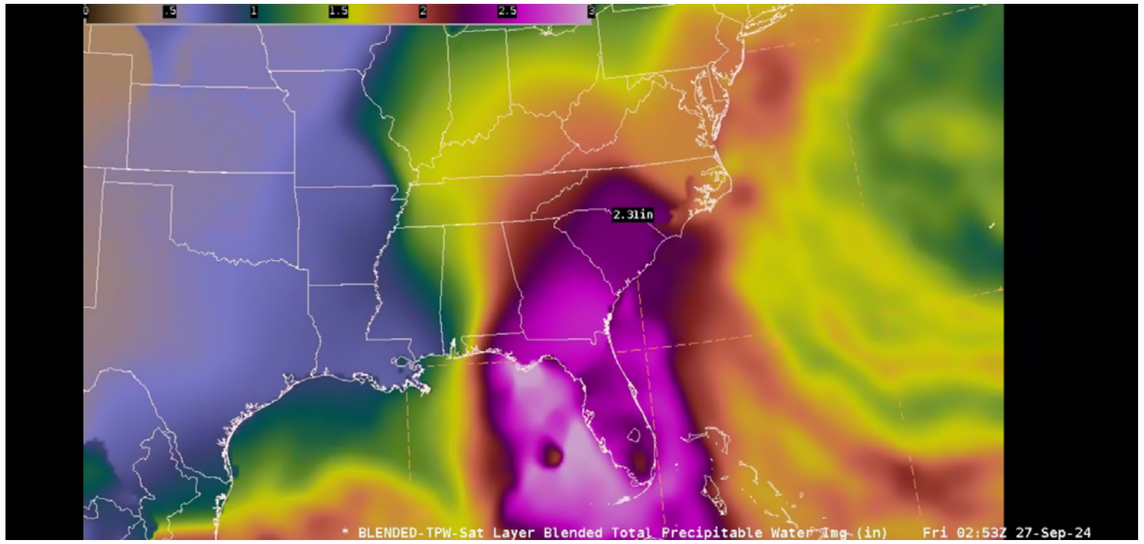
Precipitable water is a measure of the total amount of water vapor in a vertical column of the atmosphere, expressed as the depth of liquid water that would result if all the vapor condensed. It is a key indicator of atmospheric moisture content and helps forecasters assess the potential for heavy rainfall. Higher values suggest a greater risk of flash flooding, as they reflect increased moisture available for precipitation. For example, a precipitable water value of one inch means that the atmospheric water vapor above that location could produce one inch of liquid precipitation if it all condensed.

On September 24, 2024, the NWS Weather Prediction Center Excessive Rainfall Discussion highlighted the developing rainfall across the Southeastern U.S., driven by tropical moisture moving northward ahead of Hurricane Helene. The operational CIRA Advected Layer Precipitable Water (ALPW) product captured the moisture transport, showing precipitable water values in four atmospheric layers exceeding two inches across much of the region (below).

The ALPW product provides a four-dimensional view of water vapor using atmospheric temperature and moisture data derived from seven polar-orbiting LEO microwave sensors, including ATMS. Observations are aligned to a common analysis time by advecting



Click image to enlarge. *The CIRA ALPW product displays precipitable water, expressed in inches, across four atmospheric layers on September 25, 2024, at 04:00Z. The panels represent the following layers: surface to 850 millibars (mb) (top left), 850–700 mb (top right), 700–500 mb (bottom left), and 500–300 mb (bottom right). Credit: CIRA/CSU, NOAA/NESDIS.*



The bTPW product for 10:53 PM EDT on September 26, 2024 (02:53Z, 27-Sep-24) shows precipitable water values between 2 and 2.5 inches across the Carolinas, with higher values observed over eastern Georgia and Florida. Credit: CIRA/CSU; NESDIS/NOAA.

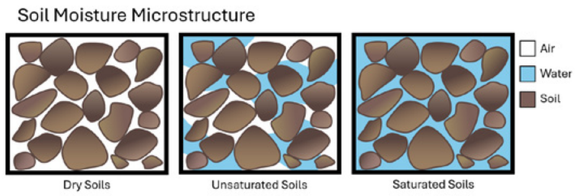
(adjusting) the satellite data swaths using wind forecasts from the Global Forecast System (GFS), then averaging them. The process generates precipitable water profiles for four atmospheric layers: surface to 850 millibars (mb), 850 to 700 mb, 700 to 500 mb, and 500 to 300 mb. This layered view allows forecasters to monitor the vertical distribution and movement of precipitable water.

Another operational tool, CIRA's Blended Total Precipitable Water (bTPW) product, also showed precipitable water values exceeding two inches extending from Florida up to North Carolina late on September 26, mere minutes before Helene made U.S. landfall (above). The bTPW product blends meteorological data from several LEO instruments, such as ATMS and AMSU, along with surface-based and geostationary data sources over land. The result is an hourly continuous global map of atmospheric water vapor.

These LEO satellite-derived precipitable water products provide beneficial data for numerical weather prediction models, strengthening forecast reliability. They can also reveal early signs of atmospheric moisture buildup that may not yet be fully captured by model output, enabling earlier detection of potential extreme rainfall events, improved decision-making, and more timely public safety measures.

Beneath the Surface: Sensing Saturation

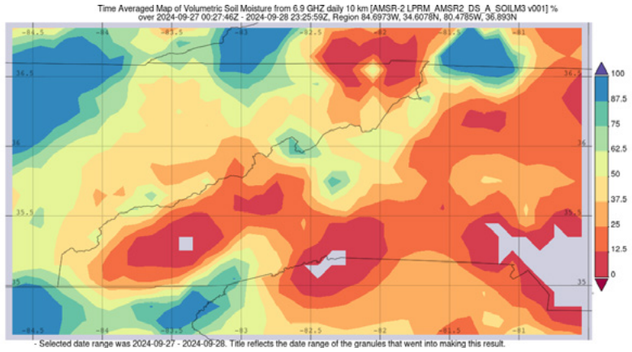
In the days leading up to Hurricane Helene's arrival in Western North Carolina, steady rainfall soaked the region. By the time the storm reached Southern Appalachia, the ground was already saturated, leaving little capacity to absorb additional rainfall. The saturated soil also left trees more vulnerable to uprooting, contributing to widespread treefall as Helene's strong sustained winds with gusts up to 105 miles per hour swept through the mountains.

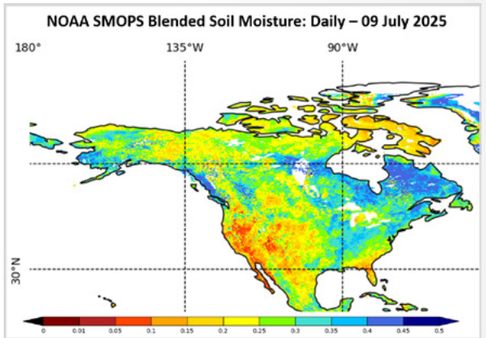


Click image to enlarge.

Soil moisture is an early indicator of flooding and landslide risk. Many satellite-based soil moisture products depend on data from LEO satellite sensors such as microwave sounders, scatterometers, and imagers. One example is NOAA's Soil Moisture Operational Products System (SMOPS), which generates global soil moisture maps in 6-hourly and daily intervals. The system combines observations from several LEO microwave sensors, including GMI, the Advanced Microwave Scanning Radiometer 2 (AMSR2) on the JAXA/NASA collaborative GCOM-W1 mission, the Advanced Scatterometer (ASCAT) on MetOp satellites, and NASA's Soil Moisture Active Passive (SMAP) mission. SMOPS estimates the percentage of the soil's volume occupied by water for the top 1-5 centimeters (cm) of soil, expressed as percent volume over volume (%volume/volume). Operational since 2012, SMOPS provides data for weather models and hazard monitoring. (See Feature 7 for an in-depth exploration of the SMOPS product.)

In addition to contributing to SMOPS, data from AMSR2, ASCAT, GMI, and SMAP are also used to generate stand-alone products. For example, AMSR2 provides measurements of soil moisture, global precipitation, atmospheric water vapor, brightness temperature, snow depth, and more. These observations are valuable for identifying conditions that often precede geomorphic hazards like landslides, debris flows, and flash floods. With regional-scale spatial resolutions—25 km for SMOPS and down to 10 km for AMSR2—these products support situational awareness by allowing emergency managers, forecasters, and others to monitor conditions and respond more effectively to emerging regional threats. Example soil moisture imagery from SMOPS and AMSR2 is shown below.





Click images to enlarge.

Left: Composite map of AMSR2-derived volumetric soil moisture at 10-km resolution, covering the period from 8:27 PM EDT (local time) on Thursday, September 26, (prior to Helene reaching North Carolina) to 7:25 PM EDT on Saturday, September 28, 2024. Surface soil moisture in the mountainous regions surrounding Asheville ranged from 50% to more than 75%, saturated ground conditions caused by several days of persistent rainfall. Source: NASA GIOVANNI.

Right: Example imagery from the global NOAA SMOPS Blended Soil Moisture Daily product on July 9, 2025, showing soil moisture values (%volume/volume) for the top 1-5 centimeters of soil, reflecting the percentage of the soil's volume occupied by water. Source: NOAA Office of Satellite and Product Operations (OSPO).

Locating Landslide-Affected Areas From Space

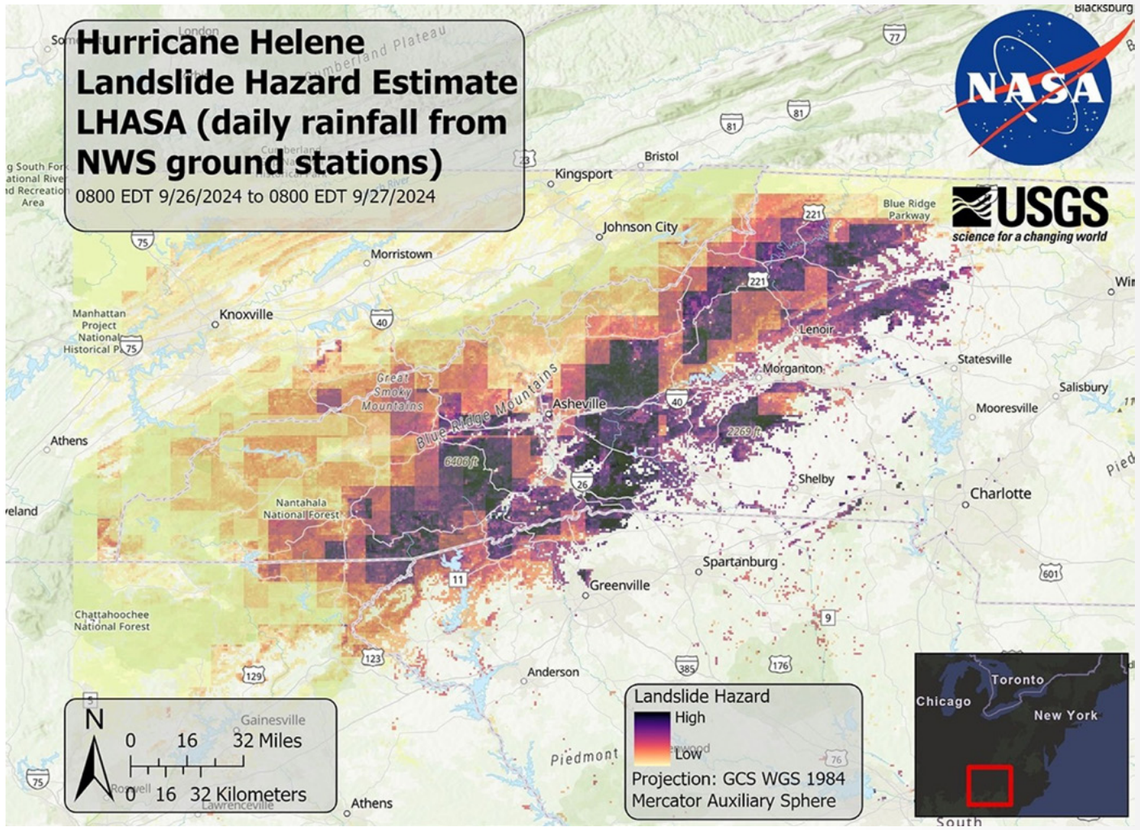
Hurricane Helene caused more than 2,200 landslides, with most concentrated in the mountains of Western North Carolina. In and around Asheville, homes, vehicles, and even semis were swept downriver. The landslides also toppled tens of thousands of trees, which forced the closure of the entire 469-mile Blue Ridge Parkway, and caused widespread debris and communication outages by damaging critical infrastructure.

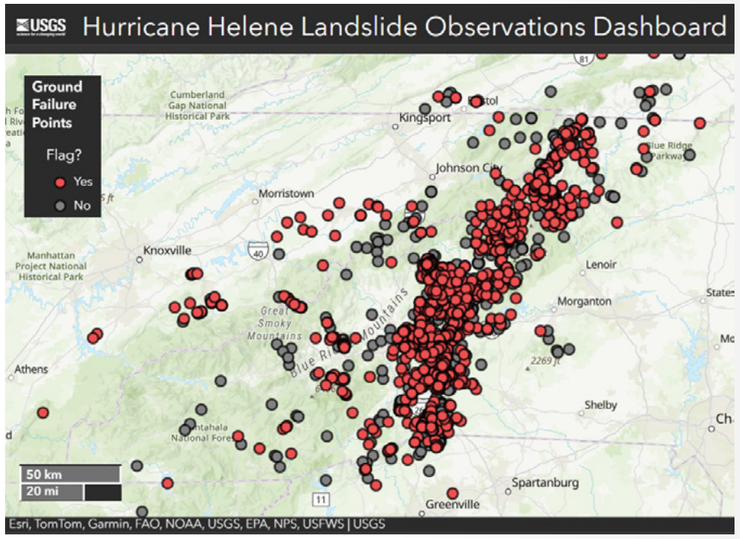
In the aftermath of Hurricane Helene, the U.S. Geological Survey (USGS) issued several landslide hazard maps to aid in emergency response. The maps highlighted areas at risk for landslides and debris flows, helping guide reconnaissance and response planning. A key tool was NASA's Global Landslide Hazard Assessment for Situational Awareness (LHASA) product, which was adapted specifically for this event. LHASA applies machine learning to estimate where and when landslides are most likely to occur, based on precipitation data and landslide susceptibility factors, producing 1-km resolution gridded output.

LHASA typically relies on current and past rainfall estimates from the satellite-based IMERG precipitation product (discussed above) and forecasted rainfall from the Goddard Earth Observing System—Forward Processing (GEOS-FP) global weather prediction model. Both data sources integrate observations from LEO satellite sensors, including radiances from ATMS and CrIS. However, given the urgency of Helene's response, IMERG estimates were replaced with NWS ground-based precipitation measurements to expedite delivery. Because LHASA is calibrated for satellite-derived inputs, substituting ground observations may have introduced

Debris flow damage in Fairview, North Carolina, which caused 13 fatalities. Credit: S. Slaughter/USGS.

some variation in the model's output. Even so, the adapted LHASA product provided emergency responders with rapid insight into areas most likely affected by landslides and debris flows. The Helene-specific LHASA map is shown below, alongside reported landslide and debris flow locations for the same region.



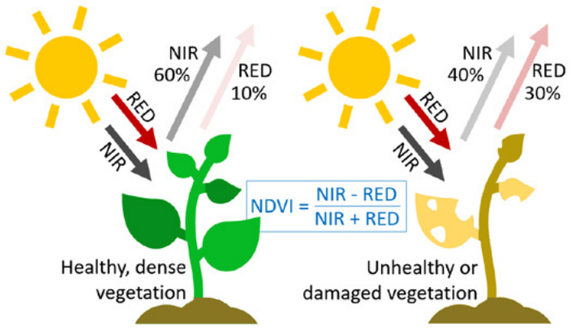


Above: NASA's Global Landslide Hazard Assessment Model (LHASA) version 2.1 shows estimated landslide hazard levels in the southern Appalachian Mountains during Hurricane Helene. This map incorporates 24-hour rainfall totals from 8:00 AM EDT on September 26 to 8:00 AM EDT on September 27, 2024, provided by the NWS Greenville-Spartanburg Forecast Office. Colors represent the relative probability of landslide occurrence, ranging from 0 (low, yellow) to 1 (high, dark purple) for the same period. LHASA provides a global estimation of landslide hazard and is not a substitute for local site investigations. Source: USGS/ScienceBase.gov.

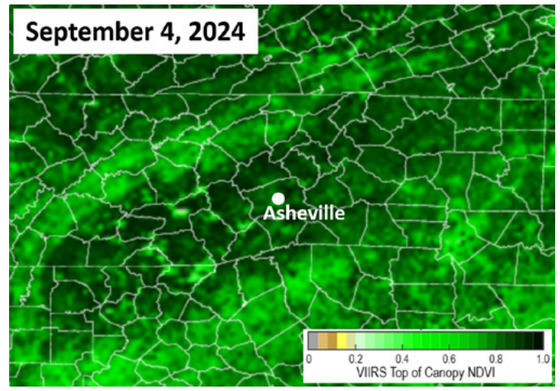
Right: Landslides and debris flows reported for Hurricane Helene in the Southern Appalachians, as documented in the USGS Landslide Observations Dashboard.

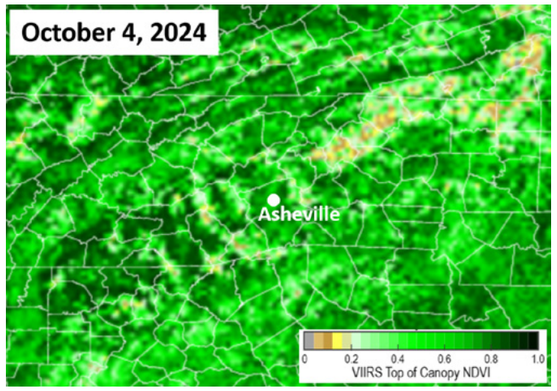
Another method for identifying areas that may have been affected by landslides is through satellite-based vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). The NOAA/NESDIS Center for Satellite Applications and Research (STAR) produces operational NDVI products using data from LEO satellite sensors, including the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard JPSS satellites. VIIRS captures data in 22 spectral bands, spanning visible, near-infrared, shortwave infrared, and thermal infrared wavelengths. This multispectral capability enables the analysis of high-contrast data like NDVI, an estimation of vegetation health.

NDVI is calculated by taking the difference between near-infrared (NIR) and red visible light reflected from Earth's surface and dividing it by their sum. Healthy vegetation absorbs most of the red light for photosynthesis and reflects a large portion of NIR light. In contrast, sparse or stressed vegetation reflects more red light and less NIR light. NDVI values range from -1 to +1, with values closer to 1 indicating denser, healthier vegetation.



When a landslide occurs, it often strips away trees and plants, leaving exposed soil or rock behind. This sudden loss of vegetation can result in noticeably lower NDVI values. Comparing NDVI values from before and after an extreme weather event helps scientists identify areas where vegetation has suddenly disappeared, signaling potential landslide activity. Analyzing NDVI over time is also helpful for monitoring vegetation recovery after slope failure and provides valuable insight into the long-term ecological impacts.





Click image to enlarge. *NOAA-20 VIIRS NDVI imagery highlights changes in vegetation across Western North Carolina between September 4, 2024 (before Hurricane Helene), and October 4, 2024 (shortly after the storm). Brown areas reflect reduced or absent vegetation, likely due to landslide activity. Source: JSTAR Mapper.*

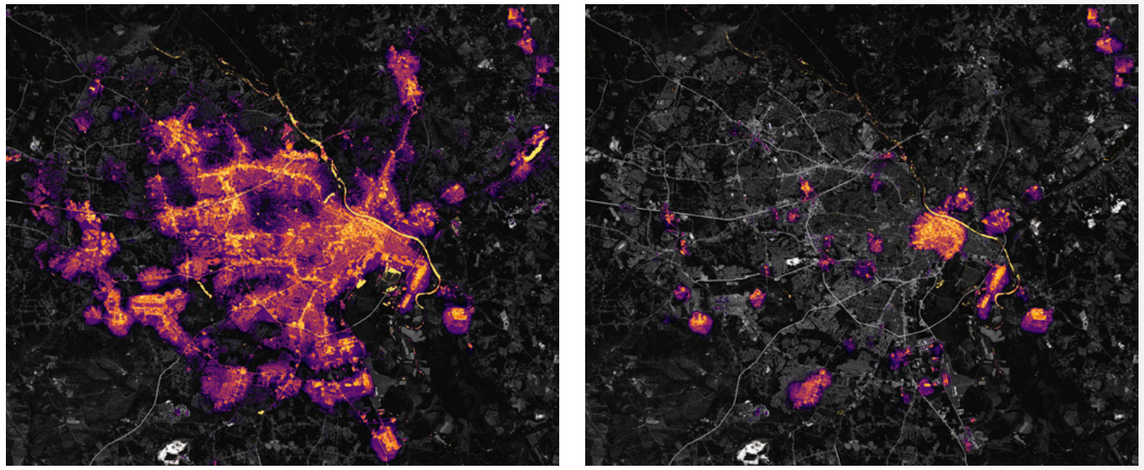
No Lights, Big Insights: Observing Outages With JPSS

The widespread destruction across the Southeastern U.S. left roughly 16.2 million people without power, with many, like Dissen, experiencing extended outages. "We were out of power for almost seven days," she says, crediting her survival to her parents' preparedness, including battery backups, a

generator, and a range of emergency supplies. In her 15 years living in Asheville, she had never encountered anything like it. “This is the first time in my life I’ve had to deal with this,” she remarks. “The level of destruction and power of this flood and rainstorm was so immense—imagine a shipping container being washed away and wrapping itself around a transmission power line like a blanket—that is the image that [stays with] me.”

When hurricanes, tropical storms, blizzards, or high winds cause widespread power outages, JPSS satellite data can provide essential insights. Its VIIRS instrument is equipped with a unique Day/Night Band (DNB) that detects extremely faint sources of light at night, including city lights, gas flares from oil and gas production, and lights from fishing vessels at sea. This nighttime imaging capability extends well beyond power outage detection and can be used to monitor urbanization patterns, energy use, wildfires, and illegal fishing activity.

One of the most valuable applications of the VIIRS DNB is its ability to detect power outages to support emergency response. Comparing nighttime imagery from before and after a severe weather event provides a way to quickly identify areas without electricity, helping emergency managers gauge the extent of outages across large regions served by multiple power providers. These observations assist decision-makers in directing resources to the hardest hit areas and in monitoring power restoration, offering a powerful means of estimating community impacts following major storms.



NASA’s Black Marble product, which provides daily nighttime light data derived from the VIIRS Day/Night Band (DNB), shows electrification across Augusta, Georgia before (left, August 31, 2024) and after (right, September 28, 2024) Hurricane Helene. Source: NASA Earth Observatory.

Perspective

Hurricane Helene left a trail of destruction across the Southeastern U.S., with an estimated $78.7 billion in damages, at least 250 lives lost, and millions affected. Communities across Florida, Georgia, North Carolina, South Carolina, Tennessee, and Virginia faced prolonged power outages, weeks or months without clean water, and impassable roads that restricted access to food, medicine, and emergency services. A deadly mix of hurricane-force winds, tornadoes, flooding, landslides, and debris flows crippled infrastructure, isolated towns, and overwhelmed public health systems, leaving lasting impacts on safety, well-being, and daily life throughout the region.

Amid this widespread devastation, LEO observations proved vital for local forecasting and emergency response. In the Asheville region, these data, combined with other NOAA resources, helped generate accurate forecasts that informed life-saving decisions. “These data enabled the [National Weather Service] Greenville-Spartan Office [Warning Coordination Meteorologist] Trisha Palmer to grasp the severity of model outputs and relentlessly communicate with emergency managers multiple times a day to convey the catastrophic weather event,” Dissen explains. She adds, “LEO data, with human intelligence and engagement, not only saves lives. I have directly witnessed and am part of the community that leverages this data for rebuilding—bringing together the small and large businesses to provide supplies in times of crisis.”

Experiences like this highlight the importance of preparedness in reducing the toll of extreme weather events. Recognizing early warning signs and improving forecasting accuracy help communities take timely action and reduce risk. A coordinated approach that integrates surface, airborne, radar, and satellite observations allows for a more comprehensive understanding of developing hazards. LEO satellite data products strengthen this effort by providing valuable insights into storm structure, rainfall intensity, soil moisture, landslide risk, and other environmental conditions before, during, after a storm. With two more JPSS missions slated to launch in 2027 and 2032, and the next-generation Near Earth Orbit Network (NEON) in development, NOAA’s LEO satellites will continue to advance global Earth observation capabilities, improve weather forecasting accuracy, and strengthen disaster preparedness and response for years to come. ✦

Learn More

Hear Jenny Dissen recount her experience in Asheville, North Carolina during Hurricane Helene on the Weather Geeks podcast episode, *Rebuilding Resilience: Lessons from Hurricane Helene*.

Discover how NOAA’s low Earth orbit (LEO) and geostationary (GEO) satellites work together to monitor hurricanes in this web story from NESDIS.

Explore an in-depth analysis of Hurricane Helene in the NOAA National Hurricane Center’s Tropical Cyclone Report.

Story Source

The information in this article is based, in part, on the May 12, 2025, LEO Science Seminar, "Boots on the Ground in Asheville, North Carolina During Hurricane Helene," presented by: Jenny Dissen, Engagement and Partnerships Lead, North Carolina Institute for Climate Studies (NCICS), North Carolina State University.

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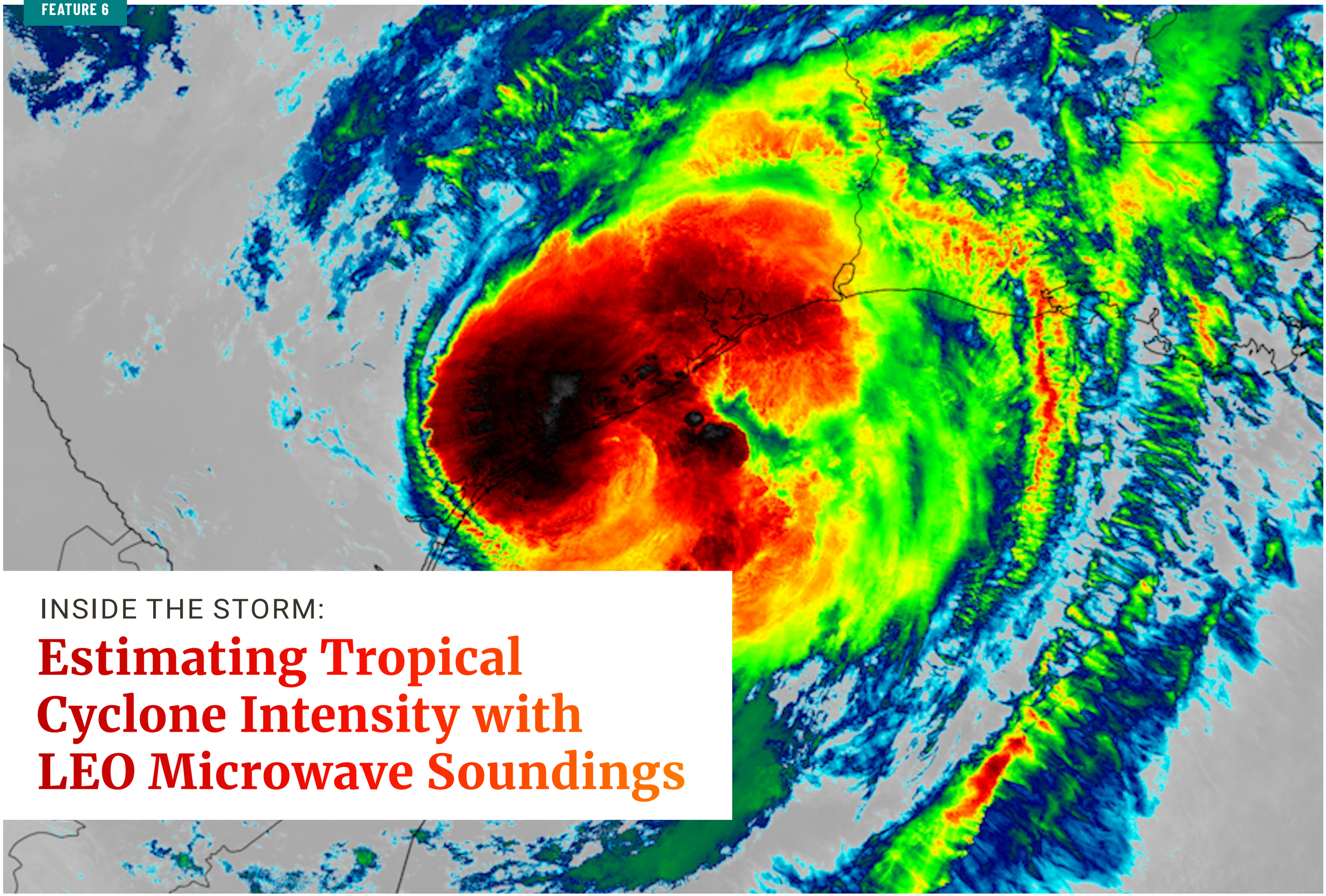
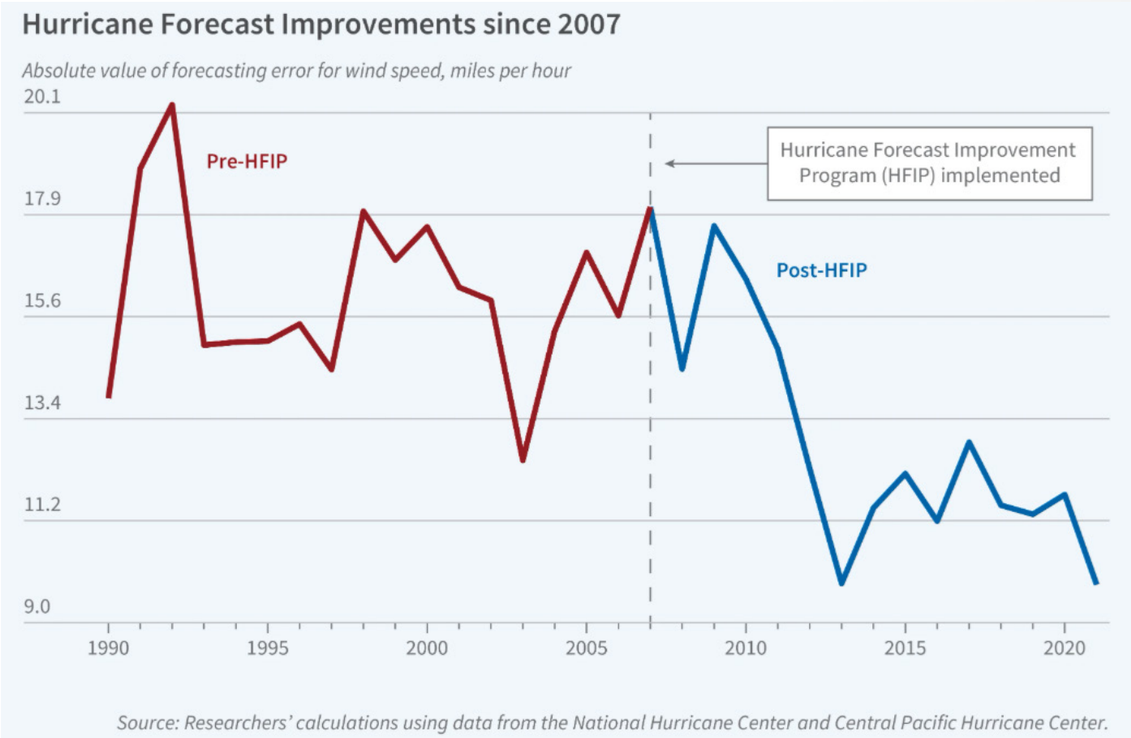


INSIDE THE STORM:

Estimating Tropical Cyclone Intensity with LEO Microwave Soundings

Composite infrared imagery compiled from the Visible Infrared Imaging Radiometer Suite (VIIRS) Band I-5 on the Suomi NPP, NOAA-20, and NOAA-21 satellites captures Hurricane Beryl making landfall in Texas on July 8, 2024, after rapid intensification. The colors represent temperatures at the top of the clouds, with blue indicating cool temperatures, red indicating warmer temperatures, and black indicating the warmest temperatures, highlighting the storm's warm core. Source: CIRA Satellite Library. Image: CIRA/CSU; NOAA/NESDIS.



National Hurricane Center (NHC) hurricane forecast intensity errors, 1990-2022. Wind intensity forecasts have shown about a 50% improvement since the NOAA Hurricane Forecast Improvement Program (HFIP) started. Image credit: National Bureau of Economic Research (NBER) Working Paper 32548, DOI 10.3386/w32548.

Accurate tropical cyclone forecasts are essential for protecting lives, property, and the U.S. economy from devastating storms. Advances in technology and research have led to more advance notice for hurricane warnings in the U.S., giving people more time to secure property, plan evacuations, and gather essential supplies. These improved capabilities save lives and reduce the financial toll of powerful storms, which can destroy businesses, disrupt supply chains, raise insurance costs, and negatively impact tourism and agriculture. This progress has translated into measurable benefits: Since 2007, improved forecasts have reduced total costs associated with major hurricanes by 19%, saving an average of $2 billion per U.S. landfalling storm, according to the National Bureau of Economic Research. These savings highlight the economic value derived from advances in observations, modeling, and data assimilation that have reduced forecast errors. Accurate forecasts also lessen the economic burden of over-warning, limiting costly and unnecessary evacuations.

Official forecasts from the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC) include information on tropical cyclone track, intensity, and wind structure, which are key factors in determining storm hazards, identifying areas likely to be affected, and issuing timely advisories and warnings. Forecasts from both agencies incorporate data such as wind speed and extent, and their accuracy depends on reliable estimates of these variables.

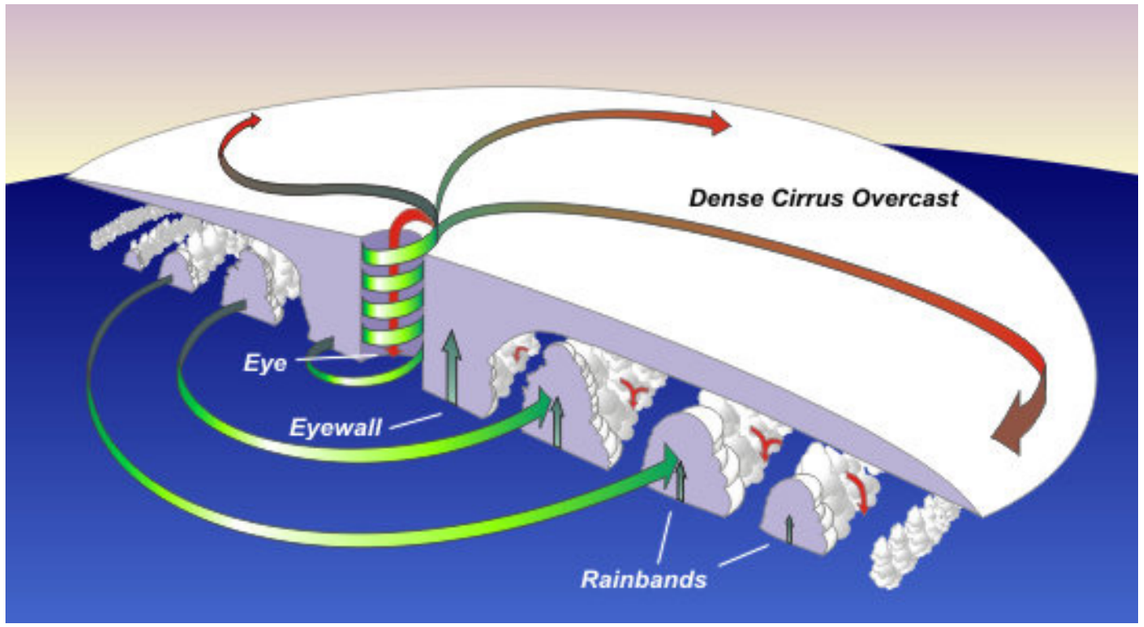
Intensity is primarily defined by the maximum sustained wind speed measured 10 meters above the surface and minimum sea level pressure. Even small changes in the atmosphere or ocean can cause rapid and unpredictable shifts in intensity, making forecasting a challenge. The wind structure of a tropical cyclone describes the pattern and distribution of its winds. Wind radii are key to assessing storm size, defined as the farthest distance from a storm's center where sustained winds exceed specific thresholds, typically 34 knots (tropical storm force), 50 knots (storm force), and 64 knots (hurricane force).

Most tropical cyclones form in remote ocean regions where aircraft, radar, buoys, and ships cannot provide adequate observations. Because of this, satellites are essential for tropical cyclone analyses. "Satellite data are assimilated into numerical forecast models, but we can also use it independently to provide tropical cyclone diagnostic parameters independent of the models, like intensity, wind radii, and storm structure," explains Galina Chirokova, PhD.

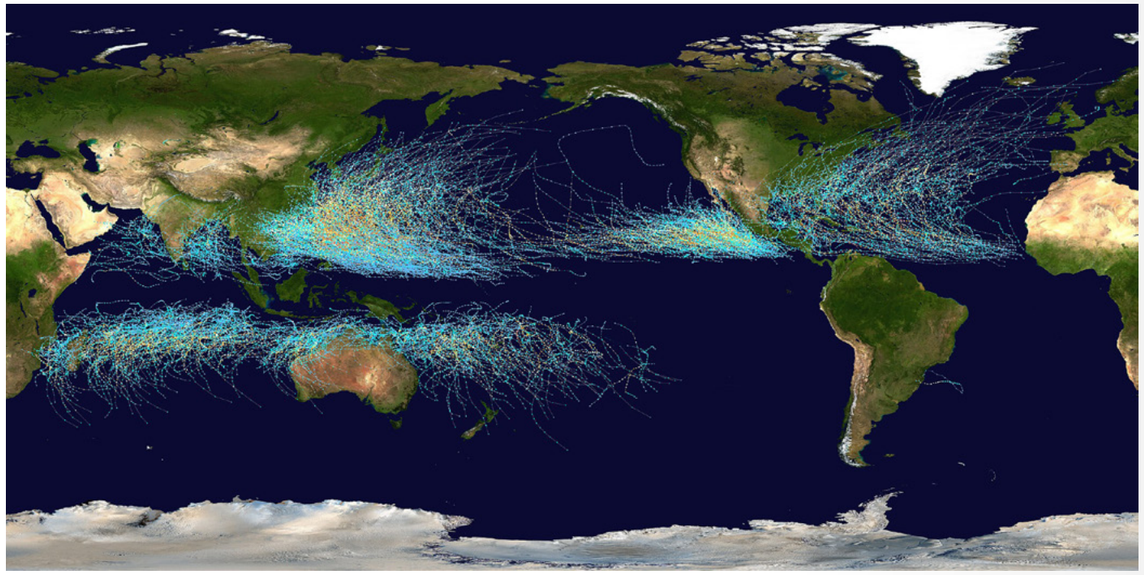
Tropical Cyclones 101

Tropical cyclones are powerful, rapidly rotating storm systems that form over warm tropical or subtropical waters. They are characterized by a warm core, low-pressure center, strong winds, and a spiral of thunderstorms that produce heavy rainfall. Tropical cyclones range in size and intensity, and depending on wind speeds, are classified into different categories:

- **Tropical Depression:** *Maximum sustained winds of 38 miles per hour (mph) or less.*
- **Tropical Storm:** *Maximum sustained winds between 39 and 73 mph.*
- **Hurricane/Typhoon/Cyclone:** *Maximum sustained winds of 74 mph or higher.*



Cross section of a typical hurricane. Source: NOAA.



Click image to enlarge. *Global tropical cyclone tracks from 1985 to 2005. Source: Wikipedia Commons (public domain).*

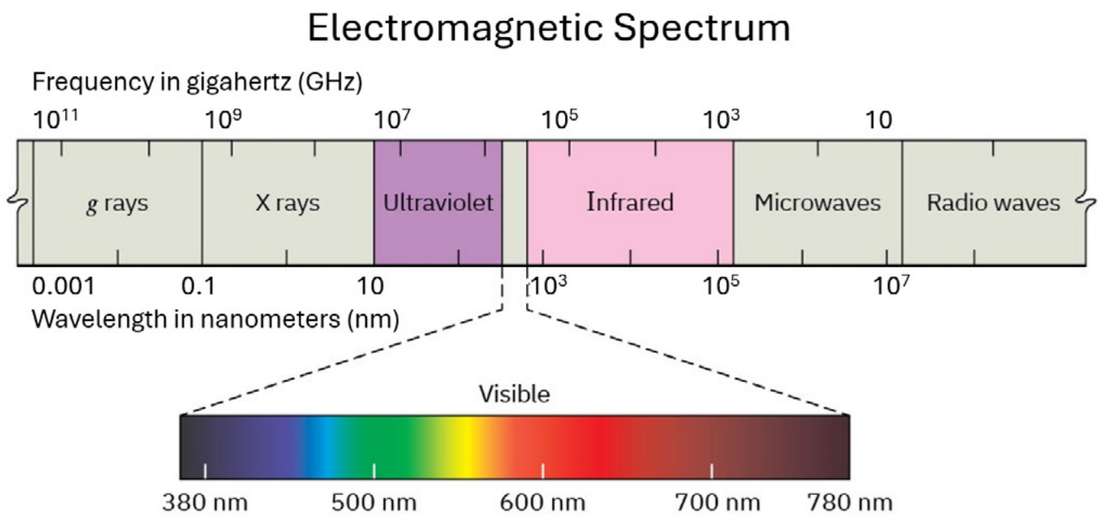
Chirokova is among several researchers at the Cooperative Institute for Research in the Atmosphere (CIRA) based at Colorado State University (CSU) who are developing tropical cyclone applications with data from microwave sounders onboard low Earth orbit (LEO) satellites. At the June 2025 LEO Science Seminar, she and her colleagues, Mark DeMaria, PhD, and Zhixing Ruan, PhD, presented an overview of CIRA's Hurricane Intensity and Structure Algorithm (HISA) and their team's efforts to expand and refine tropical cyclone monitoring and analysis.

From Measurements to Meaning

Unlike in-situ instruments, Earth observing satellites do not measure environmental conditions directly. Instead, their instruments measure spectral radiance, which quantifies the intensity of radiation emitted or reflected from a terrestrial or atmospheric source, per unit area, per unit solid angle, and per unit wavelength or frequency. For example, measuring the spectral radiance of microwave energy coming from a tropical cyclone provides scientists with quantifiable data on the storm's temperature and moisture content.

Satellite instruments measure spectral radiance within defined wavelength (or frequency) ranges, called spectral bands or channels, that correspond to specific regions of the electromagnetic spectrum. The way light and other forms of electromagnetic energy interact with an object reveals valuable information about its properties and characteristics. When these interactions are measured across multiple wavelengths, they create a detailed pattern called a spectral signature that is unique to the observed target.

Scientists use sophisticated algorithms to transform these radiance measurements into usable geophysical variables such as atmospheric temperature and moisture, wind speed, sea surface temperature, and more. These variables feed into models and decision tools that support a wide range of functions, from numerical weather prediction and tropical cyclone forecasting to ship navigation and many other applications. In



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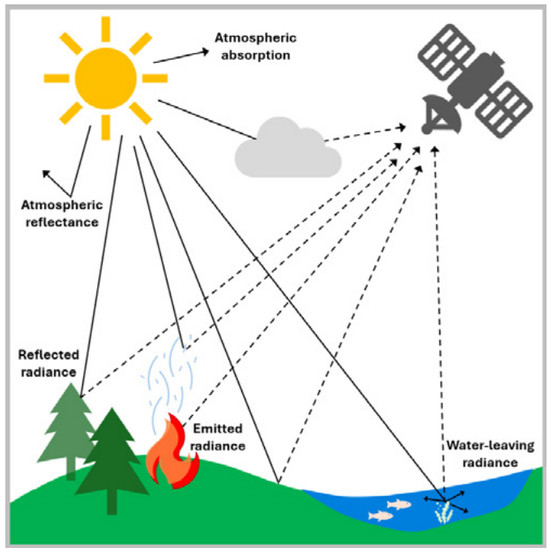
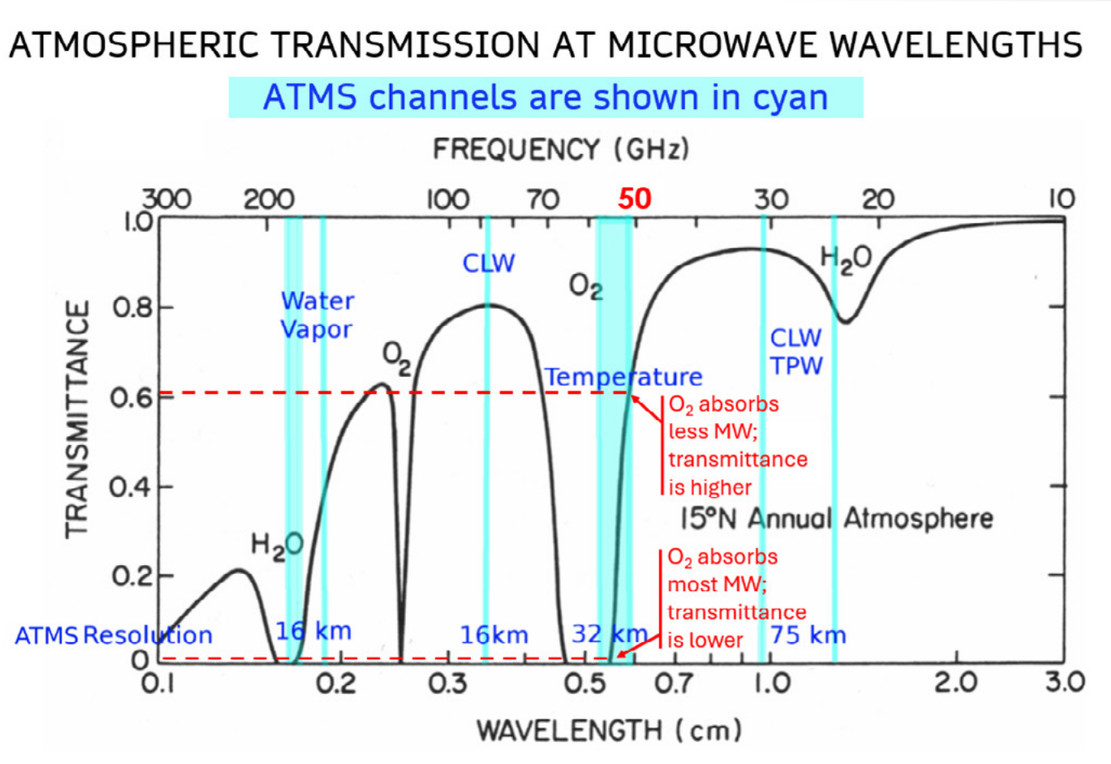
essence, spectral radiance measurements are the ingredients, and mathematical equations are the recipes that turn them into meaningful environmental information.

"For tropical cyclone applications, we need to convert radiances to [atmospheric] temperature and specific humidity profiles," says DeMaria. LEO microwave sounders are an important source of this data. "Typically, these instruments operate on the edge of an absorption band—temperature usually uses an oxygen absorption band," he explains. For example, the Advanced Technology Microwave Sounder (ATMS) on Joint Polar Satellite System (JPSS) satellites use channels near 50 gigahertz (GHz), along the edge of an oxygen absorption band, to profile atmospheric temperature. "The idea is that on the edge of the band you're seeing deeper and deeper into the atmosphere as the wavelength of the spectral radiance changes," DeMaria continues.

To understand why, it helps to look at how atmospheric gases absorb microwave radiation. Certain gases, such as oxygen (O_2), absorb microwaves at specific frequencies, creating absorption lines or bands within the electromagnetic spectrum. At the center of an absorption band, absorption is strongest, greatly limiting the amount of microwave radiation that can be transmitted. For example, atmospheric oxygen molecules absorb microwaves in the 50–70 GHz range, with absorption strongest at the center around



Click image to enlarge*. Simplified diagram illustrating the principle of measuring radiance using passive microwave sensors.*



Microwave radiance measured by ATMS is used to infer important variables for weather applications such as atmospheric temperature, water vapor, cloud liquid water (CLW), and total precipitable water (TPW). ATMS channels near 50 GHz sample along the edge of an oxygen (O_2) absorption band, where microwave transmittance (black line) is relatively high compared to the center frequency of the O_2 absorption band (around 60 GHz), where O2 strongly absorbs microwaves. Image courtesy of Galina Chirokova, adapted from Kidder, S. Q., & Vonder Haar, T. H. (1995).

60 GHz. At this frequency, absorption is so strong that most microwave signals originating from the lower atmosphere, where oxygen is concentrated, are absorbed before reaching the satellite. As a result, ATMS channels near 60 GHz primarily detect microwave energy from higher in the atmosphere, where less oxygen allows it to travel farther before being absorbed.

In contrast, absorption weakens along the edges of an absorption band, away from the center peak. Microwave frequencies at these edges undergo relatively less absorption by gases, allowing greater transmittance of signals. This enables microwave sounders to probe deeper into the atmosphere. For example, ATMS channels near 50 GHz, at the edge of an oxygen absorption band, can measure the intensity of microwave radiation from lower parts of the atmosphere.

Although their operating frequencies differ, all LEO microwave sounders exploit the way atmospheric gases absorb microwaves. Scientists use these instruments to measure the intensity of microwave radiation emitted by the atmosphere across multiple frequencies to infer the vertical distribution of atmospheric temperature and moisture—essential data for tropical cyclone forecasting. Converting microwave radiance observations into a variable of interest, however, is difficult and requires advanced techniques to resolve the challenges involved.

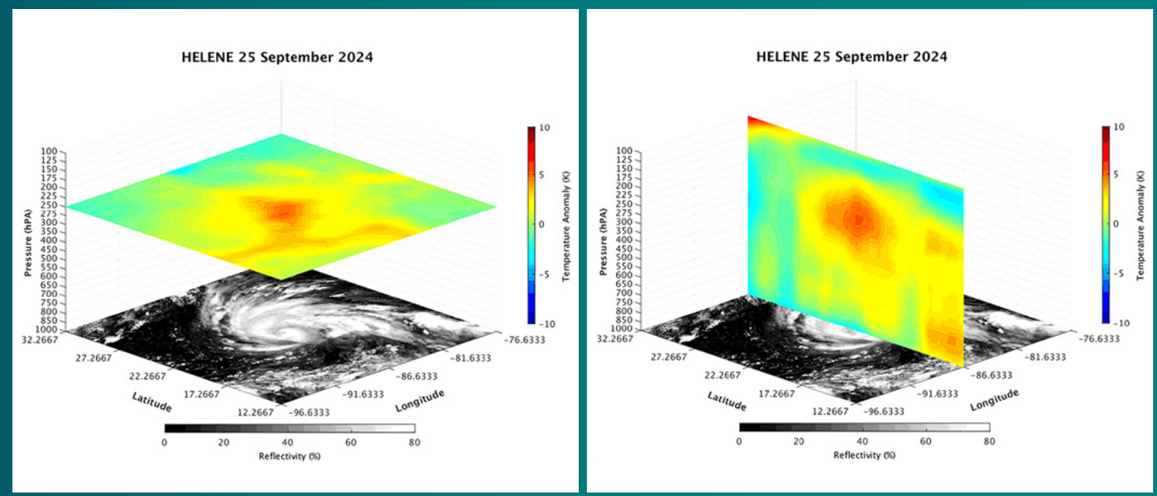
Retrieving Atmospheric Profiles

An atmospheric profile, or sounding, is a vertical measurement of the physical properties of a column of air, such as temperature and humidity. Obtaining atmospheric soundings from microwave radiance is complicated by many factors, including complex atmospheric interactions and various sources of uncertainty that need to be addressed. In atmospheric science, this process is called a retrieval. Many techniques have been developed to perform temperature and moisture retrievals, including sophisticated algorithms using statistical, machine-learning, and physically-based approaches.

Microwaves: Passing On Through

Temperature data from LEO microwave sounders provide information about tropical cyclones that is not readily available from other sources. Microwaves have longer wavelengths than visible or infrared light, enabling them to pass through clouds with minimal scattering. As a result, microwave sounders can penetrate the dense cloud cover of tropical cyclones, revealing inner core features not observable with visible and infrared sensors, such as warmer temperatures that correlate with storm intensity.

The ATMS instrument operates in 22 channels ranging in frequency from 23.8 GHz to 183.3 GHz, each designed to sense microwave radiation from different layers of the atmosphere. These measurements are used to derive vertical profiles of atmospheric temperature and moisture, providing critical insight into atmospheric dynamics. The radiance measurements themselves are also assimilated into numerical weather prediction models, where they serve as essential input for improving forecasts.



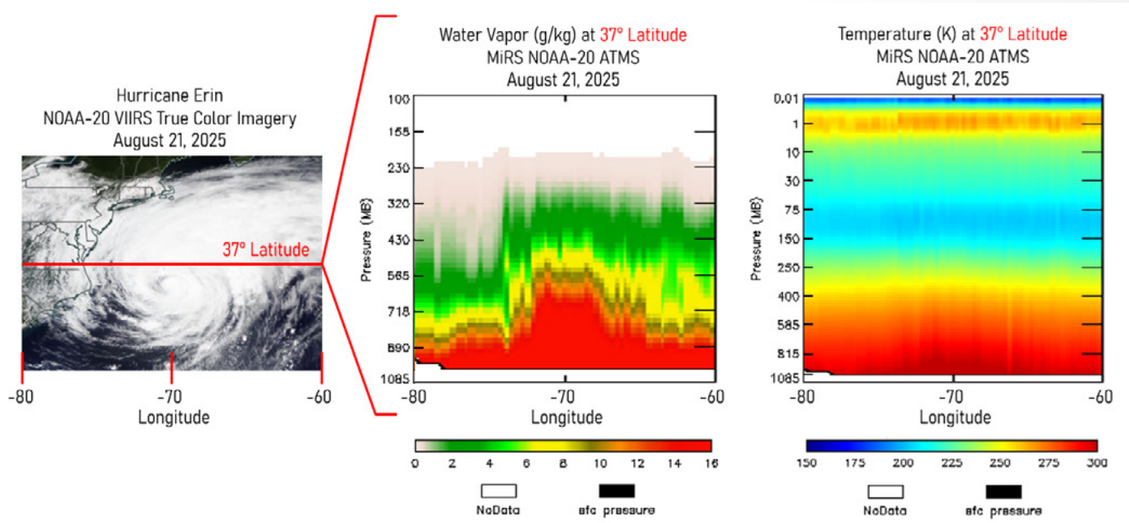
***Click images to enlarge**. ATMS-derived cross-sections capture temperature anomalies associated with Hurricane Helene on September 25, 2024, notably its warm core. This region of warmer temperatures near the storm's center is shown in red and orange and signals a strong, organized system. The presence of a warm core is a key indicator of hurricane intensity and serves as an important metric for meteorologists tracking the storm's development. Surrounding this central region, cold temperature anomalies appear in the spiral rainbands, depicted in turquoise blue along the edges of the storm. Credit: NOAA NESDIS Center for Satellite Applications and Research (STAR).*

Physically-based retrieval algorithms apply the fundamental laws of physics to mathematically model how microwave radiation is emitted from and interacts with Earth's surface and atmosphere. One example is NOAA's operational Microwave Integrated Retrieval System (MiRS) that simultaneously solves for surface and atmospheric variables using microwave radiance from several LEO microwave instruments onboard polar-orbiting satellites, including JPSS's ATMS, and the Advanced Microwave Sounding Unit-A (AMSU-A) and Microwave Humidity Sounder (MHS) on EUMETSAT's MetOp series (collectively referred to as AMSU), among others. MiRS applies a one-dimensional variational retrieval (1D-Var) technique that compares the satellite observations with a computer model of the atmosphere, adjusting the model until it aligns with the observations.

At CIRA, ATMS-MiRS and AMSU-MiRS retrievals are used as input for various tropical cyclone applications. These data, along with other satellite observations, are processed using eTCeTerra (Easy Tropical Cyclone Exploration Through Enabling Rapid Research of the Atmosphere), a CIRA-developed application that aligns each satellite overpass with the center of the tropical cyclone and regrids the data to a storm-centric cylindrical grid. This "TC-centered" scheme, which collocates satellite observations with the storm's moving center, provides the basis for all analyses in the CIRA Hurricane Intensity and Structure Algorithm (HISA).

Hurricane and Intensity Structure Algorithm (HISA)

Originally developed in 2001[1], HISA quantifies intensity and wind structure for all global tropical cyclones, as well as for tropical weather systems being closely monitored for potential development into stronger storms known as "invests," short for "investigative areas." The first operational version, based on AMSU data from NOAA-15, -16, -18, and -19 satellites (predecessors to JPSS that are now decommissioned), was implemented at the National Centers for Environmental Prediction (NCEP) in 2005. Since then, HISA has been updated several times, with the latest version now operational at the National Environmental Satellite, Data, and Information Service (NESDIS). This version incorporates data from ATMS onboard JPSS satellites (Suomi NPP, NOAA-20, and NOAA-21), as well as AMSU on MetOp-B and MetOp-C satellites.



Click image to enlarge. *The left panel shows true color imagery from the NOAA-20 Visible Infrared Imaging Radiometer Suite (VIIRS), capturing Hurricane Erin as a Category 2 storm on August 21, 2025. The red line at 37° latitude marks the location of NOAA-20 ATMS-MiRS vertical profiles of water vapor (middle) and temperature (right) on the same day. Both profiles show enhanced water vapor and elevated temperatures near 70° longitude, corresponding to the vicinity of the storm center. Source: NOAA/NESDIS STAR (MiRS profiles); NASA Worldview (VIIRS imagery).*

The algorithm package provides estimates of maximum sustained surface wind speed (V_{max}), minimum sea level pressure, and the radial extent of 34-, 50-, and 64-knot winds in four quadrants (northeast, southeast, southwest, and northwest) relative to the tropical cyclone's center. Additionally, HISA generates two-dimensional (2D) wind fields at standard pressure levels, gradient winds, and vertical temperature cross-sections.

These metrics are critical for evaluating the potential impacts of tropical cyclones, which can affect the U.S. even when storms remain at sea. For example, in August 2025, Hurricane Erin caused coastal flooding and life-threatening rip currents along the U.S. East Coast, despite never making landfall. Although Erin stayed about 200 miles offshore, its powerful tropical-storm-force winds extended up to 370 miles from its center, reaching the coast and prompting widespread beach closures, emergency advisories, and evacuation orders. Events like this highlight the value of HISA's intensity and wind radii data in helping forecasters to anticipate hazardous conditions far from a tropical cyclone's center, enabling earlier warnings and more effective decisions to protect public safety.

Click image to enlarge. *NOAA Emergency Response Imagery shows coastal flooding in Buxton, North Carolina on August 22, 2025, caused by storm surge from Hurricane Erin, several hundred miles offshore. Credit: NOAA Remote Sensing Division.*

Inside the Algorithm

HISA estimates are derived from TC-centered ATMS and AMSU soundings retrieved using MiRS, combined with the hydrostatic relationship and statistical methods. The process involves a series of steps to derive wind estimates, which are then used to determine intensity.

Geopotential Height & Pressure Gradients

Geopotential height is a variable used in meteorology with pressure as a vertical coordinate that accounts for variations in gravity with altitude and latitude. It approximates the height of a point in the atmosphere relative to mean sea level.

The gradient of geopotential height (the rate of change of geopotential height over a distance) on a constant pressure surface is proportional to the **pressure gradient** on the same surface. This relationship is fundamental in atmospheric dynamics and is derived from the temperature via the **hydrostatic equation**.

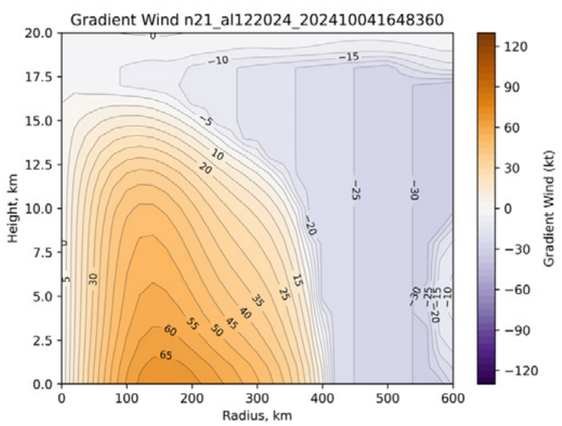
Pressure gradients describe how quickly atmospheric pressure changes over distance and are key to understanding wind speed and direction. Stronger pressure gradients indicate stronger winds, while weaker gradients suggest lighter winds. The direction of the pressure gradient (from high to low pressure) helps determine the direction of air movement.

Using MiRS retrievals as input, DeMaria explains, "we first apply the hydrostatic equation in the vertical to obtain geopotential height from the MiRS temperature profiles." The equation is integrated downward from 100 hectopascals (hPa)—roughly 33,000 to 50,000 feet above mean sea level (AMSL)—to the surface, which provides the geopotential height. "[Geopotential height] is kind of an analog of the pressure field, so we can determine the pressure gradients [from these data]," he adds.

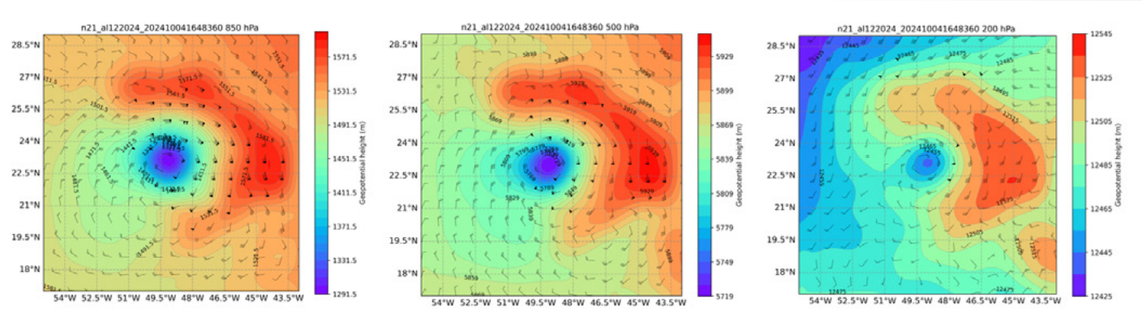
Next, balance equations are applied to the pressure gradients to determine the wind field, which describes how winds are spatially distributed. "We use the gradient wind equation to get symmetric tangential winds," DeMaria emphasizes, referring to the azimuthally averaged rotational winds of a circular vortex, such as a cyclone, at a given radius from its center. It is a key metric for understanding the structure and intensity of circular weather systems.

To determine 2D horizontal winds, the nonlinear balance equation is applied to pressure data. This yields wind speed and direction on a horizontal plane at standard pressure levels, allowing forecasters to analyze the storm's three-dimensional structure by examining how the wind field changes with both height and location.

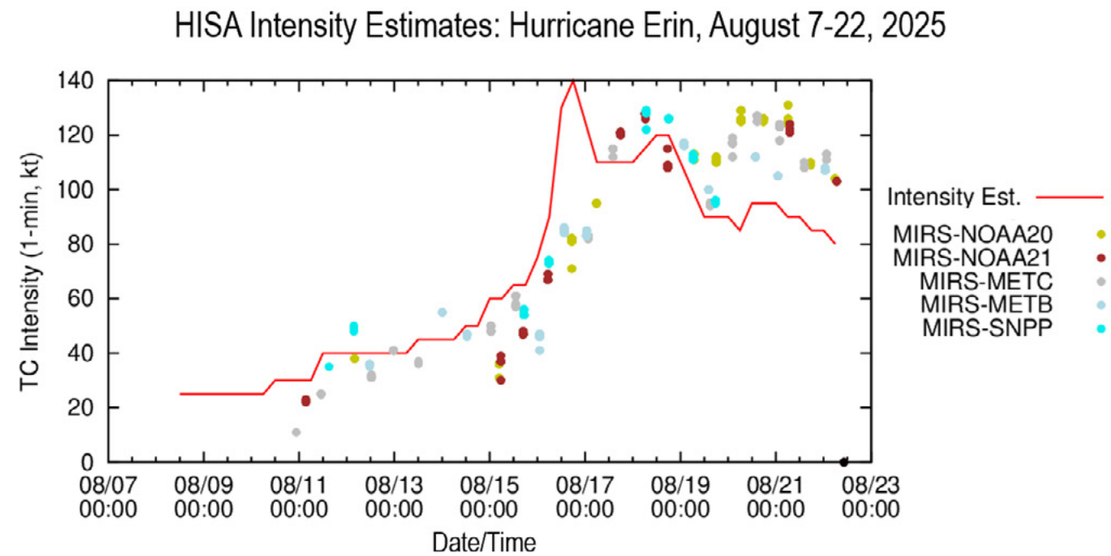
As a final step, intensity metrics, including maximum wind, minimum sea level pressure, and wind radii, are estimated statistically using the physical parameters from the wind and temperature fields as input. These estimates are available to forecasters at NHC and JTWC in Automated Tropical Cyclone Forecasting System (ATCF) "F-deck" format, a data file that contains storm position and intensity information estimated from observations. HISA estimates are also being reviewed for integration into the Advanced Weather Interactive Processing System (AWIPS), the primary system used by the National Weather Service (NWS) to display, analyze, and process meteorological data for producing weather forecasts and warnings.

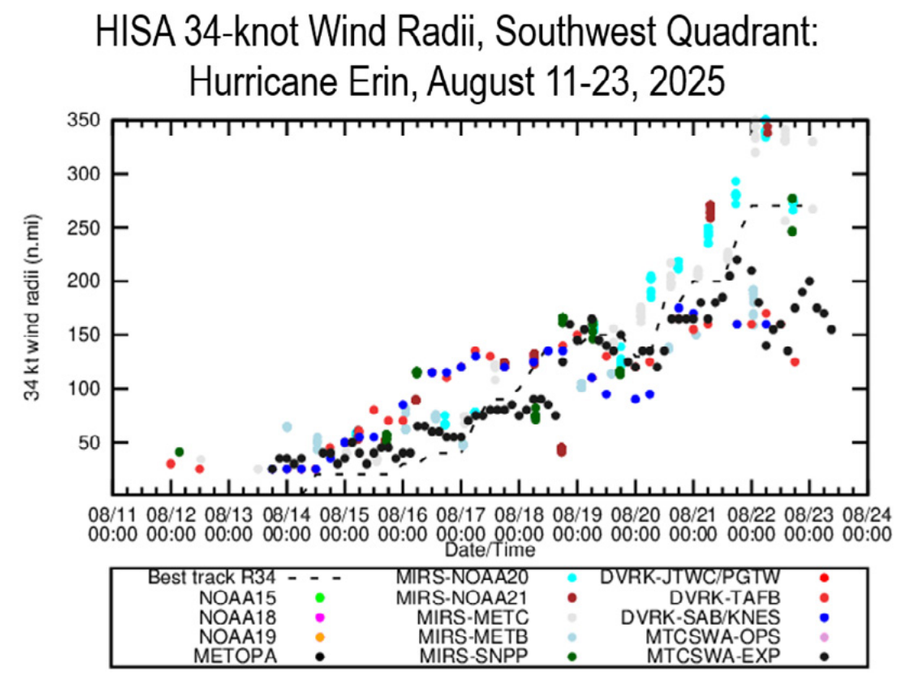


Click image to enlarge. *Left: HISA Gradient Wind from NOAA-21 ATMS data for Hurricane Kirk on October 4, 2024, at 1648 UTC. The plot shows how gradient wind speed (in knots) changes with atmospheric height in kilometers and distance from the storm's center (radius in kilometers).*



Click image to enlarge. *HISA 2D horizontal winds and geopotential height from NOAA-21 ATMS data at 850 hPa (left), 500 hPa (middle), and 200 hPa (right) highlight the structure of Hurricane Kirk on October 4, 2024, at 1648 UTC. The plots reveal a well-defined eye, strong cyclonic circulation, and the storm's vertical organization across different atmospheric levels. Hurricane Kirk, a powerful Category 4 storm during the active 2024 Atlantic hurricane season, remained over open water but generated large ocean swells that traveled far from the storm, leading to dangerous surf and rip currents along much of the U.S. East Coast. Courtesy of Galina Chirokova and Mark DeMaria (CIRA).*





Top: HISA intensity estimates for Hurricane Erin illustrate the storm's rapid intensification on August 16, 2025, when it reached Category 5 with maximum sustained winds near 139 knots (160 miles per hour). The red line shows the HISA intensity estimate, while individual estimates from MiRS retrievals from different instruments and satellites are indicated by colored dots: ATMS onboard Suomi NPP (cyan), NOAA-20 (mustard yellow), and NOAA-21 (burgundy), and AMSU onboard MetOp-B (light blue) and MetOp-C (gray).

Bottom: HISA 34-knot wind radii for the southwest quadrant of Hurricane Erin, shown in nautical miles, highlight the storm's growing wind extent over its lifetime. Radii determined by HISA from MiRS retrievals are marked with dots: ATMS onboard Suomi NPP (dark green), NOAA-20 (cyan), and NOAA-21 (burgundy), and AMSU onboard MetOp-B (light blue) and MetOp-C (gray). Credit: John Knaff, NESDIS.

The HISA Advantage: Enhancing the Forecaster's Toolkit

HISA generates global tropical cyclone intensity estimates independent of the widely used Dvorak technique. The operational Dvorak technique is inherently subjective, as it depends on human analysts interpreting cloud patterns in visible and infrared satellite imagery to assign intensity estimates, which can lead to inconsistencies between forecasters. Automated versions reduce this subjectivity using computer algorithms or artificial intelligence, but all versions of the Dvorak technique base intensity estimates on cloud top features.

The Dvorak Technique

The Dvorak technique uses visible and infrared imagery from geostationary satellites, providing frequent updates but limited insight into the storm's inner core when it is obscured by cloudiness. The technique applies an empirical statistical framework to correlate observed cloud patterns with established intensity guidelines.

Learn about the origins of the Dvorak technique in this NOAA Technical Report written by its creator, Vernon Dvorak: https://repository.library.noaa.gov/view/noaa/19322.

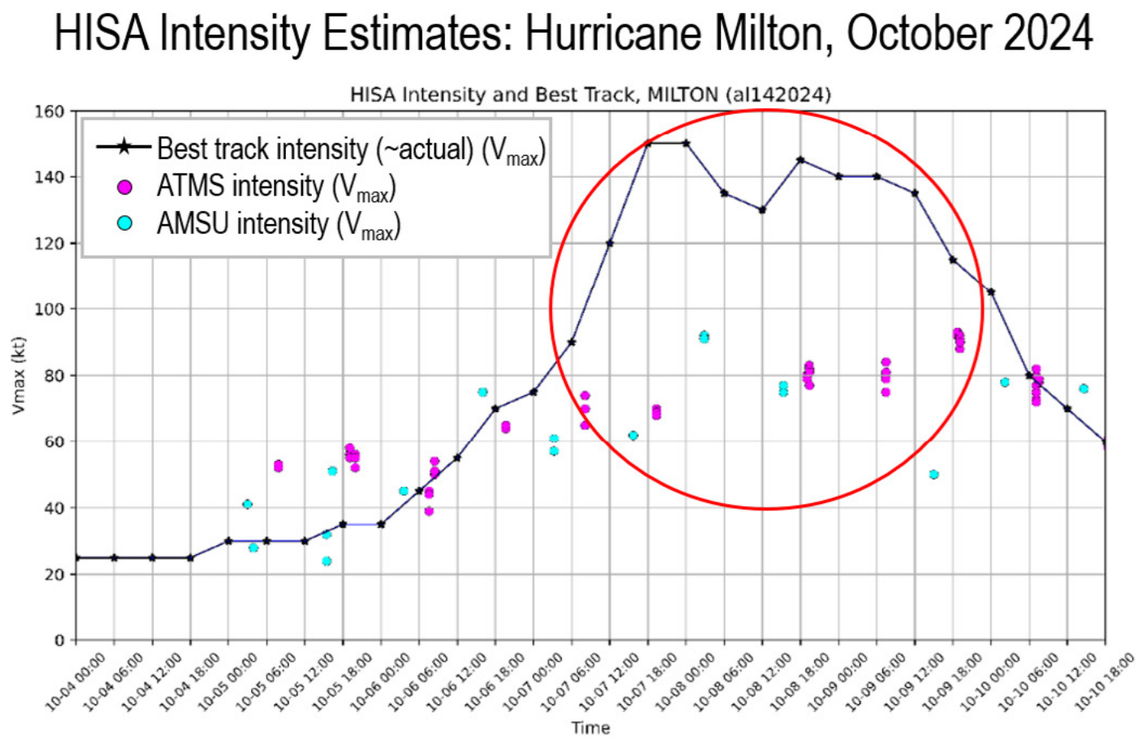
In contrast, HISA estimates intensity by directly measuring a storm's thermodynamic structure and deriving wind fields from those data, providing an objective approach that avoids the subjectivity inherent in manual Dvorak analysis. While this offers some advantages, HISA complements rather than replaces the Dvorak technique, with each method offering distinct strengths that together give operational forecasters a more complete picture of a tropical cyclone's destructive potential.

In addition to estimating storm intensity, the National Hurricane Center must also determine the radial extent of surface winds at 34, 50, and 64 knots every six hours. Wind radii observations are frequently obtained from reconnaissance missions, ship reports, buoy measurements, and satellite scatterometer data. However, each of these sources has limitations, with gaps in spatial and temporal coverage and inconsistencies among data products. As a supplementary tool, HISA provides additional data that strengthens the overall reliability of operational wind structure estimates.

All Things Have Limitations

Despite its many strengths, HISA has some known limitations. Chirokova points out that one challenge is accurately estimating the intensity of small tropical cyclones. "For [Hurricane] Milton, ATMS and AMSU both significantly underestimated the storm's intensity," she says (see figure on the following page). CIRA is investigating ways to improve HISA's performance for smaller storms, exploring whether refinements to the algorithm or additional data sources could enhance intensity estimates.

Another limitation stems from the temporal resolution of LEO microwave sounders. A single LEO satellite in sun-synchronous orbit (such as NOAA-21 or MetOp-C) provides only two passes per day over a specific location in the tropics, leaving gaps in tropical observations. Using data from multiple JPSS and MetOp satellites helps reduce these gaps, but opportunities for



improvement remain. Advances in LEO smallsat missions, including new commercial platforms, are making higher-frequency monitoring more feasible, as constellations of smallsats can be deployed at relatively low cost. Building on this potential, CIRA is testing the HISA algorithm with data from NASA's TROPICS constellation and Tomorrow.io smallsats to evaluate the reliability of miniaturized microwave sounders for estimating tropical cyclone intensity and structure. Smallsats represent a promising avenue for increasing the frequency of weather observations and closing gaps in global tropical cyclone monitoring.

Looking to the Future

CIRA continues to develop innovative ways to use LEO microwave sounder data to advance tropical cyclone analysis and forecasting. The team is creating an AI-based version of HISA, called LeoGuidance, to provide real-time tropical cyclone intensity estimates, supported by the NOAA/NESDIS Office of LEO Observations. They are also developing new applications, including JPSS Extratropical Transition Classification (JETClass), a machine learning algorithm that objectively diagnoses storm type and identifies extratropical transitions in real time using JPSS data.

Chirokova, DeMaria, and others at CIRA are also evaluating the use of MiRS moisture retrievals to estimate the horizontal moisture flux inside a tropical cyclone. The team are testing methods to measure vortex tilt directly from HISA 2D horizontal wind estimates, as well. Understanding vortex tilt is particularly valuable for intensity prediction: Weak storms with small tilts, where the circulation is more vertically aligned, are more likely to intensify rapidly than those with a large tilt.

NOAA's next-generation LEO satellite program, the Near Earth Orbit Network (NEON), is expected to further enhance tropical cyclone forecasting. The program's first new instrument, the Sounder for Microwave-Based Applications (SMBA), is a hyperspectral microwave sounder that will provide far more channels across the microwave spectrum than ATMS and AMSU combined. Capturing higher-resolution temperature and moisture profiles represents a major step forward, especially given that observations from LEO microwave sounders are a cornerstone of global forecast models. According to DeMaria, these advancements will strengthen CIRA's tropical cyclone products, providing significant improvements over current observing capabilities. Together, these innovations set the stage for a new era of tropical cyclone forecasting, where high-resolution data and AI inform timely decision-making. ✦

Learn More

Take a closer look at NOAA's operational Microwave Integrated Retrieval System (MiRS) in this journal article published in IEEE Transitions on Geoscience and Remote Sensing.

Learn about how HISA estimates are generated for operational use in the *HISA Products External Users' Manual*.

Explore the origins of HISA in the journal article *Improvement of Advanced Microwave Sounding Unit Tropical Cyclone Intensity and Size Estimation Algorithms*.

Story Source

The information in this article is based, in part, on the June 24, 2025, LEO Science Seminar titled, "Improving Tropical Cyclone Intensity Forecasts and Intensity and Structure Estimates Using Microwave Sounder Data," presented by: Dr. Galina Chirokova, Research Scientist/Scholar II, Cooperative Institute for Research in the Atmosphere (CIRA)/Colorado State University (CSU); Dr. Mark DeMaria, Senior Research Scientist, CIRA/CSU; and Dr. Zhixing Ruan, Tropical Cyclone Data Analysis Scientist, CIRA/CSU.

Footnotes

[1]Demuth et al. (2004); Demuth et al (2006); Bessho et al (2006).

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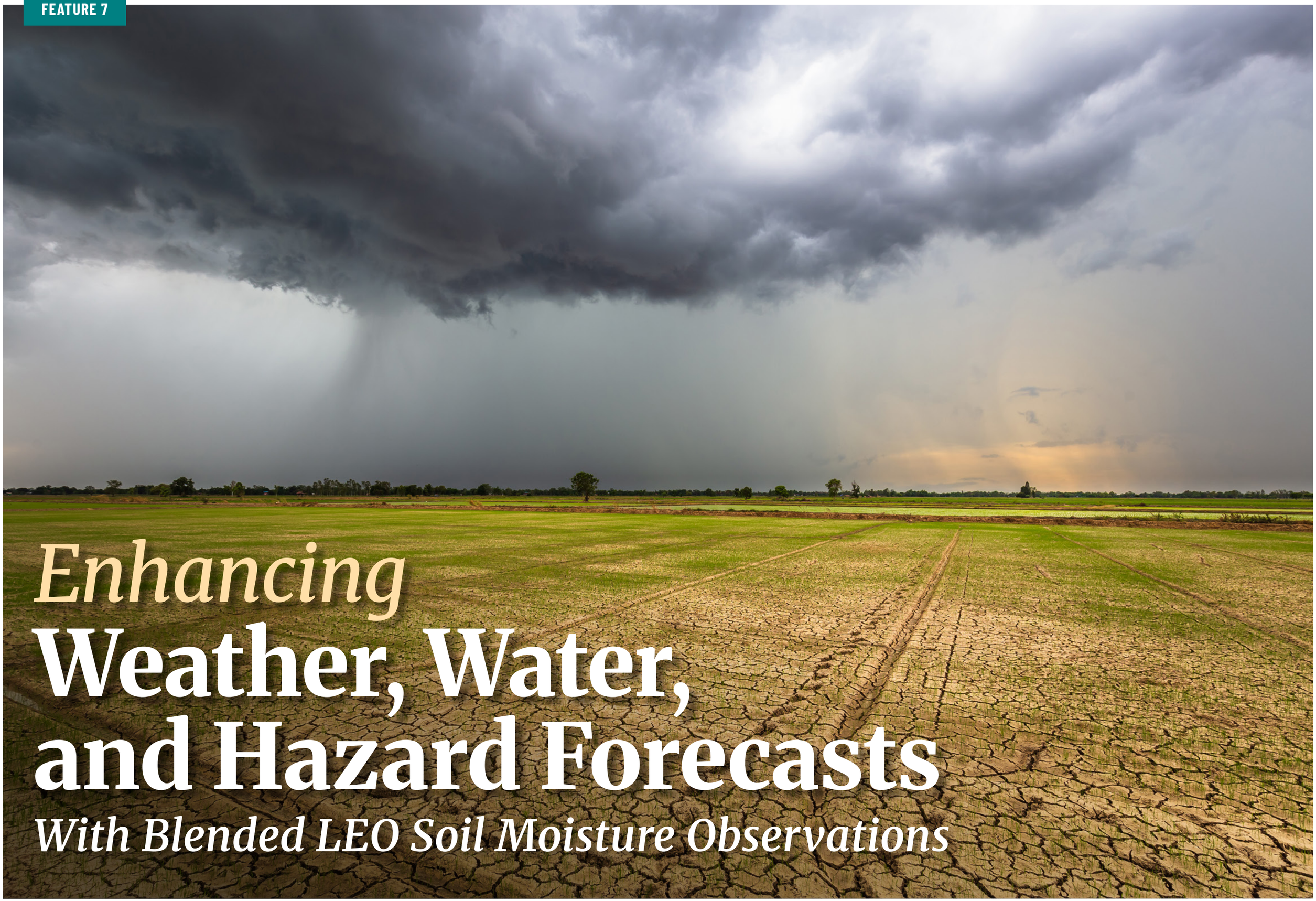
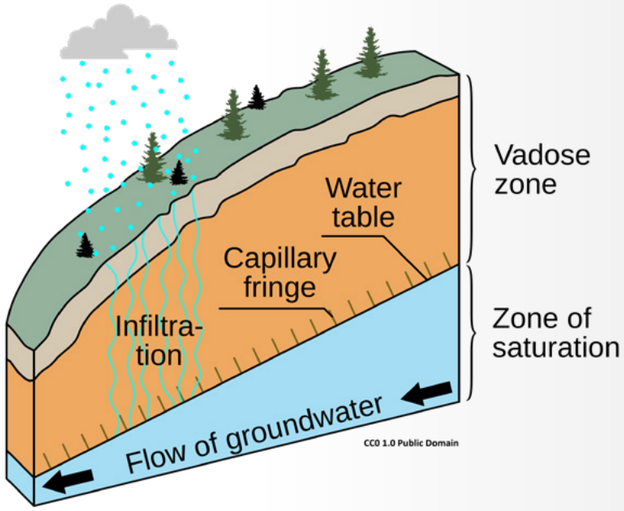


Enhancing Weather, Water, and Hazard Forecasts

With Blended LEO Soil Moisture Observations

Storm clouds generate rainfall over a field experiencing significant soil desiccation and cracking. iStock.com/patpitchaya.

Beneath our feet is a dynamic store of water that exerts a powerful influence on the atmosphere above: soil moisture. Contained within the pores of the vadose zone, between the ground surface and the water table, soil moisture is among the most important land surface properties affecting the lower atmosphere. It plays a central role in the weather we experience by regulating the exchange of heat and moisture where the land meets the air, significantly influencing weather patterns, atmospheric stability, and the hydrologic cycle.



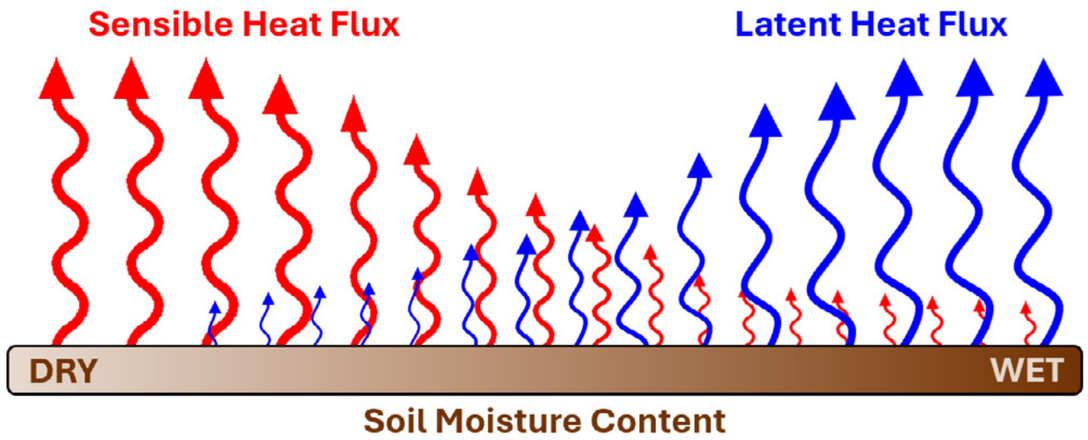
Sensible Heat vs. Latent Heat

Sensible heat is the thermal energy that causes a change in the temperature of a substance without causing a change in its physical state. Sensible heat can be "sensed" using a thermometer. Latent heat is a form of thermal energy that changes the physical state of a substance without altering its temperature. Latent heat is "hidden" and is used to break or form the bonds that hold molecules in their physical state. For example, heating liquid water from 20°C to 100°C is sensible heat, but the heat required to turn liquid water into steam is latent heat.

Soil moisture determines how incoming solar energy is partitioned between latent heat, which fuels evaporation and cools the air, and sensible heat, which heats the air. This energy balance directly influences local and regional weather by affecting temperature, humidity, and the potential for precipitation.

Wet soils provide more water for evapotranspiration (evaporation from soil and transpiration from vegetation), a process that requires substantial energy, known as the latent heat of vaporization. This energy is drawn from the surrounding air and land surface, producing a cooling effect that lowers temperatures. Evapotranspiration also adds moisture to the atmosphere, increasing local humidity and contributing to cloud formation and precipitation.

When soils are dry, the opposite occurs. With less moisture available for evapotranspiration, more of the incoming solar energy is partitioned as sensible heat, raising temperatures at the surface and in the air above. Dry soils can also limit cloud formation and rainfall, although under certain conditions they may intensify mesoscale convective systems (large-scale, organized thunderstorms). The relationship between soil moisture and precipitation is complex and variable, and highly dependent on soil characteristics, topography, vegetation, and local atmospheric conditions.

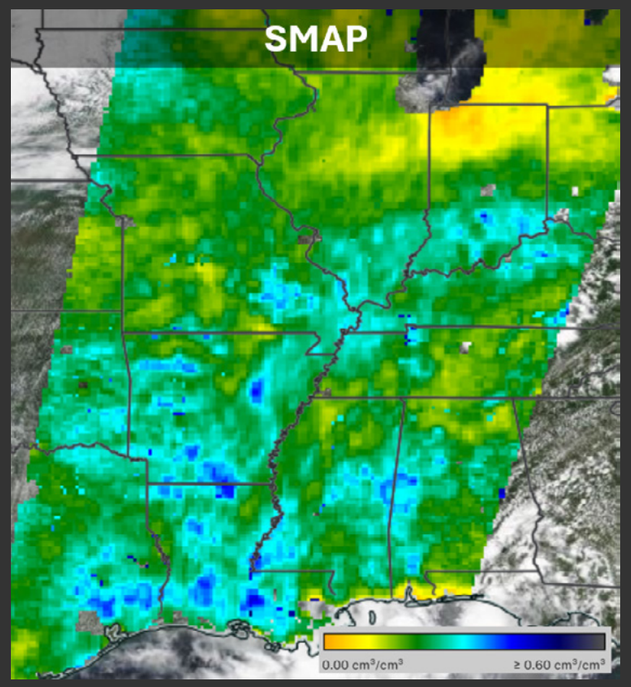


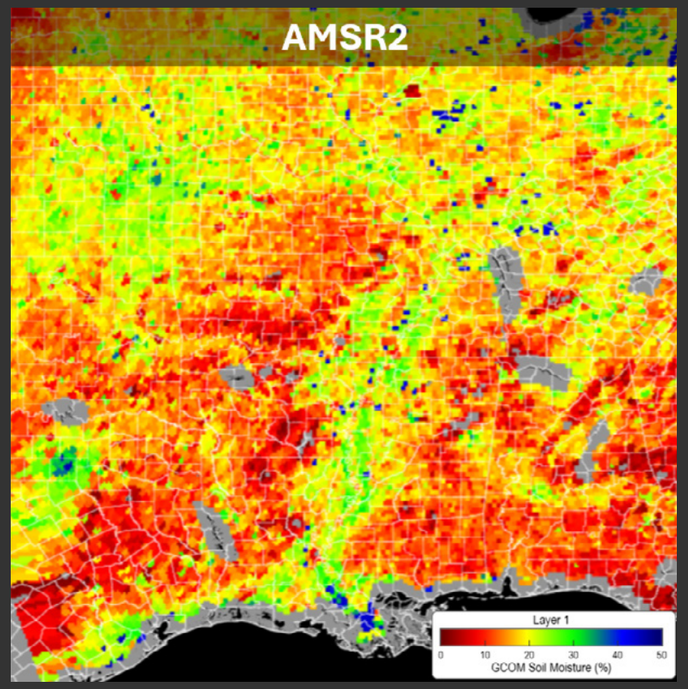
Simplified schematic illustrating how soil moisture influences the partitioning of sensible and latent heat fluxes, given a fixed amount of available energy (net radiation minus ground heat flux). Source: Hsu & Dirmeyer (2023), https://doi.org/10.1038/s41467-023-36794-5. Licensed under CC BY 4.0. / cropped.

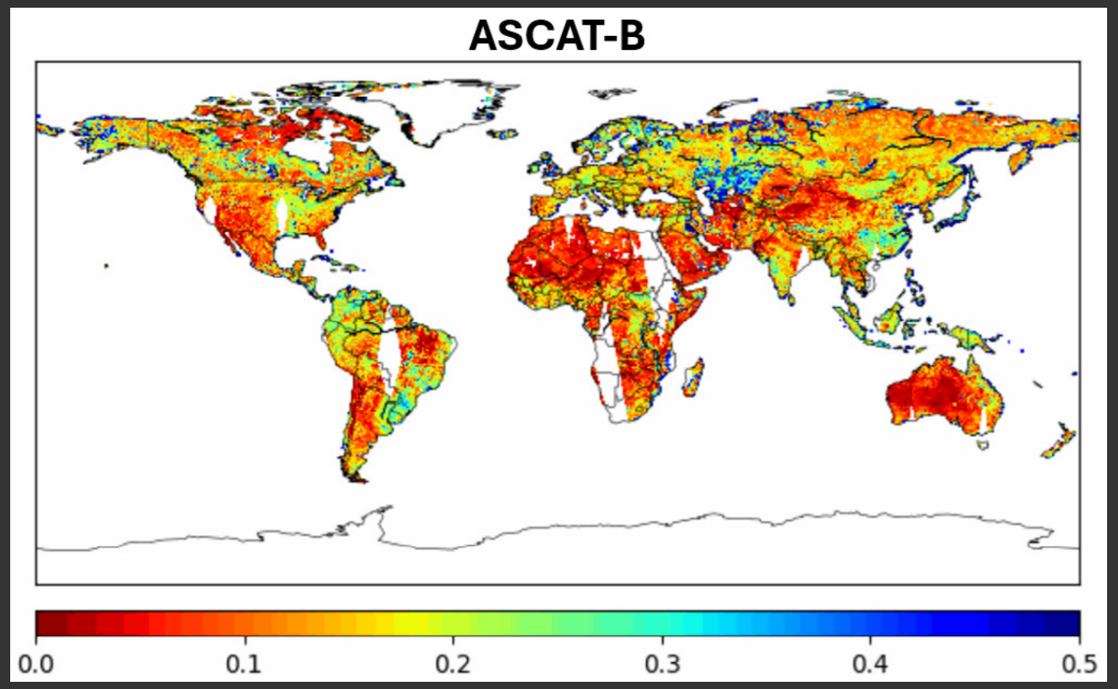
Soil moisture also determines whether precipitation infiltrates the ground or becomes surface runoff when the soil is saturated and can no longer hold any more water. Generally, dry soils can absorb more water, while wet soils produce more runoff, though this balance also depends on factors such as soil type and rainfall intensity. Whether precipitation soaks into the soil or flows over the ground affects how water moves through river systems, influences flood and drought risk, and regulates water availability for plants.

Soil moisture observations are essential for improving weather prediction, water resource management, flood forecasting, drought monitoring, and agricultural decision-making. NOAA's Numerical Weather Prediction (NWP) models and the National Water Model require soil moisture observations for parameter calibration, output validation, and data assimilation, all of which enhance forecasts of weather and streamflow. These data are central to weather prediction and hydrologic simulations, enabling more realistic representations of land-atmosphere interactions and improving the accuracy and reliability of forecasts. "We have to simulate the energy fluxes to do modeling accurately," explains Xiwu (Jerry) Zhan, PhD, a Research Physical Scientist at the NOAA/NESDIS Center for Satellite Applications and Research (STAR). "That's why we need many surface variables, including soil moisture," he adds.

Ground-based soil measurements offer high accuracy, but their limited spatial coverage leads to data gaps and an incomplete picture of soil moisture at regional and global scales. Microwave instruments onboard low Earth orbit (LEO) satellites help address these gaps by providing daily global observations across vast areas, including remote regions where ground monitoring is impractical. Many microwave instruments capable of measuring soil moisture have been launched, each with unique spatial, temporal, and spectral characteristics. With a diverse array of LEO soil moisture observations available, the challenge lies in how to use them most effectively. "The best way is to blend them together," Zhan says. This blending of observations enhances spatial and temporal coverage, accuracy, and reliability of soil moisture estimates compared with using observations from a single sensor.







Examples of LEO soil moisture observations from individual satellite microwave sensors.

Left: *Daily soil moisture across the Central U.S. on July 16, 2025, from NASA's Soil Moisture Active Passive (SMAP) mission. Values are expressed as a ratio (cubic centimeters of water/cubic centimeters of soil), representing volumetric water content, the fraction of soil volume occupied by water. Source: NASA Worldview.*

Middle: *Daily soil moisture across the Central U.S. on July 17, 2025, from the Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the Japan Aerospace Exploration Agency (JAXA) GCOM-W2 satellite. Values are expressed as a percentage (%), representing the volume of water per unit volume of soil. Source: JSTAR Mapper.*

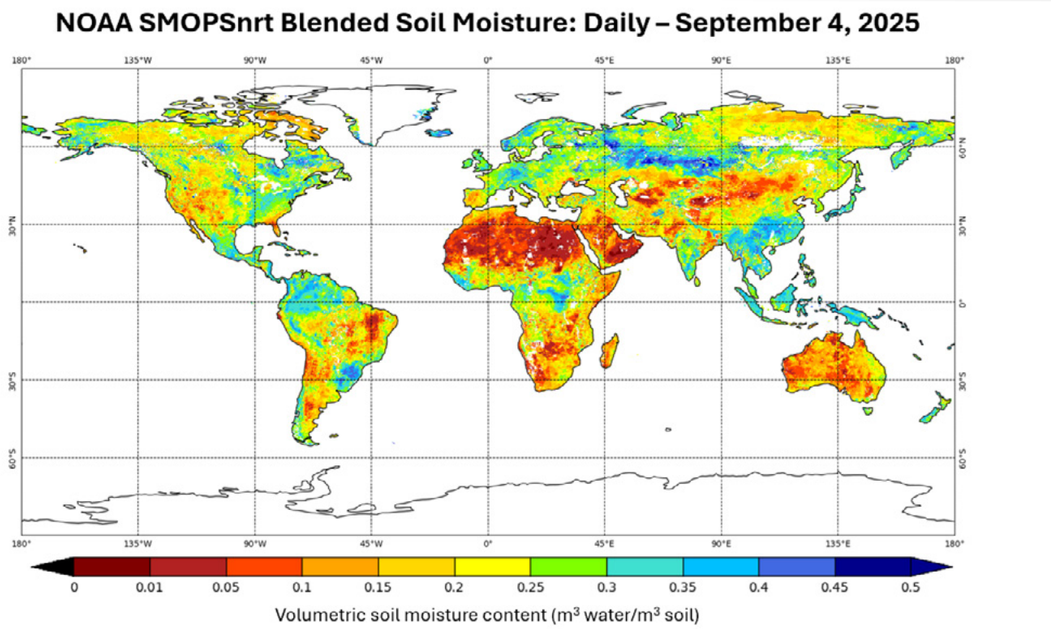
Right: *Daily global soil moisture on July 18, 2025, from the Advanced Scatterometer (ASCAT) onboard EUMETSAT's MetOp-B mission. Values are expressed as volumetric water content (cubic meter of water/cubic meter of soil). Source: NESDIS STAR*

NOAA's Soil Moisture Operational Product System (SMOPS), developed by NESDIS STAR, applies this approach by blending soil moisture data from multiple LEO microwave sensors into a single unified system. Zhan, who serves as the Development Lead on the SMOPS project team, describes SMOPS as a "one-stop shop" for soil moisture observations, providing a more complete and consistent view of global soil moisture conditions than any one sensor can achieve alone. During the August 2025 LEO Science Seminar, hosted by the NOAA/NESDIS Office of Low Earth Orbit (LEO) Observations, Zhan provided an overview of SMOPS products and highlighted recent updates to improve performance and expand applications.

SMOPS: NOAA's Global Soil Moisture Powerhouse

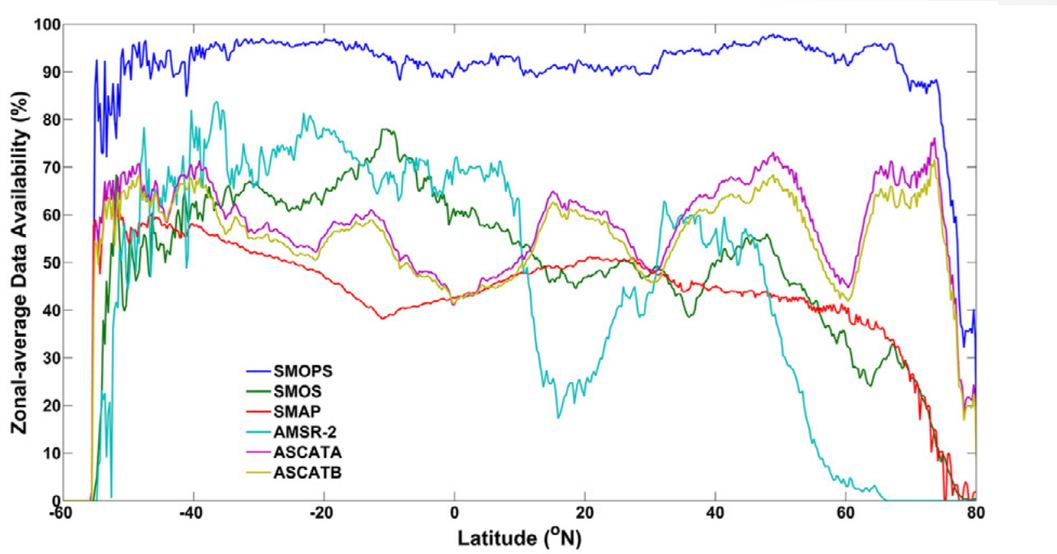
Operational at NOAA since 2013, the SMOPS near real-time product (SMOPSnrt) serves as NESDIS's global system for blended, multi-satellite soil moisture estimates, providing data to experimental and operational numerical weather prediction (NWP) and hydrologic models used by NOAA's Environmental Modeling Center, National Weather Service, and National Water Center. Over the past decade, SMOPSnrt has undergone four major updates based on user feedback to improve retrieval algorithms and integrate observations from new satellite sensors. The most recent update, Version 4.0, was released in 2024 within NOAA's NESDIS Common Cloud Framework (NCCF), an enterprise-level cloud-based platform that streamlines access and management of environmental sensing data for the weather data user community.

SMOPSnrt Version 4.0 merges soil moisture data from the Advanced Scatterometer (ASCAT) -B and -C sensors onboard European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) MetOp-B and MetOp-C satellites, the Advanced Microwave Scanning Radiometer 2 (AMSR2) on the Japan Aerospace Exploration Agency (JAXA) GCOM-W2 mission, and NASA's Global Precipitation Measurement (GPM) Microwave Imager (GMI) and Soil Moisture Active Passive (SMAP) satellite. Data are blended to create 6-hourly and daily global 25-kilometer (km) resolution maps that include the most recent 6- and 24-hour soil moisture retrievals, aligned with operational NWP model data assimilation cycles. Soil moisture in the top five centimeters (cm) of soil is measured as volumetric water content—the ratio of the volume of water to the total volume of soil—offering consistent, high-quality data for use in NWP and hydrologic modeling.



The operational SMOPSnrt Soil Moisture product shows global daily soil moisture estimates for September 4, 2025, reported as volumetric soil moisture content (cubic meter of water/cubic meter of soil). Source: NOAA Office of Satellite and Product Operations (OSPO).

"One of the key characteristics of the SMOPS product is higher spatial coverage," says Zhan. The figure below demonstrates this point by showing zonal-average data availability for a previous operational release, SMOPSnrt Version 2.0, alongside data from individual satellite soil moisture products. Zonal-average data availability represents the percentage of data available by latitude; the blue line shows that SMOPSnrt Version 2.0 consistently exceeds the coverage of the individual satellite products. Across most latitudes, Version 2.0 maintains roughly 90% data availability, a level also achieved by the current operational version of SMOPSnrt.



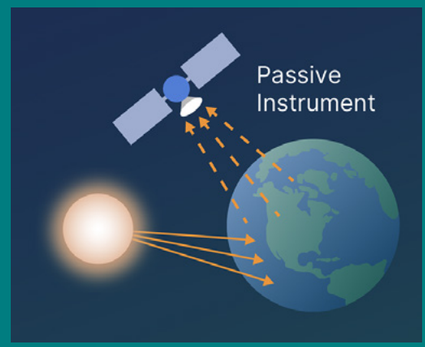
Percentage of data available by latitude for SMOPS Version 2.0, which merged data from the Soil Moisture and Ocean Salinity (SMOS) mission, SMAP, AMSR-2, and ASCAT-A and -B. Courtesy of Xiwu Zhan/NESDIS STAR. Source: Yin et al. (2019). https://doi.org/10.1029/2018WR024326.

This enhanced spatial coverage improves the consistency and accuracy of satellite-based soil moisture observations. "This is valuable for numerical weather prediction and National Water Model users," Zhan explains. For example, assimilating SMOPSnrt soil moisture data into NOAA's operational Global Forecast System using the ensemble Kalman filter (EnKF) technique has been shown to improve precipitation forecasts. Assimilating SMOPSnrt blended data also enhances surface layer soil moisture simulations within the Noah land surface model compared with data from individual satellite sensors. The Noah land surface model and its more advanced, multi-parameterization version, Noah-MP, simulate land-atmosphere interactions and are components of the Global Forecast System and National Water Model.

While SMOPSnrt provides valuable near real-time soil moisture information, operational users at NOAA also recognized the need for a long-term SMOPS dataset to improve data quality, reduce uncertainties, resolve version inconsistencies, and support prolonged data assimilation for more accurate long-term modeling. In response, NESDIS STAR developed SMOPScdr, which integrates two decades of soil moisture observations from several LEO microwave satellite sensors, providing a consistent historical record for modeling and other applications.

Signals From the Surface: How Microwaves Measure Moisture

The microwave emissivity of soil is directly linked to soil moisture through the soil's dielectric properties, which describe how it stores and dissipates electrical energy as heat. Since dry soil and water have vastly different dielectric properties, even small changes in soil moisture cause significant, measurable changes in the soil's dielectric constant. Dry soil emits strong microwave radiation, but as soil becomes wetter, its dielectric constant increases causing microwave emission to decrease. Both active and passive microwave satellite sensors exploit this relationship to estimate soil moisture, providing a reliable means of monitoring soil conditions globally from space.



Passive microwave sensors, such as SMAP, measure the natural thermal microwave radiation emitted by the Earth's surface (expressed as brightness temperature), with lower emissions indicating higher soil moisture. Active microwave sensors, like ASCAT, emit a pulse of microwave energy and measure the portion reflected back, known as backscatter. Wetter soils reflect more of the microwave signal, allowing the sensor to infer soil moisture content from changes in backscatter.

Another advantage of microwave remote sensing: Microwaves have longer wavelengths than visible or infrared light, enabling them to pass through clouds and fog with minimal scattering. As a result, satellite microwave sensors can measure soil moisture in nearly all weather conditions.

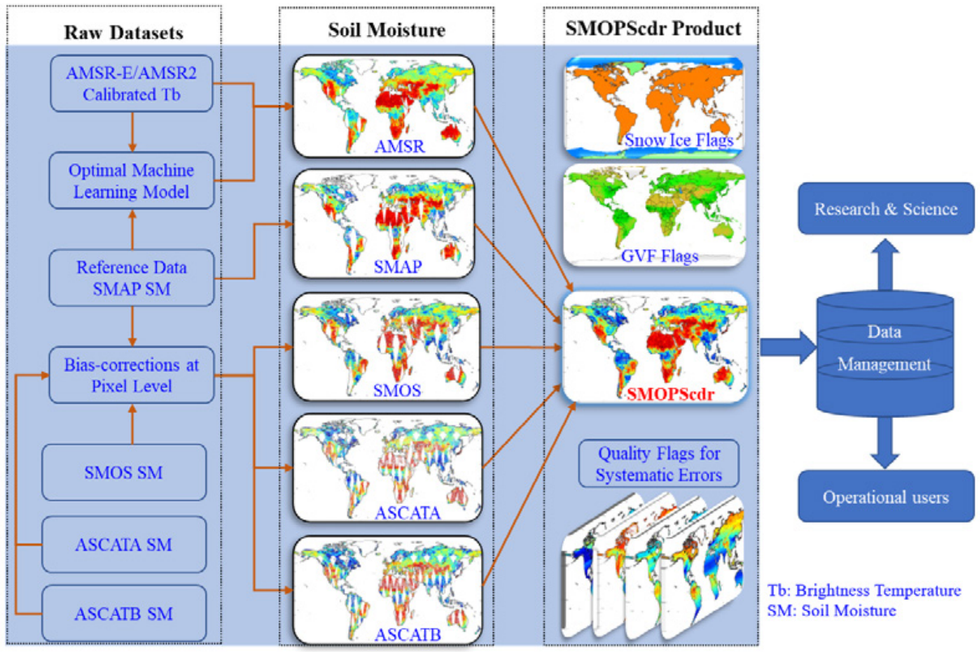
Decades of Data, One Consistent Product

In 2022, development began on the SMOPScdr long-term dataset with support from the NESDIS Office of LEO Observations, marking an important step toward building a reliable historical record of blended soil moisture data. SMOPScdr integrates soil moisture observations from four passive LEO microwave sensors (AMSR-E, AMSR2, SMAP, and the Soil Moisture and Ocean Salinity (SMOS) mission) and two active microwave sensors (ASCAT-A and ASCAT-B) to create a robust and continuous dataset from 2002 to the present. "The long-term product is very important for data assimilation," Zhan says, noting its value for land surface modeling and numerical weather prediction.

SMOPScdr incorporates advancements that include machine learning, radiance calibration, bias correction, and observation-driven quality control. These innovations improve accuracy, expand spatial coverage, and ensure consistency across the individual satellite platforms. The resulting global dataset, updated every three months with a one-year latency, supports a wide range of scientific and operational applications and is expected to be operationally produced at NOAA NESDIS.

"SMOPS [near real-time product] delivers updates within just a few hours, while SMOPScdr provides a consistent long-term record. By combining the strengths of both, SMOPS can help improve weather forecasts, water management, drought monitoring, and wildfire predictions," said Zhan's colleague, scientist Jifu Yin, PhD, in an interview about the product.

SMOPScdr tracks sub-seasonal, seasonal, and annual shifts in soil moisture, helping scientists evaluate long-term drought trends, distinguish short-term dry spells from prolonged agricultural drought, and link soil moisture with precipitation patterns to improve water management. Long-term data also reveal areas where saturated soils increase landslide risk after heavy rainfall, while extended dry periods indicate elevated susceptibility to wildfire. Flood risk assessments also benefit from monitoring soil moisture over time, as saturated soils can reduce infiltration, increasing runoff and the likelihood of flooding. Through these applications, SMOPScdr provides meaningful and actionable data that enhance flood and drought monitoring and support disaster preparedness and response.



Click image to enlarge. *The strategy for developing the SMOPScdr product. Source: Yin, J., Zhan, X., Liu, J., Barlage, M., Meng, H., Kalluri, S., Yang, J. X., Ogden, F. L., Goldberg, M. D., Zhao, L., Cosh, M., & Ferraro, R. R. (2025). Reprocessed NOAA SMOPS blended soil moisture product as a climate data record. Bulletin of the American Meteorological Society, 106(8). https://doi.org/10.1175/BAMS-D-23-0248.1. ©American Meteorological Society. Used with permission.*

National Water Model

The National Water Model (NWM), developed by NOAA, is a high-resolution hydrologic model that simulates observed and forecast streamflow. Using complex mathematical equations, it simulates processes like soil infiltration, snowmelt, and runoff while accounting for variations in elevation, soil type, vegetation, and other factors. The NWM produces hourly forecasts across the entire river network, including detailed predictions of river discharge. These forecasts provide critical guidance to support emergency managers, reservoir operators, and other decision makers in managing a wide range of water-related events and applications.

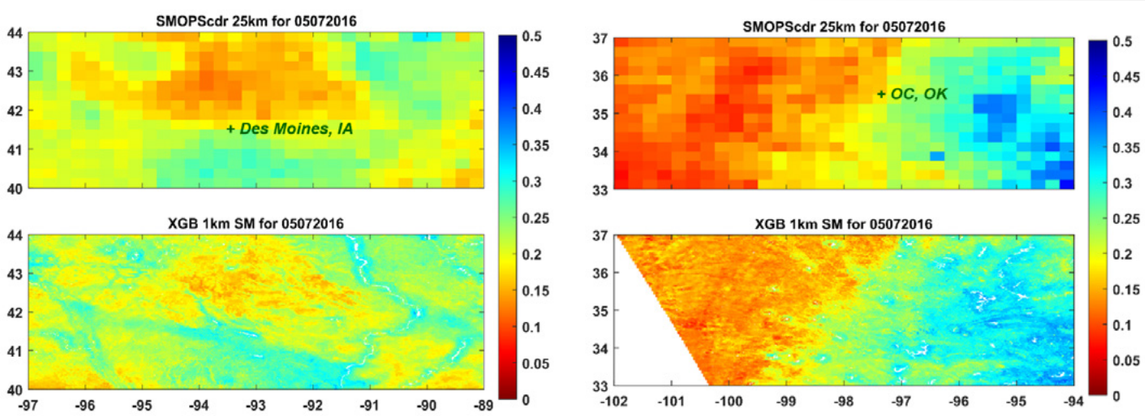
A High-Resolution Solution

While coarse-resolution soil moisture products like SMOPSnrt and SMOPScdr are well suited for applications that prioritize wide coverage, high-resolution models like the operational National Water Model require finer-scale data to accurately capture localized hydrological processes and their effects on runoff and streamflow. High-resolution soil moisture observations are important for verifying National Water Model simulations, calibrating model parameters, and improving overall model performance. To address this need, NESDIS STAR developed a downscaled version of SMOPScdr, specifically aligned with the National Water Model's 1-kilometer grid.

Developed with support from the NESDIS Office of LEO Observations alongside the 25-km SMOPScdr product, the 1-km SMOPS high-resolution dataset (SMOPShr) was created using a machine learning approach called XGBoost (XGB) to downscale SMOPScdr to fine-scale (i.e., 1 km) soil moisture estimates. "This approach does not rely on any simulations from any land surface model," Zhan explains. "All input datasets used to train the XGB machine learning algorithm are purely based on satellite observations." The resulting high-resolution dataset provides substantially greater spatial details, capturing variations that are not visible in coarser resolution products, as illustrated in the examples at the top of the next page.

XGBoost

XGBoost (XGB), which stands for eXtreme Gradient Boosting, is a powerful machine learning algorithm used for supervised learning tasks such as classification and regression. It is a highly efficient and scalable implementation of gradient boosting, a machine learning technique that builds a strong predictive model by combining an ensemble of weak prediction models.



Click images to enlarge. *Regional maps of the 25-km SMOPScdr product (top) and the 1-km SMOPShr product (bottom) for Iowa City, Iowa (left) and Oklahoma City, Oklahoma (right) on May 7, 2016. The higher-resolution SMOPShr product reveals substantially more spatial detail compared with the coarser SMOPScdr maps. Courtesy of Xiwu Zhan.*

Currently, the 1-km SMOPShr product is available only for the National Water Model domain, which includes the continental U.S., Southern Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands. "We could do global downscaling, but the computing resources required [exceed the capacity] of our local server," Zhan remarks. The NESDIS STAR team is exploring cloud computing to eventually develop a global high-resolution SMOPS product.

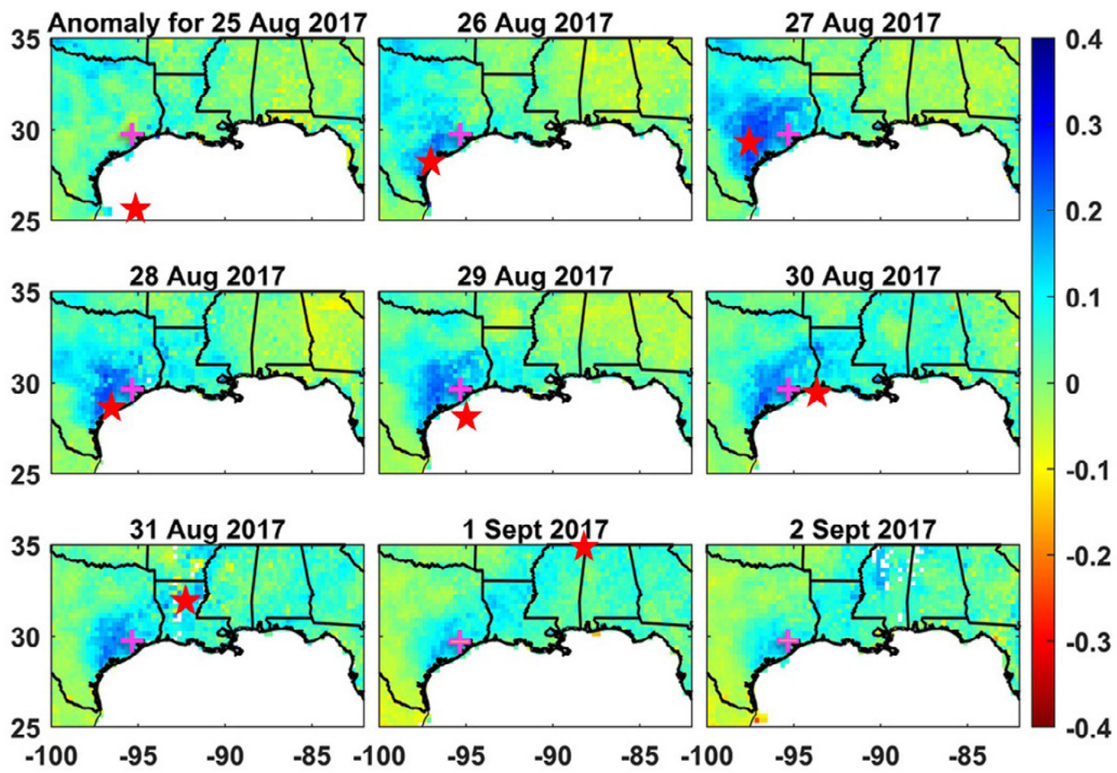
SMOPS In Action: From Data to Decisions

SMOPS blended soil moisture products support a wide range of operational and research activities across NOAA. They are used for model verification and validation, parameter calibration, and data assimilation, all of which enhance the accuracy of NOAA's weather and water models. Beyond modeling applications, SMOPS data also inform critical decision-making during events such as floods and droughts, helping to protect lives and property while supporting sectors including agriculture, transportation, and commerce.

Turning Wet Soil Into Flood Intelligence

Monitoring surface soil moisture is essential for understanding and anticipating flood potential. When soil becomes saturated, even moderate rainfall can quickly lead to surface runoff and localized flooding. Microwave satellite observations, such as those from SMOPS, offer valuable insight into these conditions. Soil moisture anomalies—deviations from historical averages—can reveal areas experiencing unusual wetness. These data provide an early indicator of flood-prone areas, helping forecasters and emergency managers monitor soil moisture patterns that may signal increased flood risk.

The SMOPScdr maps on the next page, part of a retrospective analysis, show how the product captured progression of flood conditions during Hurricane Harvey in late August 2017. As the storm approached the Texas coast and made landfall on August 26, 2017 (red star), soil moisture increased rapidly along the coastline, indicated by dark blue shading. These wetter areas expanded inland over following days as Harvey's slow movement and heavy rainfall inundated the



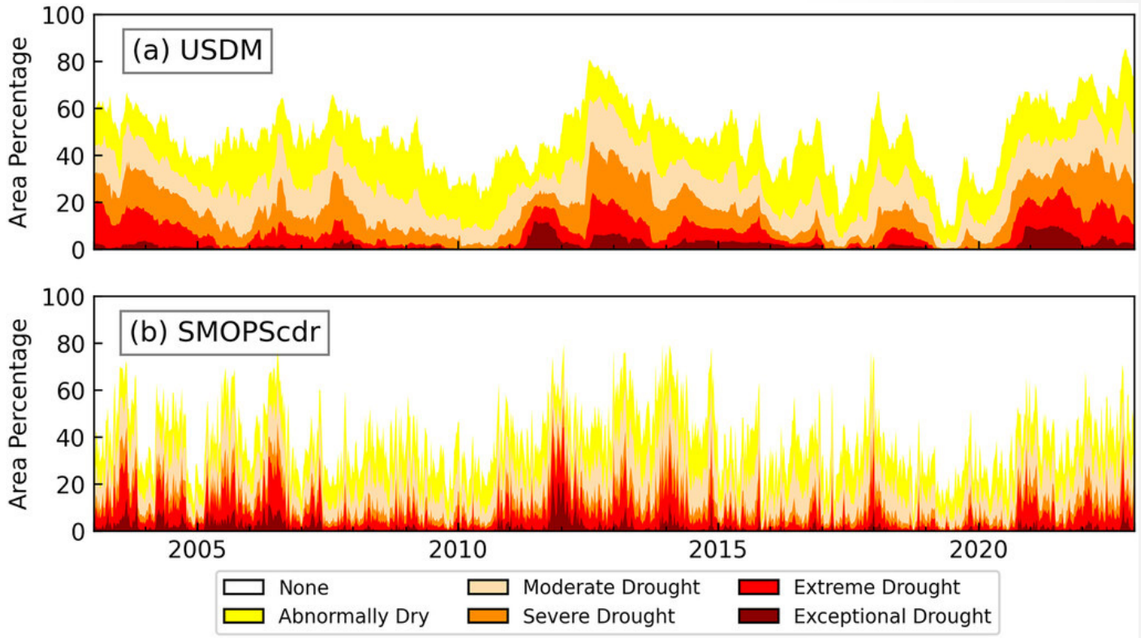
Yin, J., Zhan, X., Liu, J., Barlage, M., Meng, H., Kalluri, S., Yang, J. X., Ogden, F. L., Goldberg, M. D., Zhao, L., Cosh, M., & Ferraro, R. R. (2025). Reprocessed NOAA SMOPS blended soil moisture product as a climate data record. Bulletin of the American Meteorological Society, 106(8). https://doi.org/10.1175/BAMS-D-23-0248.1. ©American Meteorological Society. Used with permission

region. The Greater Houston area, marked by a pink cross, along with areas to the west, exhibited strong positive anomalies consistent with high soil saturation, coinciding with a period of record-breaking precipitation and catastrophic flooding across Eastern Texas. The close alignment between wet zones in the SMOPScdr data and the storm's impact area emphasizes the product's value for tracking soil saturation in support of flood monitoring and early warning.

Soil Moisture Insights for Early Drought Warning

Soil moisture is a critical indicator of drought, offering early insights into emerging dry conditions before they become severe. Microwave satellite sensors, like those used in SMOPS, measure moisture within the top few centimeters of soil. Although limited to the surface layer, these observations are closely linked to deeper soil moisture at weekly and longer time scales. This connection makes the SMOPScdr long-term record of soil moisture deficits a valuable resource for understanding drought development, which in turn informs better prediction of drought conditions.

To assess its effectiveness in monitoring drought, the NESDIS STAR team analyzed SMOPScdr soil moisture estimates for the continental U.S. from 2003 to 2022, converting the data into drought intensity metrics. These were then compared with drought intensity for the same period from the U.S. Drought Monitor (USDM), a key resource for farmers, ranchers, and foresters. Overall,



The weekly area percentage of the continental U.S. (CONUS) in drought during the period from 2003 to 2022 with drought categories colored by severity: (a) the USDM and (b) based on SMOPScdr. Both datasets capture notable severe drought events. The USDM droughts appear to persist longer, while SMOPScdr represents the surface soil moisture that responds rapidly to light and moderate precipitation. Source: Yin, J., Zhan, X., Liu, J., Barlage, M., Meng, H., Kalluri, S., Yang, J. X., Ogden, F. L., Goldberg, M. D., Zhao, L., Cosh, M., & Ferraro, R. R. (2025). Reprocessed NOAA SMOPS blended soil moisture product as a climate data record. Bulletin of the American Meteorological Society, 106(8). https://doi.org/10.1175/BAMS-D-23-0248.1. ©American Meteorological Society. Used with permission.

the comparison shows good agreement for severe drought events, highlighted in orange in the plots above. While the USDM generally shows more extensive and longer-lasting droughts than those indicated by SMOPScdr, satellite-based historical soil moisture data can be used to better understand long-term patterns that inform agricultural practices, water management, and planning.

The USDM generates weekly national drought maps by combining expert analysis with observational and modeled data on soil moisture, precipitation, streamflow, temperature, vegetation health, and other variables. While the USDM currently relies on modeled soil moisture, Zhan notes that observational data from SMOPS could be used as an independent reference to verify model output, enhancing the accuracy of USDM products.

Although SMOPS data is not directly ingested by the USDM, it does contribute indirectly through the NASA Land Information System (LIS), which incorporates SMOPS retrievals into its soil moisture estimates used by the USDM. Looking forward, SMOPS has the potential to support more accurate and responsive drought monitoring nationwide.

In Closing

Looking ahead, SMOPS remains a cornerstone of NOAA's efforts to deliver consistent, high-quality soil moisture information for operational and research applications. Its blended approach enhances data coverage, consistency, and reliability, addressing the limitations of single-sensor retrievals and strengthening confidence in downstream modeling systems. These advances support more accurate land surface flux simulations, which in turn improve weather forecasts, hydrologic predictions, water resource management, and the timeliness of emergency alerts and warnings. As part of NESDIS Common Cloud Framework, SMOPS data are readily accessible across the agency and to external users, streamlining their use in modeling and analysis.

The SMOPS development team continues to refine and expand the soil moisture product suite through ongoing innovation and integration of next-generation satellite data. For the SMOPScdr long-term product, plans are underway to incorporate ASCAT-C data once the time series becomes sufficiently long, extending product continuity. The team is also preparing to integrate observations from new LEO missions from international and domestic partners. Among these are the U.S. Space Force Weather System Follow-on Microwave (WSF-M) launched in April 2024, JAXA's AMSR3 sensor onboard the GOSAT-GW satellite launched in June 2025, and EUMETSAT's MetOp-Second Generation (MetOp-SG) mission with a scatterometer to be launched in 2026. Each of these next-generation LEO microwave instruments will further strengthen the accuracy and global coverage of SMOPS products. With every update, SMOPS advances NOAA's mission to provide timely and reliable information that benefits Americans and the U.S. economy. ✦

Learn More

Access daily operational SMOPSnrt soil moisture maps on NOAA's Office of Satellite and Product Operations website.

Dive into the details of how the SMOPScdr long-term product was created in this journal article authored by the development team.

Visit the NOAA NESDIS STAR Global Soil Moisture Data Products Portal to learn more about SMOPS.

Story Source

The information in this article is based, in part, on the August 18, 2025, LEO Science Seminar titled, "NESDIS high resolution satellite soil moisture data products and their applications," presented by Dr. Xiwu (Jerry) Zhan, Research Physical Scientist, NOAA NESDIS Center for Satellite Applications and Research (STAR), with contributions from Dr. Jifu Yin, Cooperative Institute for Satellite Earth System Studies (CIMSS) at University of Maryland (UMD), Dr. Jicheng Liu, CIMSS/UMD, and Dr. Liqun Ma, NOAA NESDIS Office of Satellite & Product Operations (OSPO).

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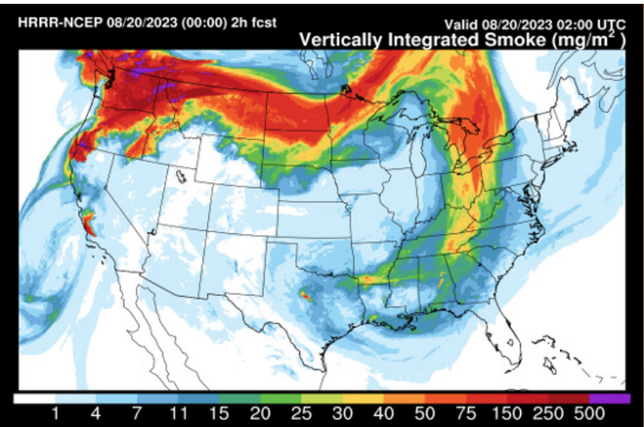
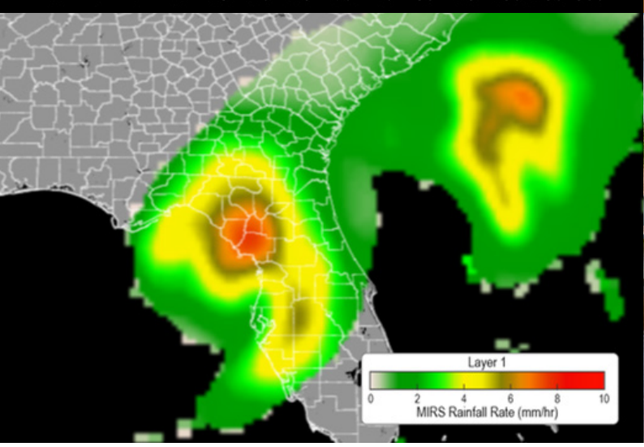
From Data to Decisions: *The Role of a Satellite Liaison*

A National Weather Service (NWS) forecaster tests experimental products during the 2023 Spring NOAA Hazardous Weather Testbed (HWT) in Norman, Oklahoma. The HWT serves as both a proving ground and training platform, allowing NWS forecast staff to gain experience with next-generation models, algorithms, and tools in a real-time, simulated environment while providing feedback that helps refine future forecasting technologies. The HWT is jointly managed by the National Severe Storms Laboratory (NSSL), the Storm Prediction Center (SPC), and the NWS Norman Forecast Office. Credit: NOAA/NSSL.



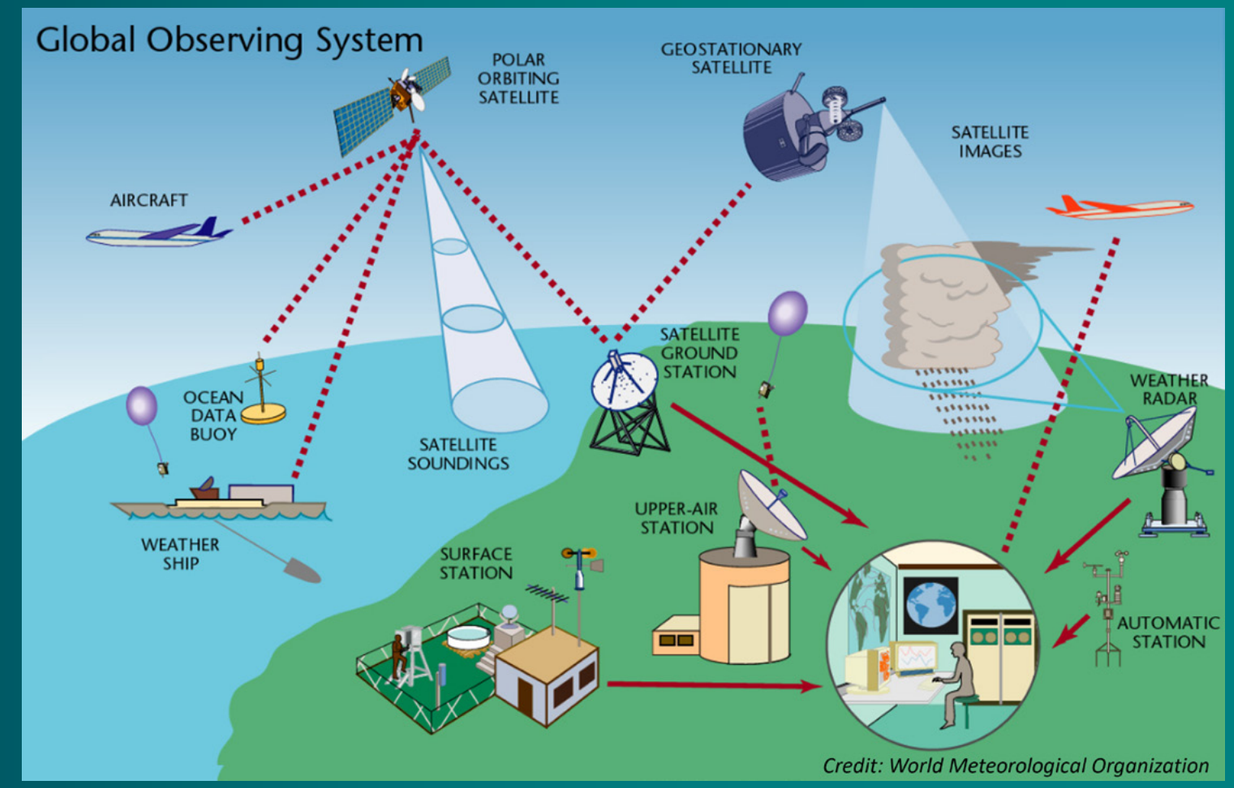


Row 1: HRRR-Smoke forecast depicts smoke from Pacific Northwest wildfires traveling thousands of miles, which can impact visibility and aviation safety (NWS). A plane flies through thick wildfire smoke (iStock/Yuriy T).

Row 2: NOAA-20 ATMS-MiRS Rainfall Rate showing heavy rainfall as Hurricane Debby makes landfall in Florida (JSTAR Mapper). Flooding in a Florida neighborhood caused by Hurricane Debby (iStock/Bilanol).

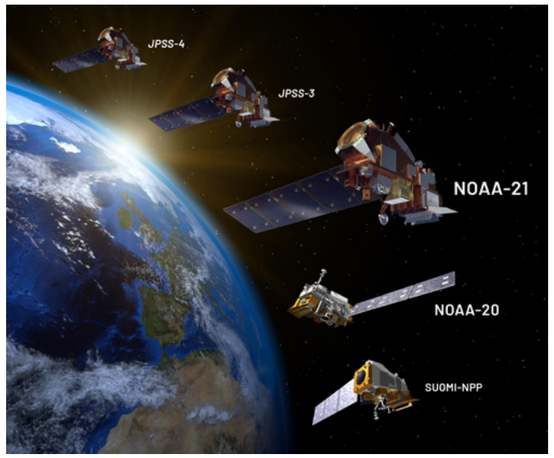
Operational forecasters at the National Weather Service (NWS) rely on a wide range of environmental data to fulfill their mission of protecting lives and property and strengthening the national economy. The forecasts, advisories, watches, and warnings they produce influence daily life, guiding decisions that range from the routine—like whether to carry an umbrella—to the critical, such as issuing evacuation orders ahead of a hurricane or grounding flights due to wildfire smoke. NWS weather products help keep people safe and the economy moving by giving the public the information they need to plan ahead and be prepared.

Satellite observations play an important role in this mission, enhancing situational awareness and helping refine forecasts for high-impact events such as hurricanes, wildfires, ice storms, and floods, as well as everyday weather. Earth observation satellites operated by NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) collectively provide a continuous, global view of land, ocean, and atmospheric conditions, complementing radar data and in-situ measurements from weather balloons, ocean buoys, ships, aircraft reconnaissance, and surface stations. NOAA's space-based observations help fill coverage gaps from other observing systems and offer critical context for understanding weather and environmental hazards.



Forecasters rely on a global network of observations to gather the continuous stream of data necessary for producing meteorological forecasts. Credit: World Meteorological Organization.

Given the importance of weather information to businesses, industries, and communities nationwide, NWS forecast staff must use the most relevant and reliable data available to produce trustworthy and accurate forecasts. To get the most out of satellite observations, forecasters need to know what datasets and products are available and how to access, interpret, and integrate them effectively into their workflows, all while managing the demands of daily operations. Satellite data training programs help meet this need by equipping forecasters with the practical knowledge, hands-on experience, and reference materials necessary to maximize the benefits of satellite observations for their regions.

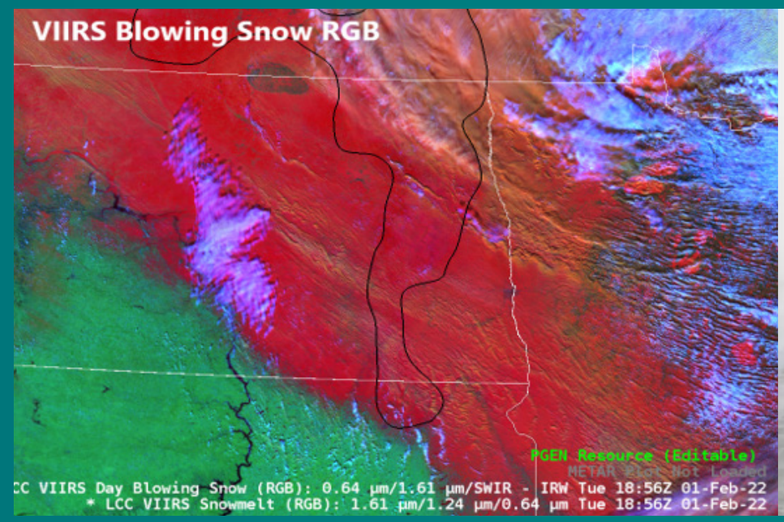


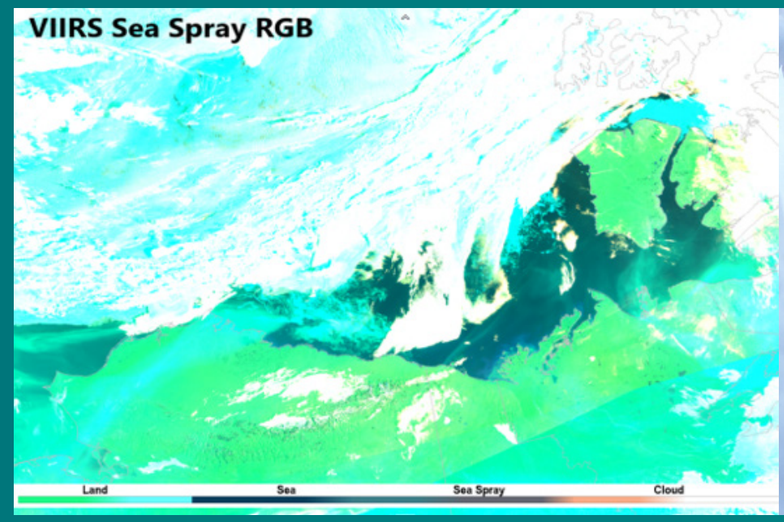
NOAA's Joint Polar Satellite System (JPSS), shown above, includes five polar-orbiting low Earth orbit (LEO) satellites. Three are currently operational: NOAA-21, NOAA-20, and Suomi-NPP. The final two, JPSS-3 and JPSS-4, are planned for launch in 2027 and 2032.

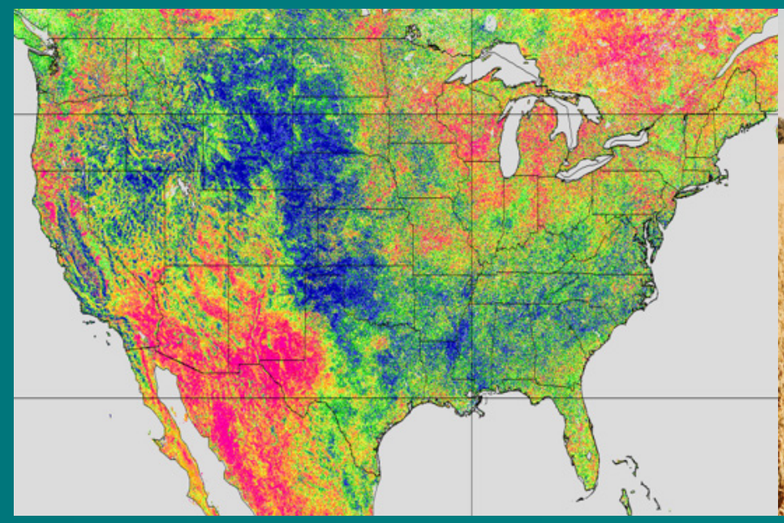
Space-Based Support

Satellite observations are essential to the NWS mission to protect lives and property and enhance the national economy. At regional Weather Forecast Offices, satellite data and imagery help NWS forecasters monitor local weather patterns, track developing storms, trace wildfire smoke, and issue timely warnings for floods, severe weather, air quality, and other hazards. Specialized NWS centers also make use of satellite observations for their operational missions: the Ocean Prediction Center tracks sea ice, wind, and ocean storms that affect maritime safety; the Aviation Weather Center monitors low clouds, wildfire smoke, icing conditions, and other aviation hazards; and the National Hurricane Center assesses the intensity and size of tropical cyclones. The Weather Prediction Center and the Storm Prediction Center use satellite observations to monitor storm development and precipitation rates, and the Environmental Modeling Center assimilates satellite data into models to improve weather and marine forecasts.

Beyond NWS, NOAA satellite imagery and data products inform decision making across many sectors of the U.S. economy, including agriculture, transportation, forestry, fisheries, insurance, retail, and energy. Timely data on ocean, land, and atmospheric conditions improve operational planning, logistical efficiency, and resource management. Across NOAA, satellite observations provide essential information that help maintain and grow the nation's economy while safeguarding lives, property, and infrastructure.







Images on the right: Various products derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard JPSS satellites.

Row 1: VIIRS Blowing Snow RGB shows blowing snow extent (CIRA/CSU; NOAA/NESDIS), which leads to low visibility and icy roads (NWS Des Moines/Mahaska County EMA).

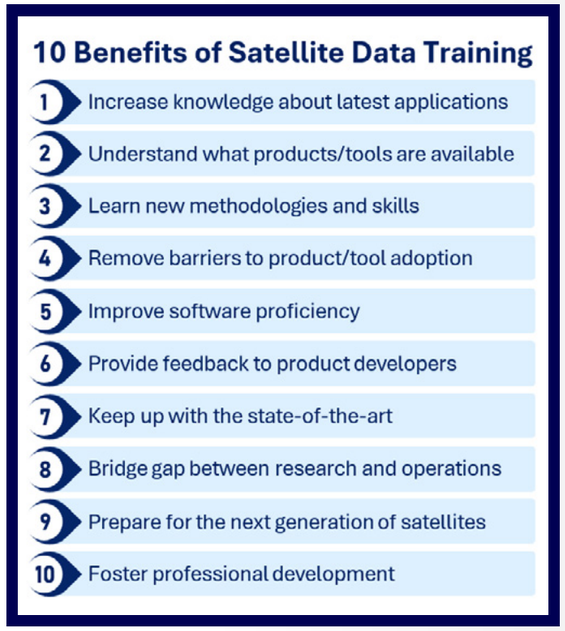
Row 2: VIIRS Sea Spray RGB supports maritime warnings (CIRA/CSU; NOAA/NESDIS). Sea spray freezes on ship equipment in cold environments, which affects ship stability (NOAA; Michael Van Woert).

Row 3: VIIRS Vegetation Health Index (VHI) provides data on drought (NOAA/NESDIS). Farmers use VHI to aid in crop planning (Nebraska Corn Board).

Strengthening Skills, Knowledge, and Decision Making

Training is a fundamental part of every NWS forecaster's career, helping them stay proficient and adaptable in a field characterized by rapid scientific advancement. Continuous learning, from coursework and seminars to live exercises and peer shadowing, ensures NWS forecast staff can interpret complex environmental data accurately and confidently. Satellite data training complements this foundation by giving forecasters the information and tools to apply satellite imagery and specialized products in operational settings. Interactive training sessions also provide forecasters with opportunities to share feedback that helps improve product algorithms, expand capabilities, and enhance data access, supporting broader use of satellite data and products. Satellite data training builds on core professional development by turning satellite observations into actionable information that benefits society.

NOAA/NESDIS often looks to their research partners, such as the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University and the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison, to design and deliver satellite data training for the NWS user community. At the center of this effort are the liaisons who serve as trainers, bridging research and operations by translating advanced satellite science into practical forecasting applications. Among them is Jorel Torres, a meteorologist and researcher at CIRA. As a Satellite Liaison for the NOAA/NESDIS Joint Polar Satellite System (JPSS), Torres develops resources and delivers satellite data training on JPSS products and applications, maintaining a two-way exchange of information between forecasters and product developers. At the July 2025 LEO Science Seminar, organized by the NOAA/NESDIS Office of Low Earth Orbit (LEO) Observations, Torres discussed his role and insights from his recent training visits to NWS Weather Forecast Offices across the country.



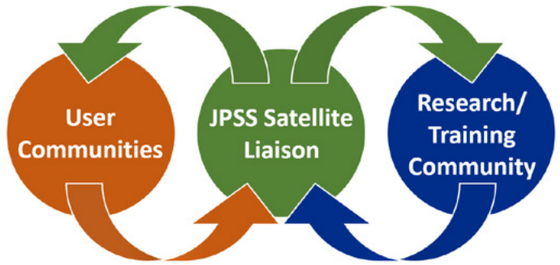
Click image to enlarge.

Different Methods for Different Needs

Satellite data training can take many forms, depending on available resources, trainee background, and training goals. Different approaches have trade-offs: in-person workshops offer personalized guidance but require travel, whereas online webinars are more convenient and affordable but provide less individual support. Designing training with the audience, objectives, and challenges in mind is key to creating effective learning experiences.

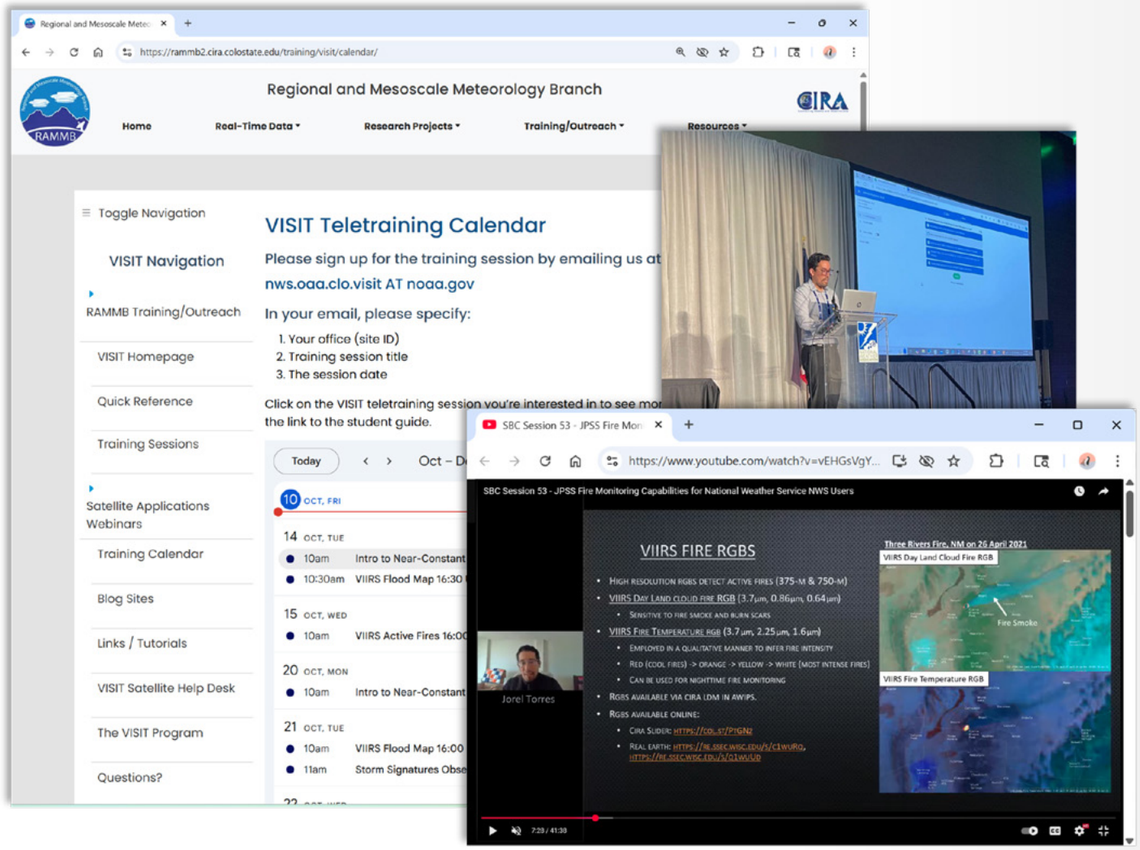
Inside the World of a JPSS Satellite Liaison

Satellite liaisons serve as a crucial link between satellite data and real-world decision making. They ensure that the right information reaches the right users for the right applications, enabling users to apply satellite data effectively in support of operational needs. Through training, communication, and collaboration, satellite liaisons translate satellite observations into practical insights that improve forecasts, enhance public safety, and advance scientific understanding.



For Torres, this means providing guidance to meteorologists and other user groups, such as hydrologists and emergency managers, on how to effectively apply JPSS observations, while also relaying valuable feedback from end users to researchers to help guide product improvements. He helps end users understand JPSS data product capabilities, interpret and integrate observations into their workflows, and address challenges or needs related to JPSS datasets and tools. In essence, he connects the operational, research, and training communities to improve the flow of information and the effective use of JPSS satellite data.

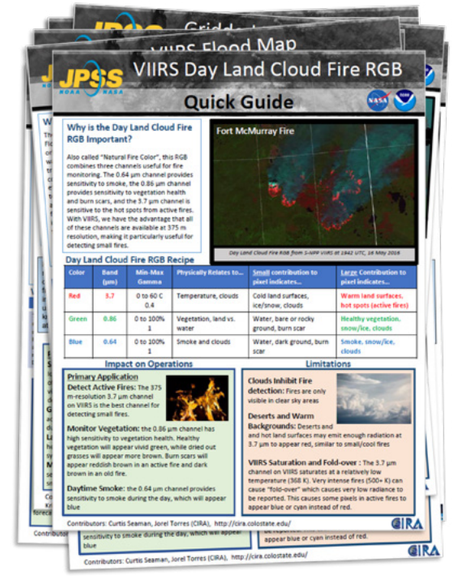
Torres' interactions as a JPSS Satellite Liaison span a variety of forums. Courtesy of Jorel Torres.



The Virtual Institute for Satellite Integration Training (VISIT) teletraining calendar on CIRA's website, Jorel Torres presenting at the National Weather Association (NWA) Annual Meeting, and Jorel Torres presenting virtually at a TOWR-S Satellite Book Club seminar on "JPSS Fire Monitoring Capabilities for National Weather Service Users."

Torres engages with NWS forecasters and other professionals through multiple forums, from in-person workshops to online seminars and teletraining. His sessions, whether in person or virtual, incorporate a range of training approaches including hands-on exercises, demonstrations, lectures, and small group discussions. For instance, he regularly leads live teletraining sessions through the Virtual Institute for Satellite Integration Training (VISIT), giving participants opportunities to explore JPSS imagery and data products, ask questions, and engage in hands-on learning. Torres is also a frequent presenter for NOAA's weekly TOWR-S Satellite Book Club, a seminar series where NOAA and affiliate scientists discuss topics related to NOAA satellites, including new data products, algorithm enhancements, and applications of satellite data in the field. Additionally, he attends meteorological conferences and meetings, such as the American Meteorological Society (AMS) Annual Meeting, where he facilitates in-person professional development workshops and delivers lectures on JPSS capabilities, fostering collaboration and knowledge exchange between forecasters and researchers.

Apart from live sessions, Torres develops reference materials, such as "Quick Guides" (product reference documents) and "Quick Briefs" (short product application videos), designed to help users quickly and easily



Click image to enlarge. *Quick Guides provide concise reference materials for a wide range of NOAA satellite data products.*

understand key information about JPSS imagery and data products. He also reaches audiences through the VISIT: Meteorological Interpretation Blog and CIRA's social media platforms, where he highlights real-world examples of JPSS observations in use. His posts demonstrate how JPSS datasets, both independently and when combined with geostationary satellite data, strengthen a forecaster's situational awareness and support applications such as severe and winter weather monitoring, fire detection, and more.

Perhaps the most impactful aspect of Torres' role as a JPSS Satellite Liaison is his direct engagement with forecast staff during visits to NWS Weather Forecast Offices. During these visits, he shares information about JPSS products that are specific to the needs and challenges of the office. Forecasters gain practical experience using JPSS data relevant to their operations, while Torres gathers feedback on product performance to share with researchers and product developers, helping refine algorithms and improve usability. In every setting, whether a conference, teletraining session, or in-person visit, Torres helps end users understand how JPSS observations relate to their challenges and how the data can be applied to improve forecast accuracy, inform decision making, and enhance operational effectiveness.

Torres speaking with NWS forecasters at the Weather Forecast Office in Cheyenne, Wyoming. Courtesy of Jorel Torres.

Bridging Research and Operations

Training extends beyond operational satellite data products to include experimental ones, especially those ready for testbed evaluation. Torres works closely with JPSS product developers to make sure that emerging products are accompanied by training materials that guide users in interpreting the data and understanding its applications, operational value, functionality, and limitations. He helps researchers identify the operational details that matter most, such as data latency, resolution, and region-specific uses, and advises on the best training approaches based on a product's maturity. The goal is to create training materials that are scientifically accurate, operationally relevant, and provide the latest product updates for users.

"If you [a researcher] need to develop a Quick Guide for your experimental product that you envision going into operations, we can help you develop it and add it to your webpage," offers Torres. Through this collaboration, complex research concepts are transformed into understandable, readily available resources for a range of audiences, from new hires to seasoned forecasters, supporting the testing and refinement of nascent data products. Ongoing collaboration ensures training materials stay up to date with new technologies and shifting operational priorities, strengthening the connection between research and operations.

Testing Tomorrow's Tools

Testbeds serve as essential environments for assessing how new satellite data products perform in operational settings. One example is NOAA's Hazardous Weather Testbed (HWT), which hosts multiple experiments each year to evaluate emerging products, models, and technologies for severe weather forecasting and warning. During the HWT, researchers, developers, and forecasters work side by side to test and refine next-generation tools. Collaborative projects like the HWT shorten the time it takes to transition tools from research to operations, ultimately improving NWS forecast capabilities.

Forecasters, researchers, and developers collaborate during the 2023 Spring Hazardous Weather Testbed at NOAA's National Severe Storms Laboratory (NSSL) in Norman, Oklahoma. Credit: NOAA/NSSL.

Navigating Challenges

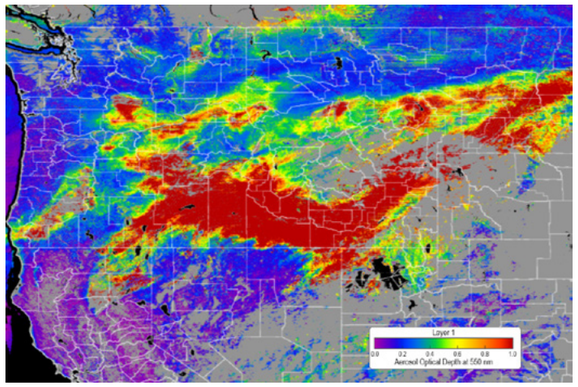
As a JPSS Satellite Liaison, Torres notes several training-related challenges that make it difficult for NWS forecasters to fully engage with and apply JPSS observations to their operations. One major hurdle is awareness: many forecast staff are simply not aware that these training opportunities exist. Even when they are, limited time and competing mandatory training obligations take priority over voluntary satellite-focused training. "One way around that," Torres says, "is to provide Quick Guides, Quick Briefs, and shorter training modules." These concise resources offer forecasters a fast, flexible way to learn about JPSS datasets and products on their own schedule.

Another challenge is access to the data itself. For many Weather Forecast Offices in the contiguous U.S. (CONUS), only a subset of JPSS data products can be accessed through AWIPS (Advanced Weather Interactive Processing System), the primary software NWS uses for forecast operations. To address this, Torres provides forecast staff with training materials about how to access JPSS data and imagery online, outside of AWIPS. One example is the operational VIIRS Aerosol Optical Depth (AOD) product (below), available online through NOAA's AerosolWatch and JSTAR Mapper data visualization tools. The VIIRS AOD product, derived from observations from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard JPSS satellites, quantifies aerosols like smoke and dust, providing a measure of their concentration in the atmosphere that forecasters can use to monitor visibility and air quality.

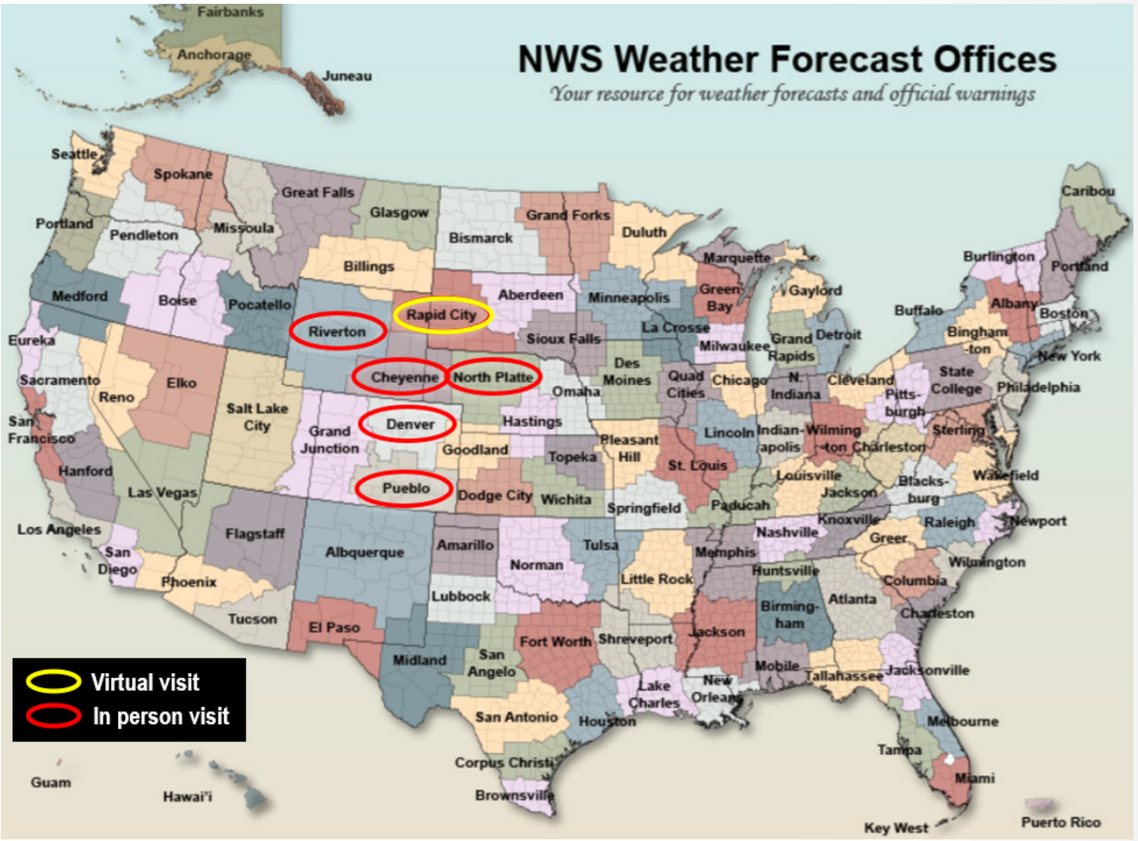
Torres' efforts show that training is more than instruction; it's about connecting people with the data and tools they need in ways that fit their workflow and schedule. His approach reflects a broader commitment across NOAA/NESDIS and its Cooperative Institutes to make satellite data easily attainable, practical, and responsive to user needs. Through online training resources and data visualization tools, the NESDIS Office of LEO Observations enables forecasters and other decision-makers to confidently apply JPSS data to real-world challenges, strengthening forecasting and benefiting communities nationwide.

Insights From Inside WFOs

As part of his ongoing responsibilities, Torres and his colleagues routinely visit NWS Weather Forecast Offices (WFOs) both in



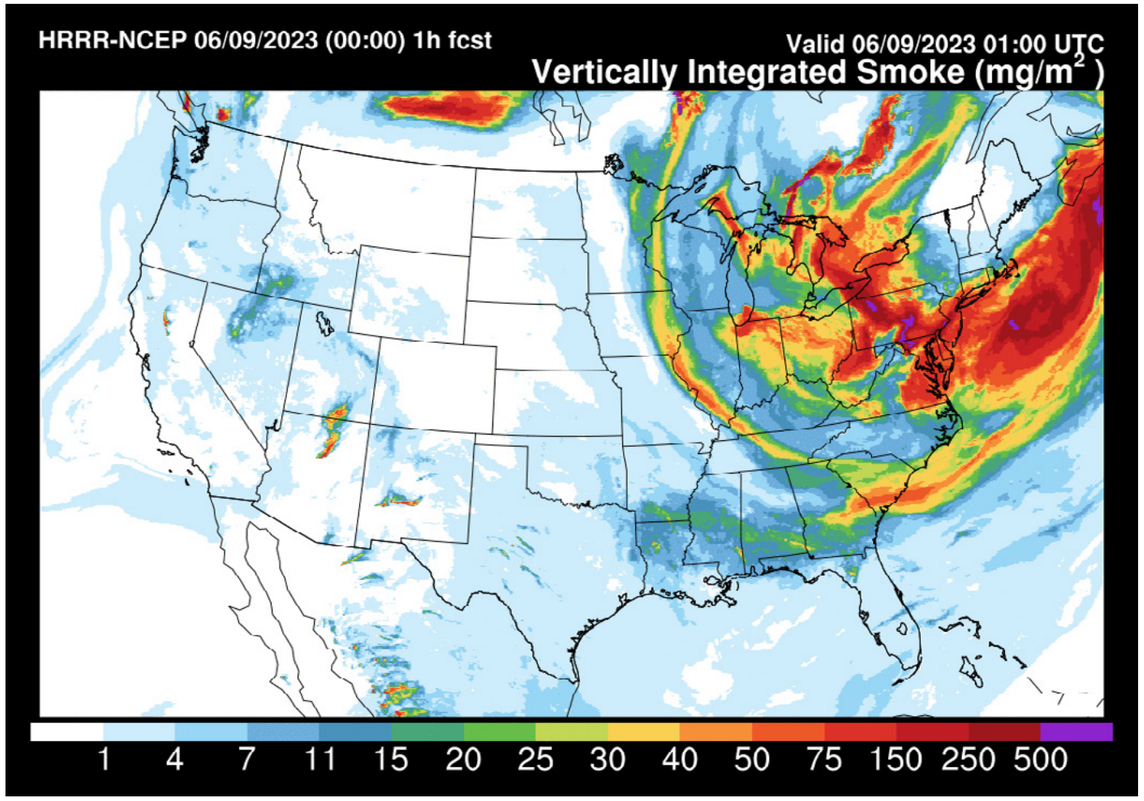
Click images to enlarge. *The NOAA-20 VIIRS Aerosol Optical Depth (AOD) product from July 26, 2024, shows dense concentrations of aerosols (red) originating from the Park Fire in Northern California and traveling hundreds of miles, reducing air quality across multiple states. Source: JSTAR Mapper. Right: Smoke from the Park Fire casts an orange glow and blankets the region in a thick haze. Credit: CAL FIRE.*

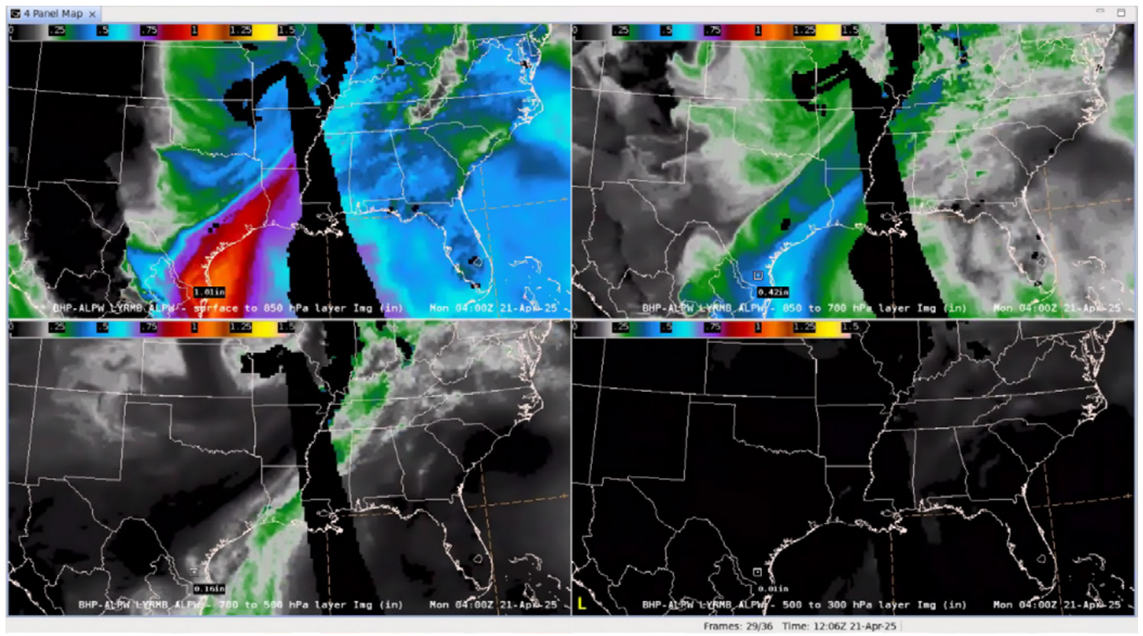


person and virtually. During these visits, they engage with NWS forecast staff on the latest NOAA JPSS and Geostationary Operational Environmental Satellite (GOES) capabilities, demonstrating applications and how to access satellite information in AWIPS and online. “We also discuss the forecast challenges that are unique to their County Warning Areas and collect feedback on the usage of satellite data in operations,” explains Torres.

“The level of satellite expertise varies from office to office, so it is valuable for satellite liaisons to visit and interact with forecasters, get their feedback, and learn about what data they like to use,” he adds. Between 2024 and mid-2025, Torres visited six WFOs across the Western and Midwestern U.S. (circled on the map), gathering information on location-specific forecast challenges and feedback on JPSS data products. While many forecasters had experience with JPSS observations, others expressed strong interest in learning more, requesting additional training materials and practical examples of how the data are applied.

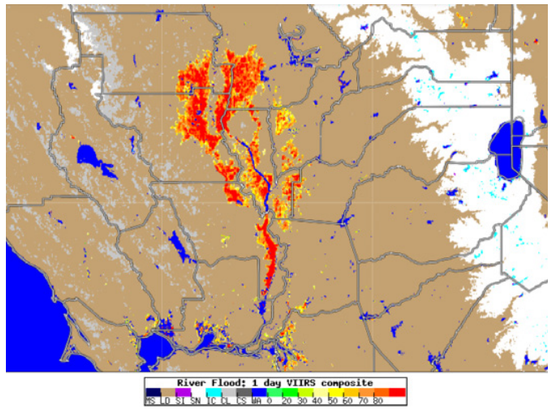
Forecasters across several of the WFOs Torres visited pointed to the High-Resolution Rapid Refresh (HRRR)-Smoke model (top of adjacent page) as an important tool for tracking wildfire smoke and issuing air quality alerts during wildfire season. The HRRR-Smoke model generates hourly forecasts of smoke concentration, with wildfire emissions estimated using fire radiative power data derived from JPSS VIIRS and NASA Moderate Resolution Imaging Spectroradiometer (MODIS) instruments. At two WFOs, forecast staff noted the operational Advected Layer Precipitable Water (ALPW) product (bottom of adjacent page) helps them analyze moisture

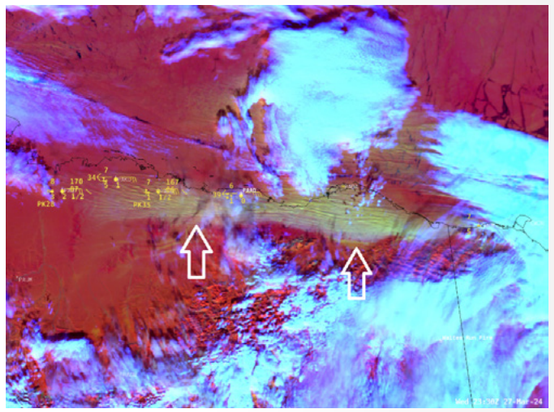




Top: The 1-hour HRRR-Smoke forecast shows thick smoke from Canadian wildfires spreading across the northeastern United States on June 9, 2023. Source: NWS.

Bottom: The operational Advected Layered Precipitable Water (ALPW) product, valid at 0400 UTC on April 21, 2025, shows water vapor in four atmospheric layers (surface-850 millibars (mb), 850-700 mb, 700-500 mb, 500-300 mb), highlighting the circulation of a strengthening surface low over Oklahoma and moisture transport from the Gulf along the Texas coast. Image exported from AWIPS. Source: Satellite Liaison Blog.





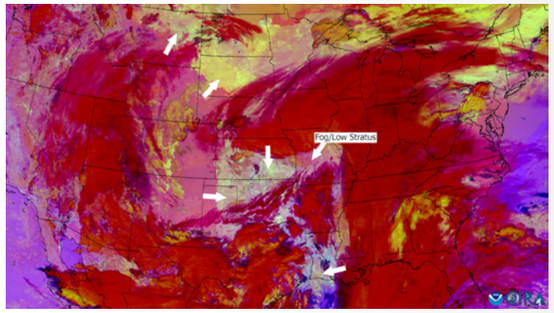
***Click images to enlarge**. Left: VIIRS 1-day Composite Flood Map shows widespread flooding on February 22, 2024, in the Sacramento Valley in California, following a series of heavy storms that hit the region. Source: RealEarth™/Space Science and Engineering Center (SSEC), Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin-Madison.*

Right: VIIRS Blowing Snow RGB imagery shows blowing snow (indicated by arrows) over northern Alaska on March 27, 2024. Credit: CIRA Satellite Library.

and track heavy rain events. The ALPW product integrates moisture profiles from several polar-orbiting microwave instruments, including the Advanced Technology Microwave Sounder (ATMS) aboard JPSS satellites, to generate a four-dimensional structure of water vapor.

Several offices also showed strong interest in the operational VIIRS Flood Map product (above left) noting its value during spring snowmelt to map the extent of floodwater and snowmelt-related ponding, which helps improve early warning systems for areas that may not have ground-based sensors. Forecasters also saw potential in using VIIRS Blowing Snow RGB imagery (above right) during localized high wind events to verify blowing snow. Wind-blown snow can create "whiteout" conditions with near-zero visibility, posing hazards for motorists and pilots. One WFO also expressed interest in VIIRS Snowmelt RGB imagery for assessing the blowability of the snowpack. This application has already proven useful at other WFOs in the region, as illustrated in the forecast discussion excerpt on the next page.

"A common forecast challenge across most WFOs we interacted with was that they experienced a lot of radar beam blockages due to high terrain," Torres notes. Topographic features such as mountains, hills, plateaus, and buttes can prevent the detection of low-level weather phenomena by radar, making it difficult to monitor low clouds and fog. Satellite observations, such as VIIRS Nighttime Microphysics RGB imagery (below), helps fill these gaps by providing crucial insights into weather conditions that affect transportation safety in regions with limited radar coverage.

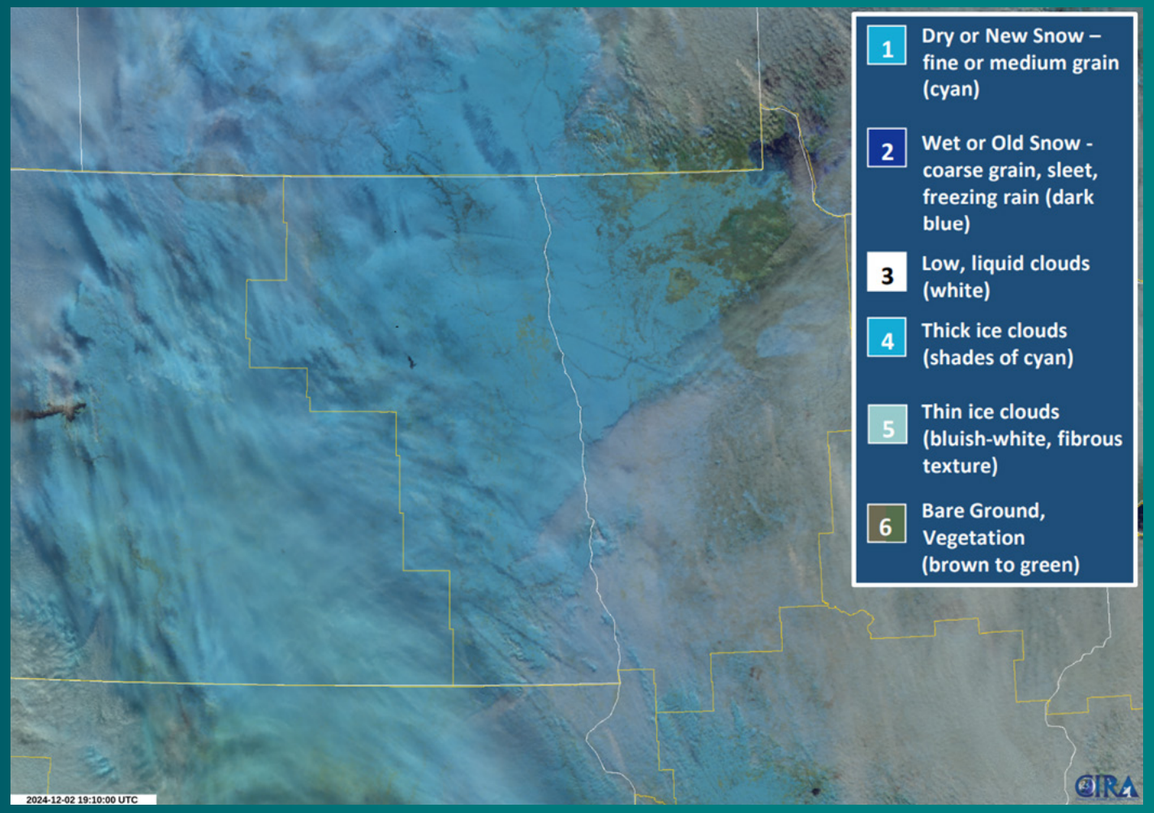


***Click image to enlarge.** VIIRS Nighttime Microphysics RGB imagery shows dense fog and low stratus clouds draping across the Central U.S. on January 23, 2024, as indicated by arrows. Credit: CIRA/CSU; NOAA/NESDIS. Source: CIRA Satellite Library.*

From the Forecaster's Desk

"Satellite imagery such as Snowmelt RGB via VIIRS today confirms this widespread, small snow crystal (not crusted over) across our entire area. This brings confidence in a snowpack that is ripe to be blown around."

NWS Grand Forks North Dakota, 2 Dec 2024: Area Forecast Discussion



VIIRS Snowmelt RGB imagery from December 2, 2024, at 19:10 UTC shows widespread new or dry snow with fine to medium grains in cyan, indicating that the snow remains easily moved by wind. Credit: CIRA/CSU; NOAA/NESDIS. Source: Satellite Liaison Blog.

Data latency is another persistent challenge. "Forecasters said they would use VIIRS imagery, which is available in AWIPS, especially for [fire] hot spot detection and nighttime low cloud monitoring, if it were available at lower latency through Direct Broadcast," Torres points out. While many operational satellite observations are distributed through the AWIPS Satellite Broadcast Network (SBN), latency varies depending on data type—for some JPSS data products, relatively high latency limits operational usefulness. The Direct Broadcast Network (DBNet) is a low latency alternative, delivering near real-time LEO data via local receiving stations around the globe, often within minutes of satellite overpass. CIRA is working with NOAA to bring the DBNet data stream to more WFOs, though as one forecaster told Torres about lower-latency options, "Getting the data is better than nothing."

Engaging with WFOs encourages greater use of NOAA satellite data in forecaster workflows, improving their situational awareness of developing weather and creating a meaningful feedback loop between operations and research. These visits also give satellite liaisons like Torres the opportunity to troubleshoot issues and help forecasters apply the data products effectively. "With all the satellite data available, knowing what satellite data to look for at different times of the year and during specific weather events is key," Torres says, highlighting the practical guidance his visits provide. Follow-up after each visit maintains communication and ensures NWS forecasters continue to make the most of satellite information in their forecasts, watches, and warnings.

The Road Ahead

As NOAA/NESDIS prepares to launch the next generation of LEO and GEO environmental satellites in the coming years, as well as two more JPSS satellites by 2032, the volume and complexity of space-based environmental data available to forecasters, researchers, and decision-makers will grow significantly. These new platforms promise unprecedented capabilities for monitoring weather and environmental hazards, creating both opportunities and challenges. To turn this wealth of data into meaningful insights, new and experienced satellite data users will need up-to-date training resources to acquire, interpret, and apply the latest observations and data products effectively.

Satellite liaisons will remain essential in meeting these training needs, translating complex satellite information into clear, practical guidance and learning resources for end users. Their work enables those on the ground and in operational settings to effectively apply satellite information to real-world scenarios, including severe weather forecasting, water resource management, disaster response, emergency planning, and more. Continued investment in satellite data training will ensure that operational communities are prepared for emerging technologies and products, enabling them to use the most advanced satellite observations for applications that enhance public safety, protect property and infrastructure, and support commerce. ✦

Learn More

Learn about the instruments onboard JPSS satellites and NOAA's next generation of polar orbiting LEO environmental satellites, the Near Earth Orbit Network (NEON).

Access JPSS data product tutorials, online training, visualization tools, informative blogs, webinars, and other training resources through the NOAA/NESDIS Office of LEO Observations.

Discover how Weather Forecast Offices operate and the key roles of their staff on the National Weather Service website.

Story Source

The information in this article is based, in part, on the July 21, 2025, LEO Science Seminar titled, "JPSS: Recent Visits to Weather Forecast Offices (WFOs), Training Resources, and Data Access Updates," presented by Jorel Torres, Research Associate III/ JPSS Satellite Liaison, Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University (CSU), with contributions from Bill Line, NOAA/NESDIS Center for Satellite Applications and Research (STAR), Dan Bikos, CIRA/CSU, and Erin Sanders, CIRA/CSU.

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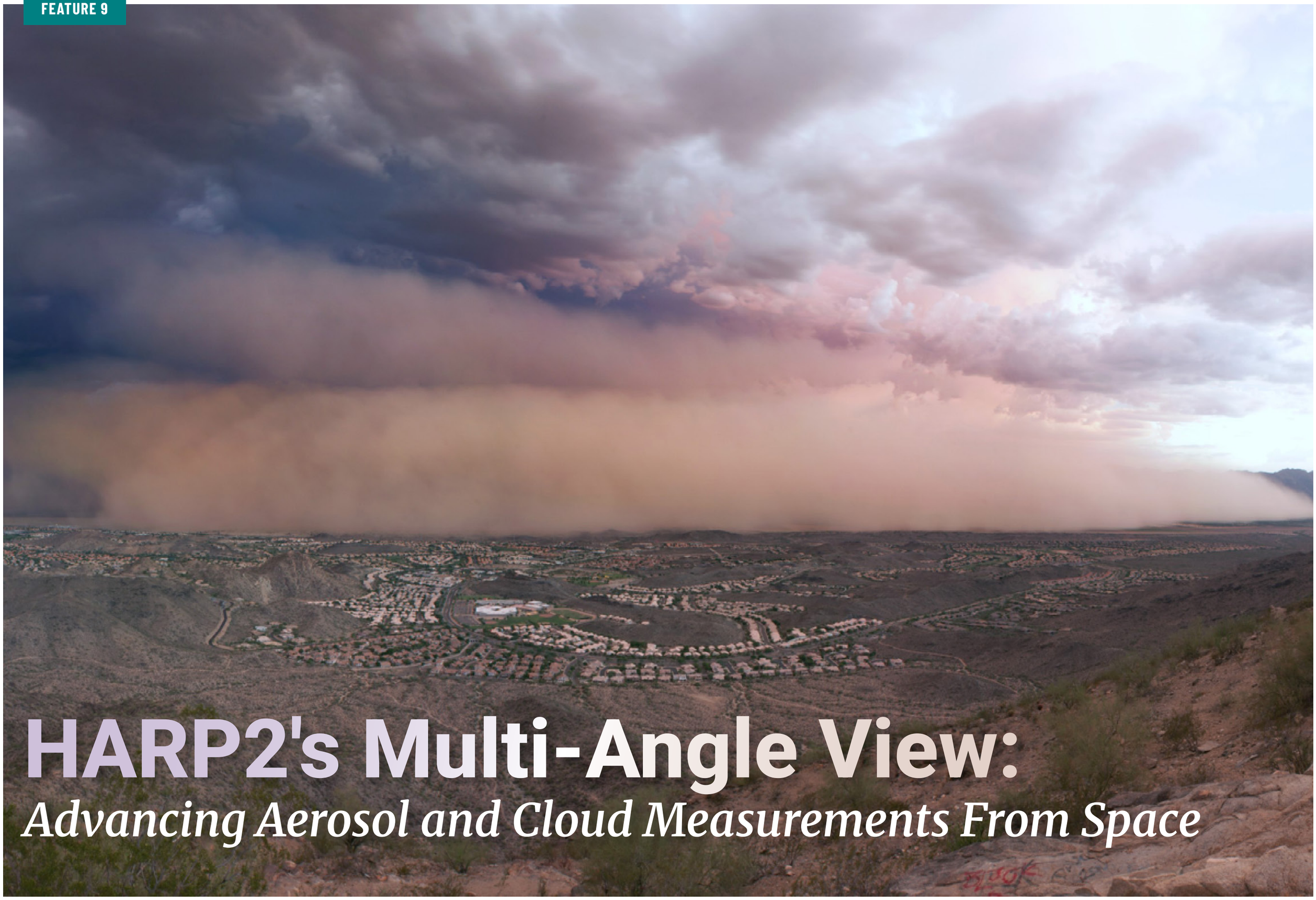


HARP2's Multi-Angle View:

Advancing Aerosol and Cloud Measurements From Space

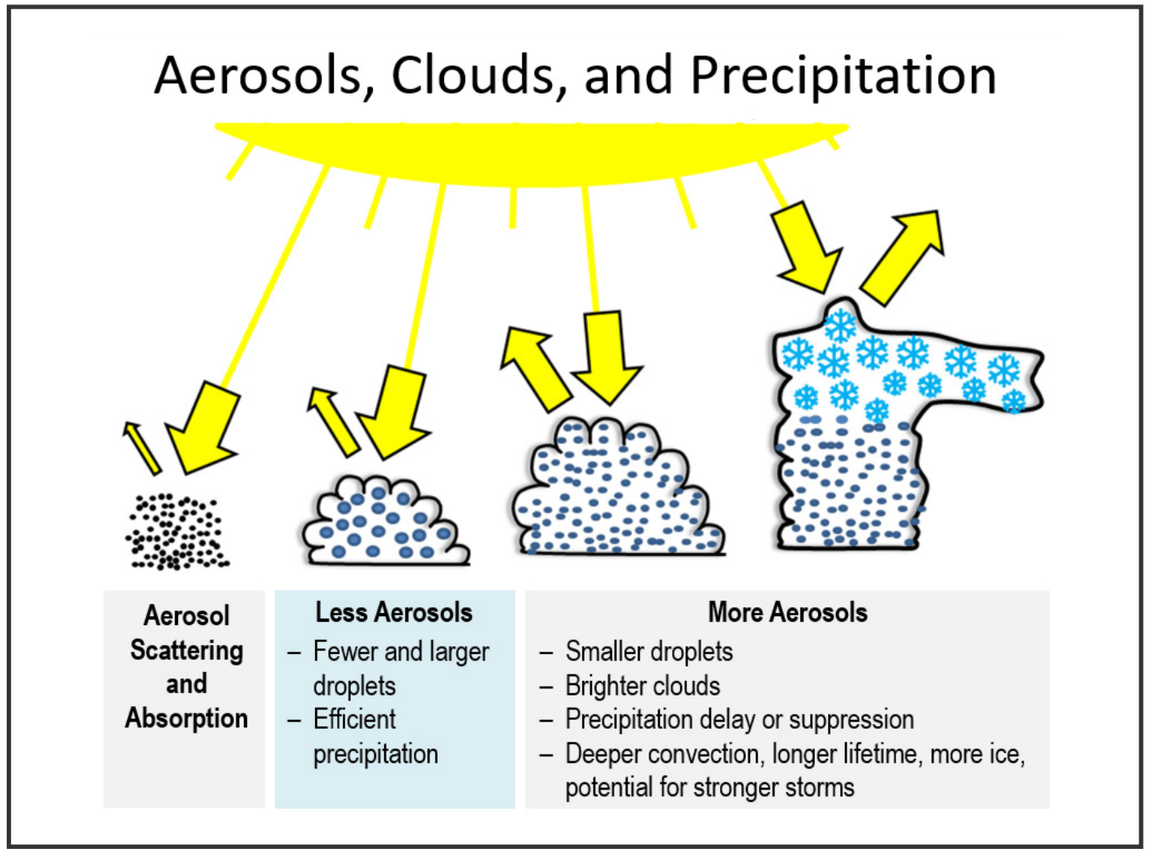
An intense dust storm called a haboob heads towards Phoenix, AZ on July 31, 2011. Photo: Alan Stark via Flickr, CC BY-SA 2.0 (modified).

A SpaceX Falcon 9 rocket with NASA's PACE spacecraft encapsulated atop is raised to a vertical position at Cape Canaveral Space Force Station in Florida on February 5, 2024. Photo: NASA.

In the early hours of February 8, 2024, NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite launched into space, entering low Earth orbit (LEO) with three next-generation instruments designed to transform our understanding of Earth's oceans, atmosphere, and land. Among them is the Hyper-Angular Rainbow Polarimeter #2 (HARP2), a multi-angle polarimeter that measures properties of aerosols and clouds, along with ocean and land surface features. HARP2 measures the polarization of light reflected off atmospheric particles, liquid droplets, and surfaces from multiple viewing angles, providing more detail about their properties than was previously available.

Aerosols are tiny liquid and solid particles suspended in the atmosphere, originating from sources such as dust storms, sea spray, wildfire smoke, and volcanic ash. They influence cloud formation, weather patterns, and Earth's radiation balance, affecting many aspects of daily life.

Aerosols play a direct role in precipitation processes, serving as cloud condensation nuclei (CCN). Depending on their size and concentration, aerosols can either enhance or suppress rainfall, directly impacting water availability and weather predictability. Monitoring aerosols from sources like wildfire smoke, volcanic ash, and windblown dust is also critical for transportation safety. In the air, these particles can obstruct pilot visibility and disrupt flight operations, while on the ground, they can reduce visibility for drivers, leading to hazardous road conditions.



Credit: Martins, UMBC, CC BY-ND (modified). Source: www.eoportal.org/satellite-missions/harp#polarimeter-specifications

Aerosol monitoring is also important for economic stability. In agriculture, anticipating smoke or dust events that could block sunlight or harm crops enables farmers to take proactive measures, such as adjusting irrigation or implementing dust suppression. For the workforce, smoke and dust forecasts help minimize exposure-related illnesses, lowering healthcare costs and absenteeism, resulting in greater productivity and reduced labor costs. Understanding the behavior of aerosols is essential for improving weather forecasts and informing decision-making across many economic sectors.

Atmospheric aerosols are constantly transforming and moving. Factors such as shape, size, and distribution influence their behavior, making detailed spatial and temporal characterization essential for understanding and mitigating their broader impacts. Their high variability, however, presents significant challenges for space-based observation.

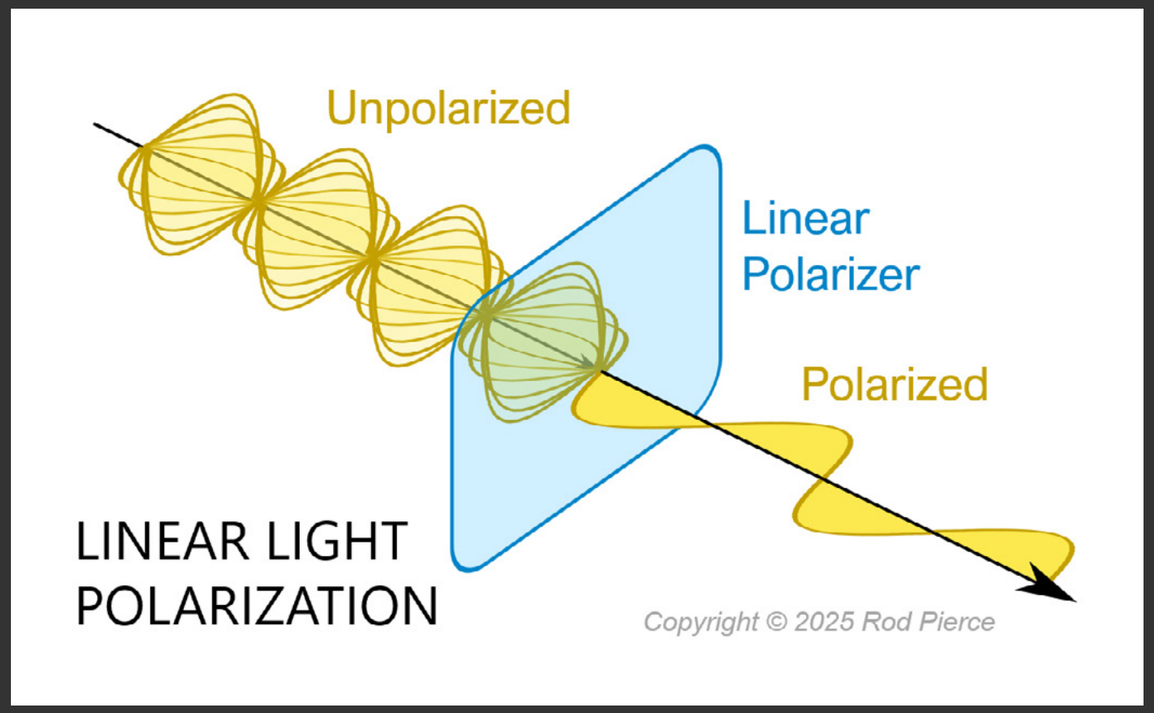
Multi-angle polarimetry is recognized as "one of the most promising types of remote sensing for improved characterization of atmospheric aerosols." HARP2 leverages this technology, retrieving atmospheric and surface observations from multiple viewing and polarization angles in different wavelengths. This enhanced data improves our ability to assess the impact of aerosols on weather patterns, weather-driven airborne hazards, and atmospheric processes, leading to better forecasts and improved public safety.

Tiny Particles, Big Impact

Aerosol observations from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard NOAA's Joint Polar Satellite System (JPSS) missions are among the many data assimilated into numerical weather prediction (NWP) models used by the National Weather Service to forecast future weather. These data improve the models' representation of aerosols in the atmosphere, which in turn can lead to more accurate forecasts of air quality, temperature, precipitation, and other meteorological conditions. The PACE HARP2 instrument provides a valuable independent dataset to verify and validate VIIRS aerosol data, strengthening confidence in the predictions of NWP models.

Polarization: Transforming Light

Polarized light is a type of light in which all the waves vibrate in the same direction, unlike unpolarized light, where the waves vibrate in many directions. Polarized light is produced when normal (unpolarized) light—such as light from the sun or an incandescent lamp—is transformed so that vibrations occur on a single plane.



HARP2 operates on the principle of linear polarization, using a specialized filter that absorbs all light waves except those oscillating in a specific plane, producing an electric field aligned in a single direction.

From Inspiration to Orbit

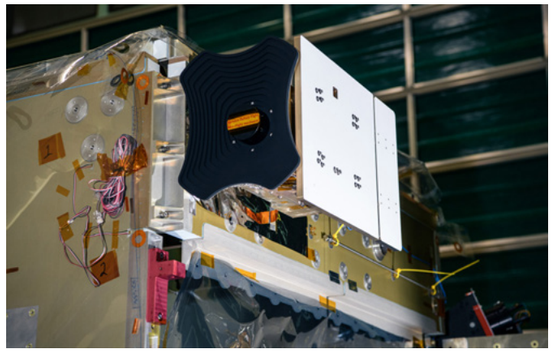
For more than a decade, J. Vanderlei Martins, Ph.D., Director of the Earth Space Institute (ESI) at University of Maryland, Baltimore County (UMBC), has led the development of the HARP instrument series, from the original AirHARP and HARP CubeSat prototypes to the HARP2 sensor on PACE. The idea behind these polarimeters began during a flight over the Pacific Ocean, where Martins, looking out the window, placed a polarizer over his camera lens and noticed rainbows in the clouds. That simple observation set the direction for the future of HARP.

The core HARP team, (l to r) Vanderlei Martins, Roberto Borda, and Dominik Cieslak, with the HARP CubeSat instrument. Photo: Marlayna Demond for UMBC.

Martin's vision first took shape with AirHARP, an aircraft-mounted prototype that flew in 2017 on NASA's UC12 and ER-2 aircraft during the Lake Michigan Ozone Study (LMOS) and the Aerosol Characterization from Polarimeter and Lidar (ACEPOL) field campaigns. These flights helped verify the instrument's performance and provided data to improve the technology—a critical step toward preparing HARP for spaceflight.

Building on AirHARP's success, the UMBC team scaled the technology into HARP CubeSat, a satellite about the size of a loaf of bread. Deployed from the International Space Station in 2020, HARP CubeSat spent 777 days in low Earth orbit, successfully validating its optical system and producing valuable data to refine algorithms and guide future missions. In recognition of these achievements, the American Institute of Aeronautics and Astronautics (AIAA) named it the 2020 SmallSat Mission of the Year.

HARP2 marks the next advancement in this series, building on AirHARP and HARP CubeSat while benefiting from PACE's greater power and data capacity. Optimized for near-continuous, global operation, HARP2 measures the optical and microphysical properties of atmospheric aerosols, including size distribution, amount, refractive indices, and shape. It uses a wide-angle lens to combine data from up to 90 along-track viewing angles (60 in the red spectral channel, and 10 each in the blue, green, and near-infrared channels), all without moving parts. "Each angle measures three different [linear] polarizations, so it's a big dataset coming from a small instrument—you can basically hold it in your hand," Martins explained at a LEO Science Seminar. What began as curiosity at 30,000 feet is now a critical part of PACE's mission to deepen our understanding of Earth's atmosphere and oceans.



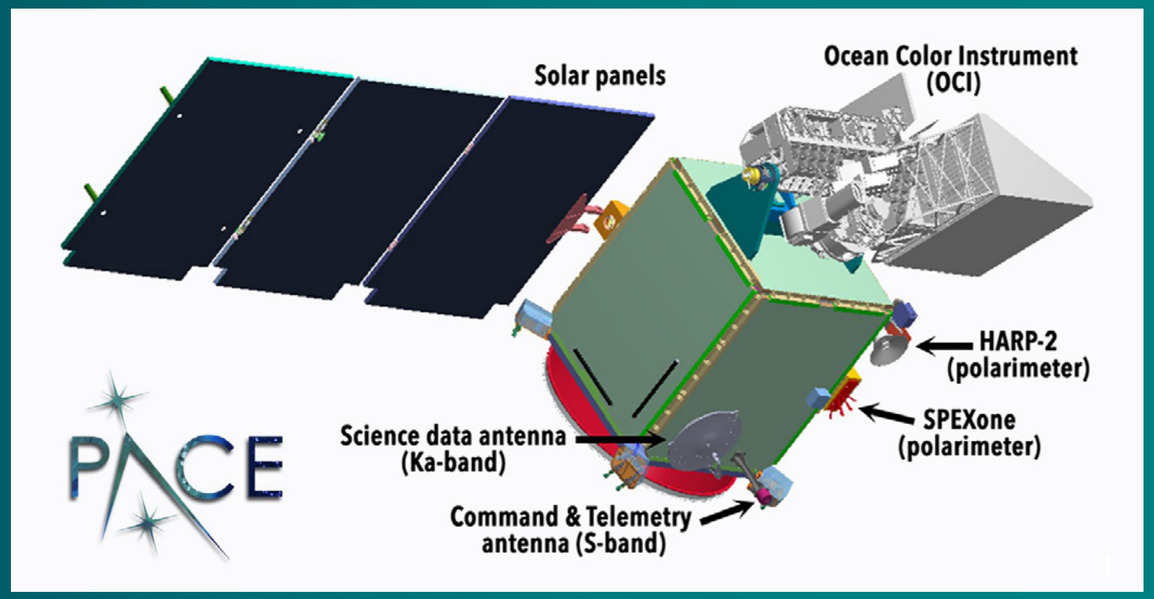
Integration of the HARP2 instrument onto the PACE spacecraft. Photo: NASA Goddard Space Flight Center.

Complementary Insights: The Three Instruments of PACE

PACE carries three advanced instruments designed to provide a comprehensive view of Earth's oceans and atmosphere: the Ocean Color Instrument (OCI), the Spectro-polarimeter for Planetary Exploration (SPEXone), and HARP2. At the heart of the mission is OCI, an advanced radiometer that measures radiance across a wide spectral range, from ultraviolet to shortwave infrared. This expansive coverage enables detailed observations of ocean color, offering new insights into phytoplankton abundance and distribution, dissolved organic matter, surface reflectance, and other ocean parameters, while also supporting atmospheric measurements. OCI is poised to provide unprecedented detail about global oceanic processes, helping us to better understand the complex systems that drive ocean ecology.

Complementing OCI are two multi-angular polarimeters, HARP2 and SPEXone, which measure both light intensity and polarization—an essential feature for more detailed and accurate aerosol and cloud characterization. Although both sensors serve similar purposes, their distinct specifications make them suited to different, yet complementary, applications. HARP2 features a wide 1,556 km swath at nadir and retrieves data from up to 90 viewing angles spanned in four spectral bands. SPEXone, by contrast, observes over a narrower 100 km swath using five viewing angles, but it provides hyperspectral resolution across a broad spectral range from ultraviolet to visible wavelengths. Both sensors also support atmospheric correction to improve the accuracy of OCI's measurements.

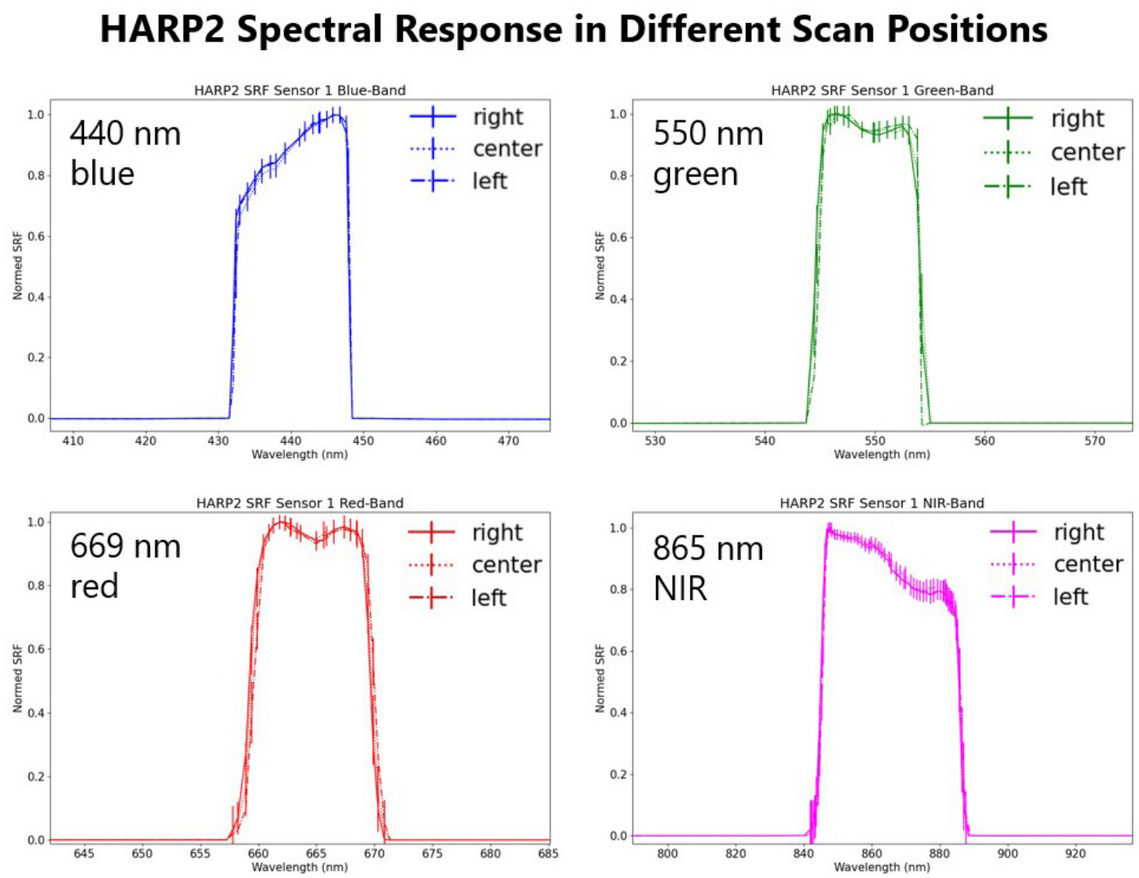
With their combined strengths and the ability to achieve full global coverage every two days, the three instruments aboard PACE work synergistically to deepen our understanding of complex global atmospheric and oceanic processes and interactions.



Many Perspectives, All at Once

As PACE orbits Earth, the HARP2 instrument captures views from multiple angles at four different wavelengths and three polarization states at once. "It's a lot of information that you get simultaneously," Martin emphasizes. The sensor constantly looks forward, backward, and all directions in between, covering a 1,556-kilometers (km) swath at nadir, which gives it a very wide field of view.

This wealth of data is collected in four spectral channels: blue (440 nanometers (nm)), green (550 nm), red (670 nm), and near-infrared (870 nm). Each target is observed from up to 60 along-track viewing angles in the 670-nm channel for clouds and from 10 angles in the other three bands for aerosols. This "hyper-angular" coverage enables HARP2 to distinguish subtle variations in how atmospheric particles scatter light, revealing details about their shape, size, type, and other characteristics.



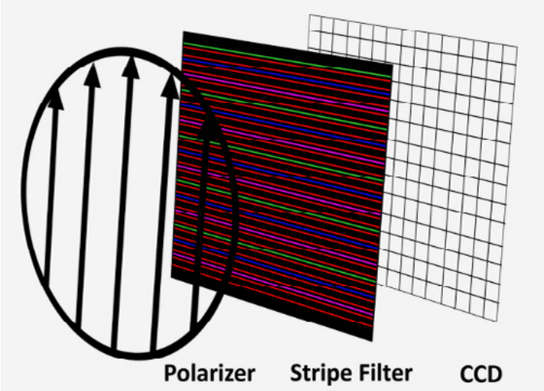
Extensive calibration has been performed across the entire HARP2 system to ensure accurate characterization of every portion of its very wide field of view, which is illustrated here. These figures display the spectral response at different field of view positions (right, center, and left) for each of HARP2's four spectral channels, demonstrating that—by design—the spectral response remains uniform across all viewing angles, ensuring that measurements taken from different parts of the field of view are indistinguishable. This approach provides a well-distributed spectral response across the detector, enhancing the reliability of the instrument's observations. Figure courtesy of Vanderlei Martins.

The Orientation of Oscillations

Light travels as electromagnetic waves, made up of magnetic and electric fields oscillating in different directions. The polarization state of light describes the orientation of the electric field oscillations. In linearly polarized light, the electric field oscillates along a specific, fixed direction within a single plane perpendicular to the direction of wave propagation. This principle is central to HARP2's design, which measures the linear polarization state of light at different orientation angles. For example, if light has a polarization state of 45 degrees, its electric field oscillates at a 45-degree angle relative to a reference direction.

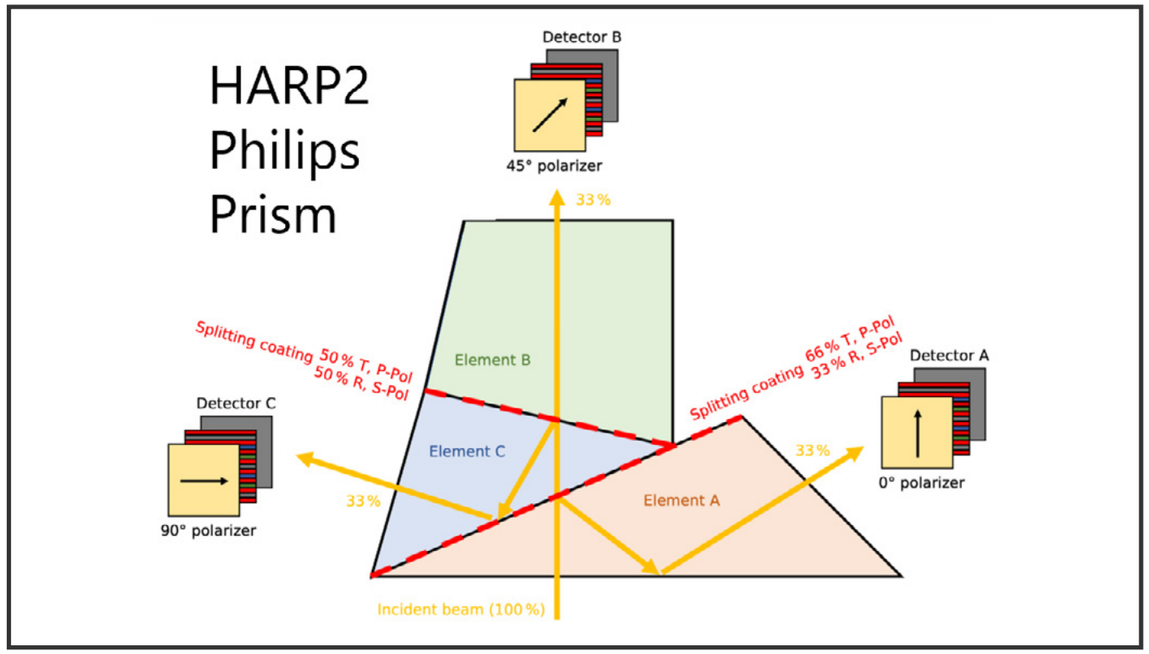
A defining feature of HARP2 is its ability to measure the polarization state of light from different viewing angles. Sunlight enters the atmosphere unpolarized, and as it interacts with molecules, aerosols, and larger droplets, it scatters in various directions. During this process, the electric field oscillations become preferentially aligned, leading to partial polarization. This change becomes more pronounced when observed from different angles, which HARP2 is designed to capture. Different types of aerosols scatter light differently, altering its polarization in distinct ways that HARP2 can measure.

Achieving this requires a "division of amplitude" method, where refractive optics split the polarization components of a light beam. This process begins as scattered sunlight enters HARP2's front lens and is guided to a modified Philips prism, which divides the beam of light into three paths, each directed toward a linear polarizer oriented at 0°, 45°, or 90°. After passing through the polarizers, the light travels through a stripe filter that separates it by wavelength and viewing angle for each pixel. The light then reaches a Charge-Coupled Device (CCD) detector focal plane array (FPA), which converts it into an electrical signal that is processed to create an image. This approach allows HARP2 to simultaneously capture images in three polarization states in all four spectral channels.

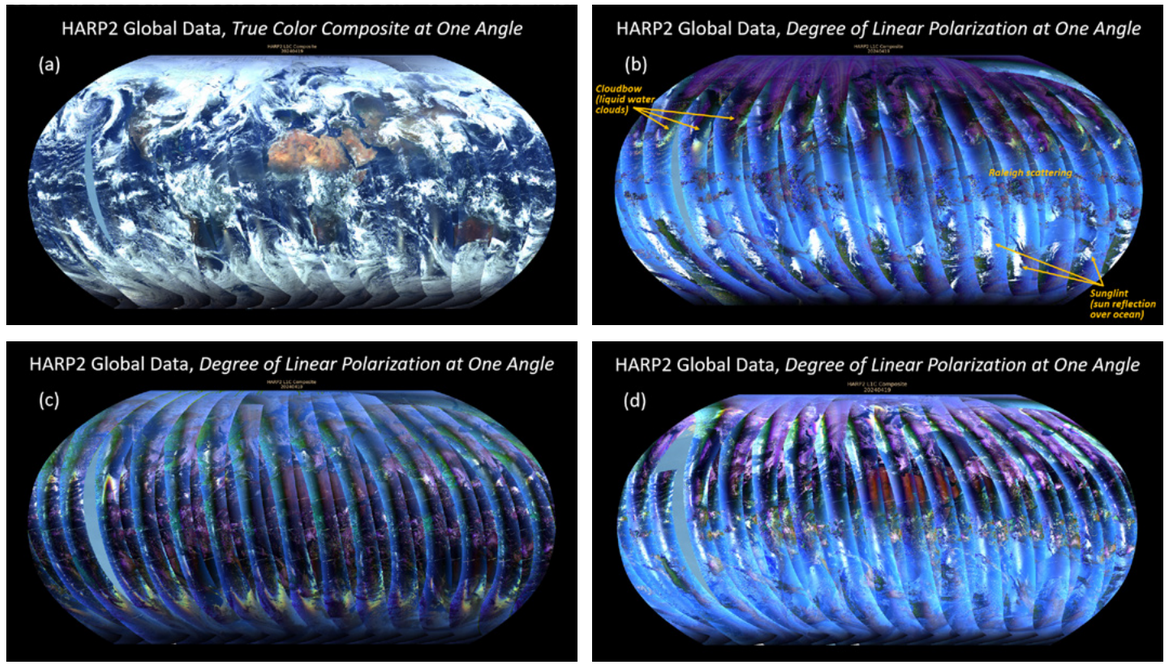


Data from the HARP2 optical path enters three separate detectors—a polarizer, stripe filter, and CCD—which have a structure as shown here.

Bringing this into context, Martins explains, "The information that you get from polarization is completely different from the information that you get from intensity [true color RGB imagery]," noting that "the information changes completely" with each viewing angle. This is illustrated in the composite polarization images at the bottom of the next page (panels b, c, and d), where data captured on the same dates from different view angles reveals distinct details from each perspective. HARP2's multi-angle capability provides a powerful advantage in characterizing atmospheric aerosols, clouds, and surface features with unprecedented detail.



The modified Phillips prism in HARP2 consists of three elements (A, B, and C) and two splitting coatings. An incident beam of light (100%) enters the prism and is split by the coatings. One coating splits the beam into 50% transmission (T) of P-polarized light and 50% reflection (R) of S-polarized light. The other coating splits the beam into 66% T of P-Pol and 33% R of S-Pol. The resulting beams are then directed to detectors A, B, and C, each with a polarizer at 0°, 45°, and 90°. Each detector receives 33% of the initial light beam. Image: McBride et al (2024), CC BY 4.0.



Click image to enlarge. *Panel (a): A true color RGB composite (Level 1C) shows unpolarized top-of-the-atmosphere radiance from a single viewing angle for April 18-19, 2024. Using HARP2's red, green, and blue channels, the image simulates what the human eye would see from space, with each channel capturing a different intensity of visible light to produce natural-looking imagery. Panels (b,c,d): The degree of linear polarization (DoLP) (Level 1C) for different view angles on April 18-19, 2024. Note in panel (b), the DoLP map emphasizes the direct reflection of the Sun off the ocean surface, the blue haze from light scattered by atmospheric molecules (Rayleigh scattering), and the cloudbow, a rainbow-like signal that originates from liquid water cloud droplets. Credit: Anin Puthukkudy/UMBC ESI.*

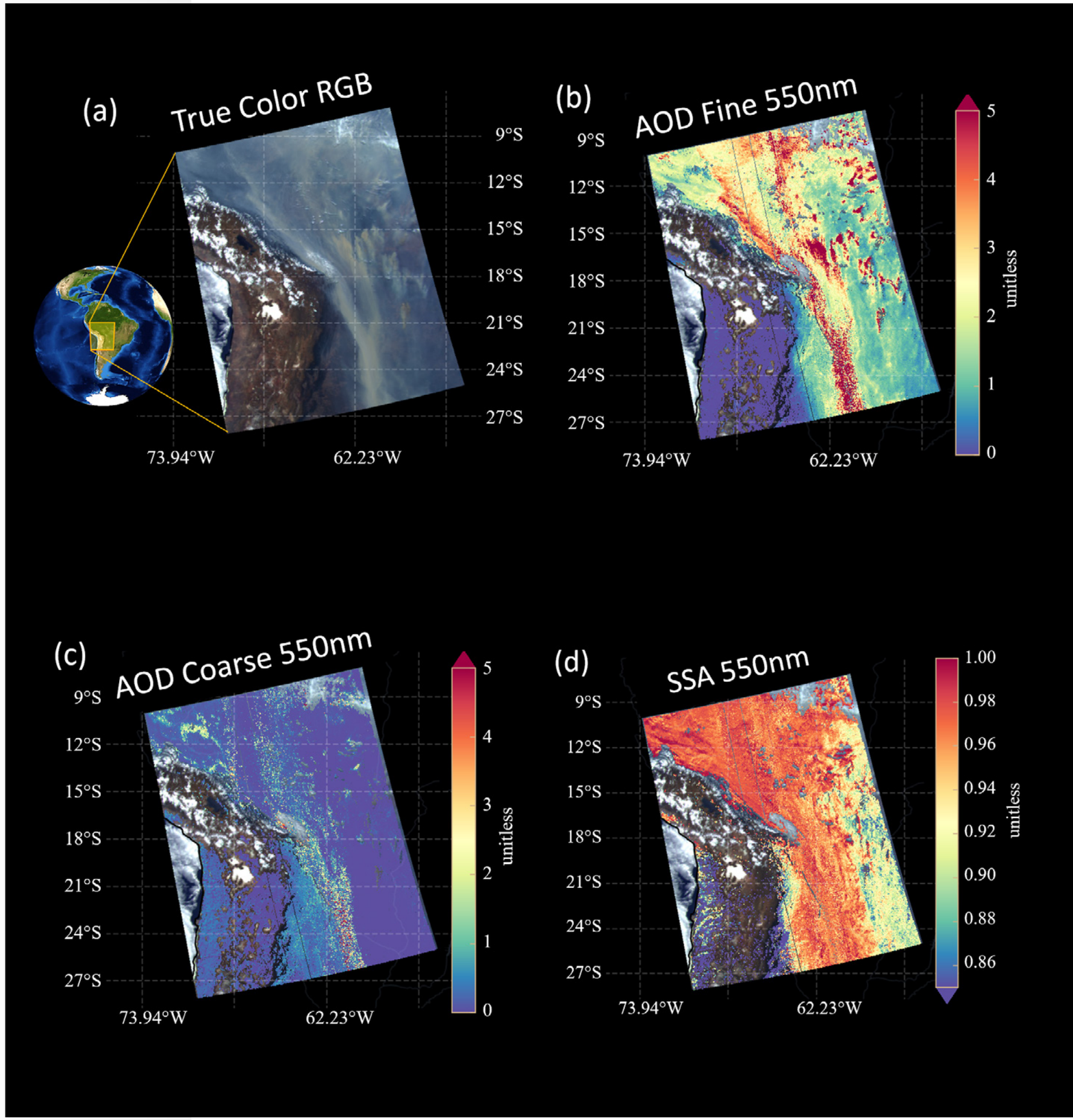
A Closer Look at Aerosol Retrievals

HARP2's multi-angle polarization measurements provide valuable data for generating key aerosol products such as aerosol optical depth (AOD) and single scattering albedo (SSA). AOD, also known as aerosol optical thickness (AOT), quantifies how much sunlight is blocked by aerosols through scattering and absorption in the atmosphere, with higher values indicating more particles and hazier conditions. Because AOD can be used as a proxy for fine particulate matter, it serves as a useful tool for air quality forecasting and has important public health and safety applications, including monitoring wildfire smoke and dust storms.

The SSA, in contrast, quantifies the ratio of scattered light to total light extinction (scattering plus absorption) by aerosols. It is an important parameter for identifying different aerosol types and understanding their local radiative effects—for example, distinguishing between light-scattering particles like dust, which cool the atmosphere, and light-absorbing particles like black carbon, which have a warming effect. SSA measurements are essential for understanding the influence of aerosols on Earth's energy balance and for reducing uncertainties in global radiative forcing models.

Martins and his team at UMBC are actively developing AOD, SSA, and other aerosol products from HARP2 data. While initial Level 2 aerosol retrievals are preliminary, the team is making steady progress. "We are still fine-tuning calibration and fine-tuning our cloud masks," Martins explains, noting that reducing cloud contamination, one of the main challenges in aerosol retrievals, is an ongoing effort. Although there is currently no official HARP2 Level 2 product over land and no dedicated funding for this work (as of April 2025), Martins continues to push forward with development as resources allow, with the long-term goal of providing reliable Level 2 aerosol products to the research and operational communities.

The images to the right offer a preview of the expected aerosol products from HARP2, using wildfire smoke over South America as an example. In panel (a), the smoke plume is visible in true color imagery as a brown haze. Panels (b) and (c) show AOD at 550 nm, separated by particle size: fine mode in panel (b) and coarse mode in panel (c). "You can see smoke is dominating in the fine mode, but we can retrieve both [fine and coarse]," says Martins. "The multi-angular polarization allows us to have a measurement of size distribution," he adds. Panel (d) displays SSA at 550 nm, where reddish-orange colors indicate values near or at 1.0, meaning the light interacting with the particles is almost entirely scattered and almost none is absorbed. This kind of detail is crucial for understanding how aerosols interact with sunlight and affect local air quality and the global radiative balance.

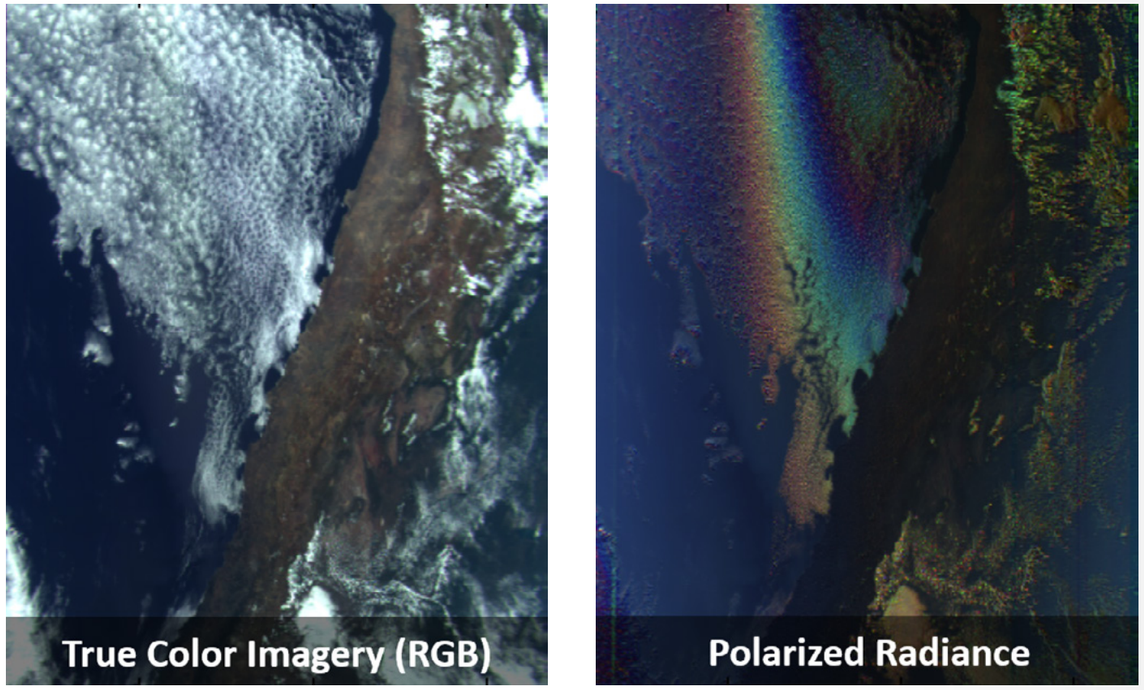


Viewing Clouds in Exceptional Detail

Complementing its advanced aerosol characterization capabilities, HARP2 provides exceptionally granular measurements of cloud droplets, revealing details that were previously unattainable. “We can do measurements such as cloud droplet effective radius and droplet size distribution,” explains Martin, adding “that kind of measurement has been done before, but in very, very coarse scale.” Unlike other multi-angle polarimeters, HARP2 measures at the pixel level, delivering high-resolution data made possible by its hyper-angular imaging capability. “No other instrument has done that before from space,” Martin says. This innovative approach allows scientists to analyze clouds in remarkable detail, including the state of water particles within a cloud, such as whether they are liquid, ice, or a mixture of both. It also provides information on droplet size distribution. Both are key factors in understanding and tracking how precipitation develops.

Measuring the Cloudbow: A Polarimetric Example

Clouds consist of countless water droplets of various shapes and sizes. The range and distribution of droplet sizes within a cloud strongly influences its optical and microphysical processes, affecting how it scatters or absorbs radiation, how it evolves, and when precipitation forms. For instance, rain tends to develop more quickly in clouds with a wider range of droplet sizes, where droplets are more likely to collide and coalesce, producing droplets large enough to fall as precipitation.



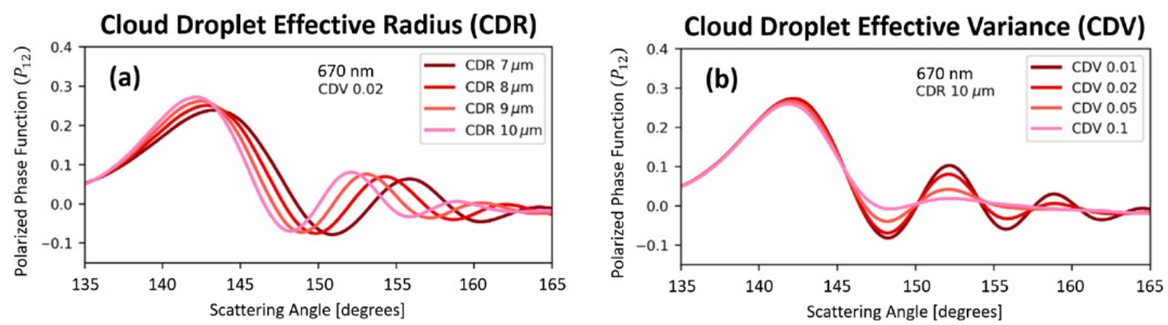
Observations from HARP2 captured cloud structures along the west coast of South America on March 11, 2024. The left image shows true color imagery, created from HARP2’s red, green, and blue (RGB) channels to approximate what the human eye would see, with each color channel representing a different intensity of light within the visible spectrum. In contrast, the right image displays polarized radiance for the same scene, revealing a cloudbow. Imagery courtesy of Vanderlei Martins.

Droplet size and the width of the size distribution are quantified by measuring the polarized radiance of the cloudbow—a rainbow-like optical phenomenon caused by sunlight scattering off cloud droplets. In true color imagery (previous page, left), which mimics what humans see, clouds appear as wisps of white. But when the same scene is viewed through a polarized filter (previous page, right), a cloudbow appears. As Martins explains, “We cannot see [the cloudbow] with our eyes, but as soon as you switch to polarization the information jumps out.” This feature makes the cloudbow an ideal target for HARP2’s polarimetric measurements.

By analyzing the angular distribution of the cloudbow polarization signal, scientists can retrieve two key cloud parameters: cloud droplet effective radius (CDR) and cloud droplet effective variance (CDV). CDR is the weighted mean radius of droplets within a cloud, while CDV quantifies the spread or breadth of the cloud droplet size distribution. Together, CDR and CDV provide crucial insight into cloud growth and their potential for precipitation, helping improve how numerical weather prediction models simulate complex cloud microphysics—ultimately leading to more accurate forecasts.

Retrieving CDR and CDV from low Earth orbit requires a multi-angle polarimeter with high viewing angle resolution. HARP2’s 670-nm red channel is well-suited for this purpose, with 60 unique view angles that can sample at high angular density. This fine viewing angle separation and HARP2’s wide field of view enables clear detection of cloudbow oscillations within the polarized cloudbow scattering angle range of 135 to 165 degrees. The figures below, based on theoretical Mie scattering simulations that mimic a polarized cloudbow, demonstrate HARP2’s hyper-angular capability to collect these measurements.

Panel (a) shows polarized reflectance as a function of the angle at which red light (670 nm) is scattered by liquid water cloud droplets with a narrow size distribution (CDV = 0.02). The cloudbow oscillations are well defined, with their spacing and width increasing as droplet radius grows from 7 to 10 microns (μm). The positions of the peaks determine the CDR. Martins notes, “By measuring the difference between the peaks, we can tell the size of the droplet with very high accuracy.” Larger droplets have a greater chance of becoming heavy enough to initiate rainfall.



Click images to enlarge. *Theoretical Mie scattering simulations for liquid water cloud droplets, with solar light incident, for (a) the 670-nm channel for variable CDR and constant CDV, and (b) constant CDR with variable CDV. Credit: McBride, B.A. et al. 2020.*

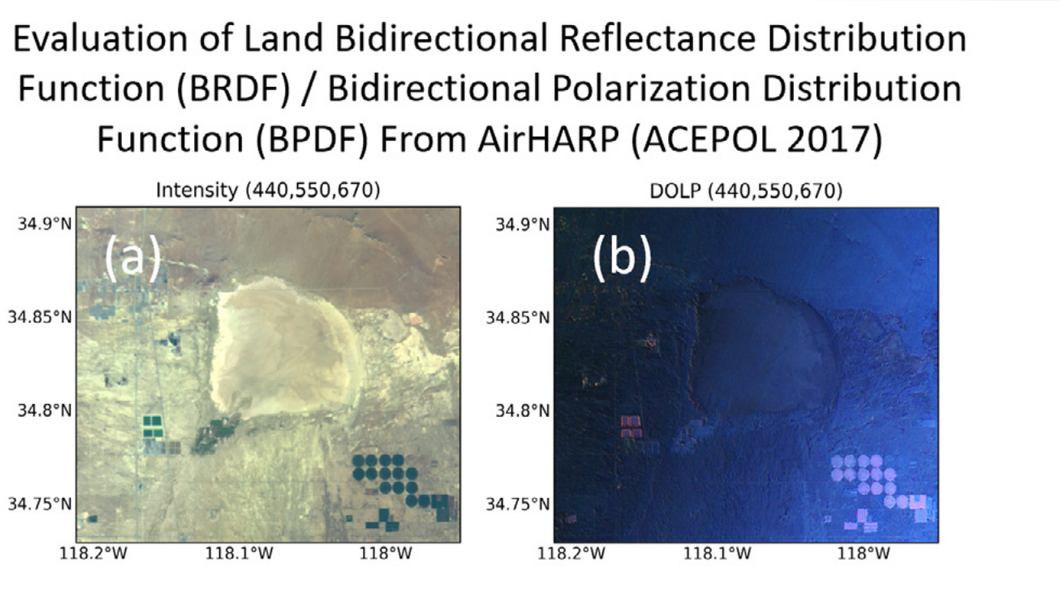
For CDV, the amplitude of the cloudbow structure is measured. Panel (b) (previous page) depicts polarized reflectance in relation to scattering angle for red light scattered by liquid cloud droplets with a large effective radius (CDR = 10 μm). As scattering angle increases, the bow begins to erode and oscillations flatten, indicating wider droplet size distributions and higher CDV values. A high CDV suggests a broader range of droplet sizes, which can enhance cloud growth and increase the likelihood of precipitation. In contrast, a low CDV reflects a narrower, more uniform size distribution, typically associated with less efficient rainfall formation.

The sensitivity of oscillation patterns to droplet size and size distribution highlights the value of HARP2's hyper-angular polarimetric observations for forecasting, and early data are promising. "Retrieval is very, very accurate as it is right now," says Martins. "It is very good for science applications, but there will be improvements." These capabilities mark a significant step forward in space-based cloud microphysics, which plays a crucial role in operational numerical weather prediction.

Below the Atmosphere: Characterizing Surface Features

The advanced algorithms that HARP2 employs to retrieve atmospheric aerosol parameters also enable the simultaneous retrieval of selected land surface and ocean properties. "We can get a lot of properties from the surface because of [HARP2's] angular measurements," Martins explains, which provides valuable data for characterizing surface conditions and dynamics.

Over land, these measurements offer insights into land cover usage and change, distinguishing features like deserts, urban areas, and different vegetation types, such as forests and grasslands. Over the ocean, HARP2 can detect surface roughness for estimating ocean wind speed and



Example land retrievals from the AirHARP instrument during the 2017 ACEPOL campaign. The images show color composites of intensity (a) and degree of linear polarization (DoLP) (b), derived from AirHARP's 440-, 550-, and 670-nm bands, over Rosamond Lake, a natural dry lake bed in the Mohave Desert, on October 25, 2017. Land reflectance in terms of DoLP indicates how much the reflected light is polarized, providing information about surface properties. These measurements preview the type of data expected from HARP2 as its products are developed. Imagery courtesy of Vanderlei Martins.

direction, and measure changes in the ocean's refractive index, which can indicate the presence of non-seawater substances like oil on the water's surface. These capabilities support a wide range of environmental monitoring applications.

Although HARP2's land surface and ocean properties data products are not yet available, their potential to generate valuable surface characterization data is clear. With HARP2 operating alongside the other instruments aboard PACE, scientists have an unprecedented opportunity to improve our understanding and representation of atmospheric and surface conditions.

Perspective

HARP2's unique ability to simultaneously capture spectral, angular, and polarization data from multiple angles provides a level of detail that surpasses traditional satellite sensors. This ability supports a wide range of public safety, human health, transportation, and economic applications, helping decision-makers assess weather-driven airborne hazards, manage wildfire smoke impacts, and reduce disruptions to sectors such as agriculture, shipping, and commercial air travel that are sensitive to reduced visibility and atmospheric conditions.

Though early in its mission, HARP2 is performing well and surpassing expectations in orbit. "We have not identified a single failure so far from our system by itself," Martin notes proudly. "We only expect the retrievals to get better and better; we're very happy with the performance." The UMBC team continues to refine the instrument's retrievals through ongoing improvements in geolocation, as well as radiometric and polarimetric calibrations.

As for data products, Martins confirms that HARP2 data has "achieved a level that allows for Level 2 data product production," marking a key milestone in its readiness for scientific use. An aerosol product over the ocean is already in development at NASA's Goddard Space Flight Center, and while there is currently no formal funding for over-land products, the UMBC team is working to develop them and move toward operational readiness. With a strong commitment to continuous improvement and a growing suite of products on the horizon, HARP2 is well on its way to becoming an operational asset—one that promises to deepen our understanding of Earth's atmosphere and deliver lasting value to Americans, the economy, and decision-makers alike. ✦

Learn More

Learn more about HARP2's technical details and view images of its construction on the PACE website.

Explore this peer-reviewed journal article for insights into early in-flight performance trends and UMBC's approach to on-orbit calibration.

Discover current and upcoming data products from HARP2 and the other instruments aboard PACE.

Story Source

The information in this article is based, in part, on the October 21, 2024, LEO Science Seminar, "HARP2 overall on-orbit performance, and potential applications," presented by Dr. J. Vanderlei Martins, Director of the Earth and Space Institute (ESI) at University of Maryland-Baltimore County (UMBC), with contributions from Dr. Xiaoguang (Richard) Xu (ESI/UMBC), Dr. Roberto Fernandez-Borda (ESI/UMBC), Noah Sienkiewicz (ESI/UMBC), Dr. Anin Puthukkudy (ESI/UMBC), Rachel Smith (ESI/UMBC), Dr. Brent McBride (ESI/UMBC), Dr. Oleg Dubovik (University of Lille, France), Greema Regmi (ESI/UMBC), Nirandi Jayasinghe (ESI/UMBC), and Dr. Lorraine Remer (ESI/UMBC).

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Guest Contributions:
From the Desk of our Intern

Charlotte Krisetya was one of several 2025 NOAA/NESDIS Office of LEO Observations summer interns, participating through the NOAA William M. Lapenta Student Internship Program. A junior at the University of Maryland, College Park, Charlotte is majoring in Environmental Science and Policy with a concentration in Marine and Coastal Management. Her academic and career interests include sustainability, marine conservation, and ecosystem management, with a growing passion for science communication and environmental advocacy.

As part of her Lapenta internship, Charlotte explored how data from the Joint Polar Satellite System (JPSS) can support early wildfire detection in California and improve forecasting and monitoring of cascading environmental effects. Her work culminated in the following article for the 2025 LEO Science Digest, where she highlighted the role of JPSS observations in understanding fire risk and post-fire landscape change. Throughout her internship, Charlotte engaged with experts in remote sensing, wildfire science, and agriculture, deepened her understanding of satellite data products, and gained insight into the broader mission of NOAA and NASA.

"This internship has been an exciting opportunity to expand on my foundational knowledge of remote sensing and explore its real-world applications," she shared. "I've enjoyed learning about how JPSS impacts people's lives, and it has strengthened my interest in pursuing a career in the environmental field to help people."

The William M. Lapenta Internship Program is a competitive 10-week paid summer internship for undergraduate and graduate students majoring in STEM fields. Interns are placed across NOAA Line Offices and work on projects under the guidance of NOAA scientists and mentors. The program aims to provide hands-on experience with NOAA's mission, helping students develop skills, professional networks, and a clearer vision of potential career paths. Charlotte's experience is one of many that illustrate how the program prepares future scientific leaders to contribute meaningfully across research, policy, and applied science fields.

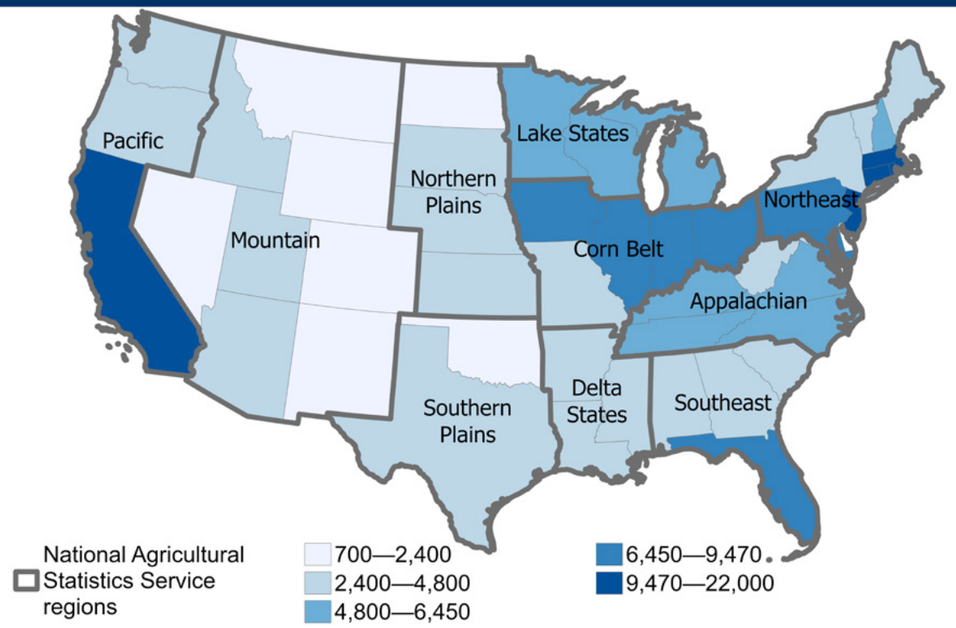
Cascading Impacts:

LEO Insights into the Effects of Wildfires on California Agriculture

Charlotte Krisetya | 2025 NOAA Lapenta Intern

An aerial view of a vineyard shows parallel rows of grapevines leading toward distant hills under late-afternoon sunlight. Credit: iStock/Dennis Swanson - Studio 101 West Photography.

U.S. farm real estate values per acre by State, 2024



Note: Farm real estate data includes land and buildings. Data reflect values as of June 1 of each year in U.S. dollars, U.S. estimates exclude Alaska, Delaware, and Hawaii. Economic regions are determined by USDA, National Agricultural Statistics Service.

Source: USDA, Economic Research Service using 2024 State agricultural land value estimates from USDA, National Agricultural Statistics Service, Quickstats.

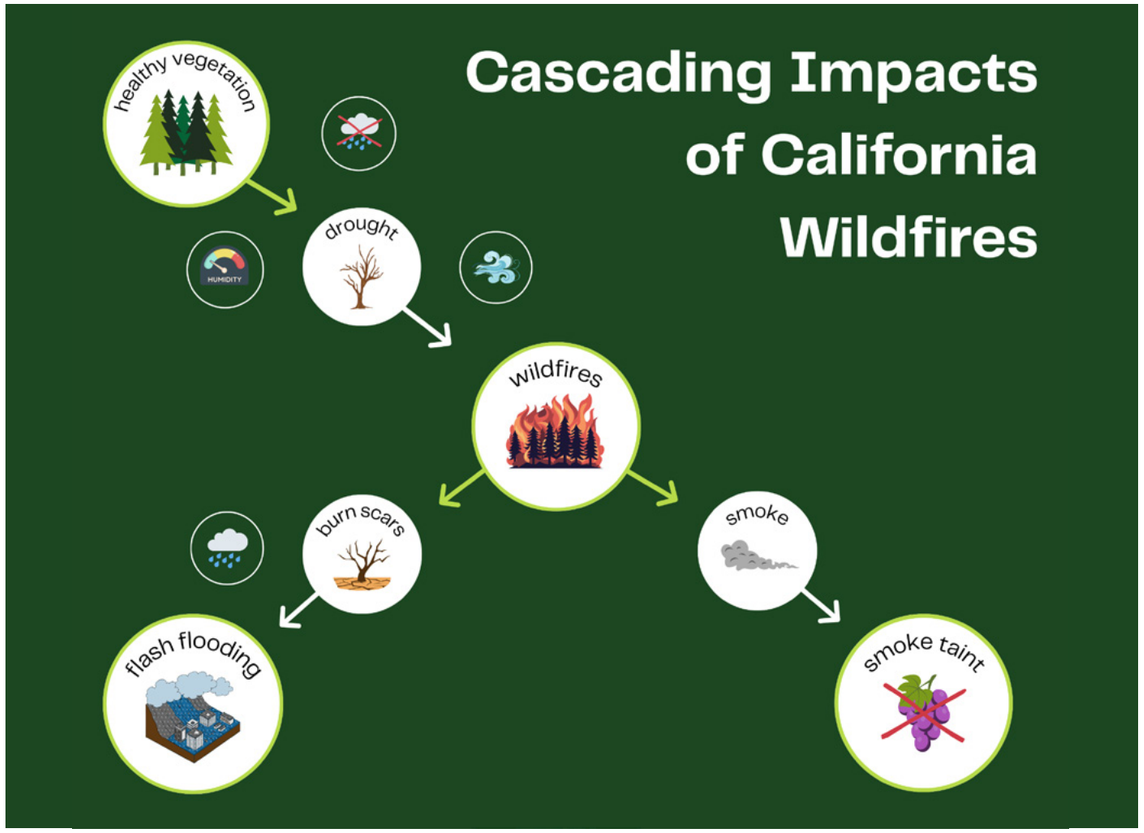
Wildfires are important to the natural cycle of the environment. They are imperative for clearing dead vegetation, stimulating new plant growth, and assisting in seed dispersal for coniferous trees. However, when fires grow out of control, they can impact the surrounding communities and valuable agricultural lands. The U.S. agricultural sector supplies products that support every citizen across the U.S. through direct consumption, material for industry, or export business. In 2024, according to the U.S. Department of Agriculture (USDA) Farms and Land in Farms Summary, the U.S. had nearly 877 million acres of farmland with California making up 23.7 million acres. California's agricultural industry produces more than a third of the country's vegetables and three quarters of the country's fruits and nuts, resulting in the highest farmland value in the U.S.

Some of California's most valuable commodities include dairy products, grapes, almonds, durum wheat, and other vegetables and fruits. California is also the biggest contributor to the U.S. wine market, responsible for 80 percent of the U.S. wine production. The California wine industry generates $170.5 billion annually in economic activity, employing 1.1 million Americans and paying $59.9 billion in wages annually. Protecting California's agricultural industry from uncontrolled wildfires is vitally important for preserving farm jobs, securing the nation's food supply, and supporting the broader U.S. economy.

Land loss due to wildfires can impact the stability of the agricultural sector and the people that rely on their products, as well as those responsible for agricultural production. Crops can be damaged by direct fire exposure and contamination from smoke. Fires often cause decreased yields, changes to crop taste, and decreased growth. Analyzing wildfires and smoke using data from instruments onboard the Joint Polar Satellite System (JPSS) satellites helps support farmers, scientists, and other stakeholders in understanding the factors driving these events and their cascading impacts. This information also supports improvements to warning systems that can help protect valuable lands to ensure agricultural productivity.

Southern California's Fires of 2025

In early 2025, California experienced some of the most destructive fires on record, two of which were the Palisades and Eaton fires. These fires had widespread effects that impacted the population and land of the area. The fires were fueled by the low humidity, dry vegetation, and strong Santa Ana winds (SAWs). Low humidity means that the air is drier due to low atmospheric water vapor, making conditions more suitable for fire. Similarly, dry vegetation has low water content making it more flammable. Large amounts of dry vegetation contribute to an ideal wildfire



Santa Ana Winds

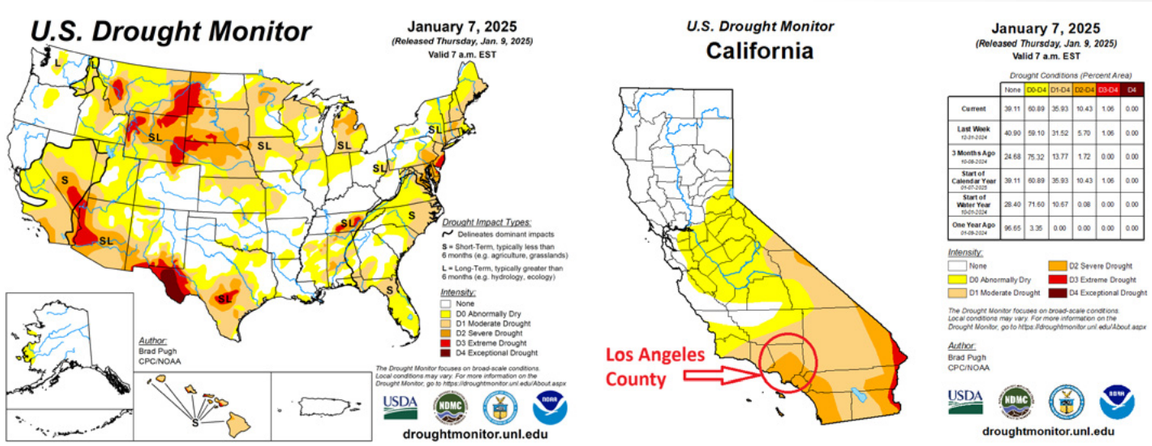
The Santa Ana winds blow from east to west through Southern California's coastal ranges, often in September through May. The region's topography and air pressure are the main drivers of the winds. The Great Basin, primarily located in Nevada, is a high elevation desert and a central high air pressure system. Southern California's low-pressure system is subject to these strong, dry winds that blow from the Great Basin from high to low pressure. The dryness and speed of these winds are particularly dangerous for wildfire spread.

Image source: USGS.

environment. Winds can be dangerous in fire situations as they push the flames, increasing their spread. In particular, the SAWs are characterized by their dry, hot air and high wind speeds, creating conditions optimal for wildfire growth.

Connecting Drought and Wildfires

In the months prior to the 2025 wildfires, much of Southern California was experiencing severe to extreme drought, in part due to a lack of precipitation. The lack of precipitation caused the dry vegetation that, along with the low humidity and SAWs, fueled the Palisades and Eaton fires that sparked in early January 2025. The severe drought conditions are shown in the U.S. Drought Monitor map below. The U.S. Drought Monitor is a compilation of many environmental data sets that allow classification of a land area into five categories of conditions: abnormally dry (area may become in drought or coming out of drought conditions), moderate drought, severe drought, extreme drought, and exceptional drought.



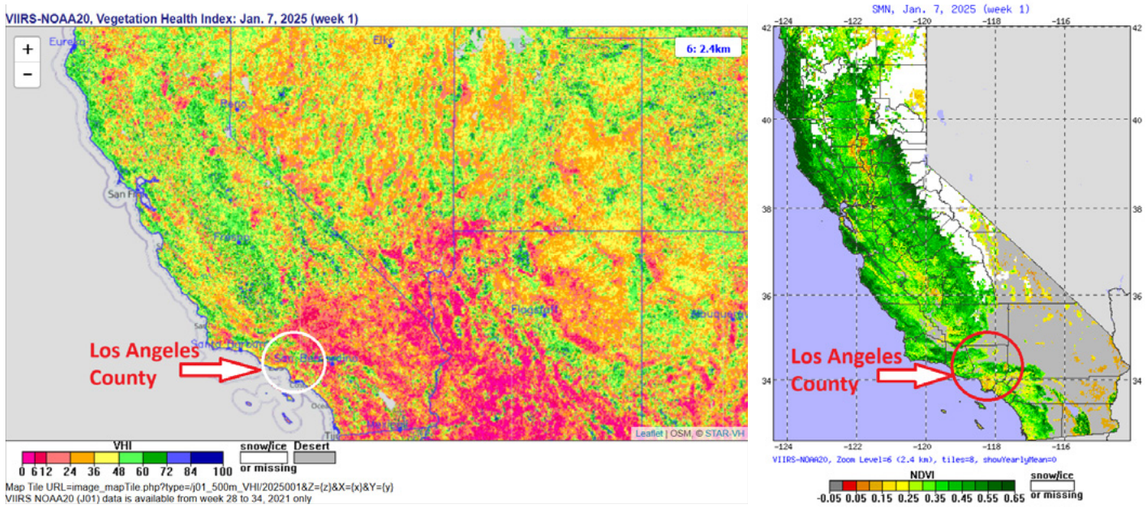
Click images to enlarge. *U.S. Drought Monitor map for January 7th, 2025. Looking at the coast of Southern California, primarily Los Angeles County, the darker orange color (D2), denotes severe drought conditions. The level of drought can be used as an indicator for vegetation health and for warnings of potential wildfires. Source: droughtmonitor.unl.edu*

Drought experts combine physical indicators including precipitation, temperature, and soil moisture to create this weekly map. Another key indicator is vegetative health. Satellite-derived vegetative health indices are used to help understand the effect on drought on agricultural and other vegetation.

Monitoring Drought Conditions With LEO Vegetation Health Products

Drought conditions can be monitored with low Earth orbit (LEO) satellite observations. An important LEO vegetation health product is the Vegetation Health Index (VHI). Global VHI products are generated daily using data from the JPSS Visible Infrared Imaging Radiometer Suite (VIIRS). VHI is used as an indicator for overall vegetative stress and can serve as proxy data for drought, greenness of vegetation, fire risk, and soil moisture. Vegetation health conditions can be an indicator of drought as drought-stressed plants typically experience higher temperatures and lower moisture levels, leading to lower VHI values. This information can aid land managers in identifying areas prone to drought.

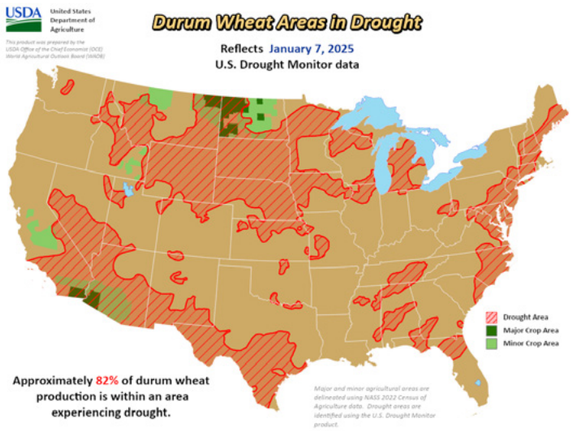
The Normalized Difference Vegetation Index (NDVI) is a metric that describes the density of vegetation by assessing its greenness. The VIIRS NDVI product is generated using near-infrared and red reflectance data from VIIRS instruments onboard JPSS satellites. An area that is greener and therefore healthier will absorb more visible light as plants use that light for photosynthesis and reflect more near-infrared light, allowing analysis using LEO satellite sensors. Vegetative health data is often combined with other data for a comprehensive assessment.

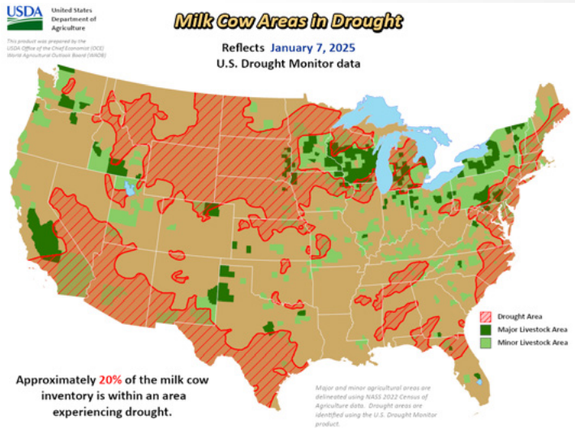


Click images to enlarge.

Left: This image shows the NOAA-20 VIIRS Vegetative Health Index product for the first week of January 2025. Red and pink hues (VHI ≤ 24) indicate extremely poor or absent vegetation, while dark greens and blues (VHI > 60) reflect healthy vegetation. The lower right portion of the map, predominantly desert, shows expected low VHI values. Source: NOAA NESDIS STAR.

Right: California NDVI for the first week of 2025, dated January 7, 2025. Lower NDVI values ranging from 0.25 to 0.05, shown in red, orange, and brown, indicate sparse or dry vegetation. Source: NOAA NESDIS STAR.





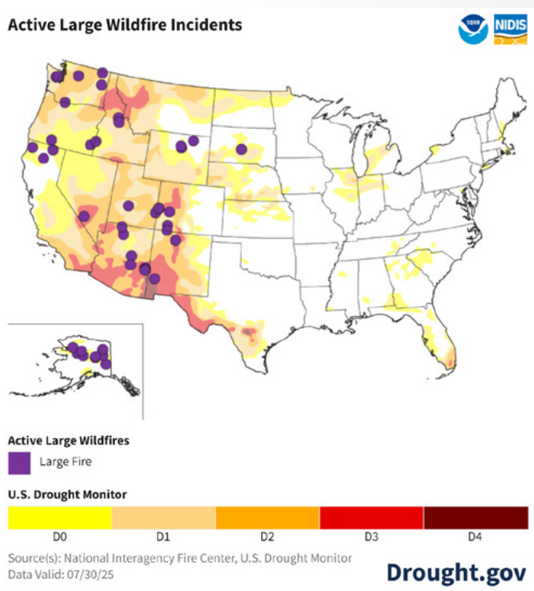
Click images to enlarge. *This image shows January 7th, 2025, U.S. Drought Monitor data (red) overlaid with major crop areas (green) for Durum Wheat (left) and Milk Cow (right), two important California commodities. Source: U.S. Department of Agriculture (USDA).*

The U.S. Drought Monitor

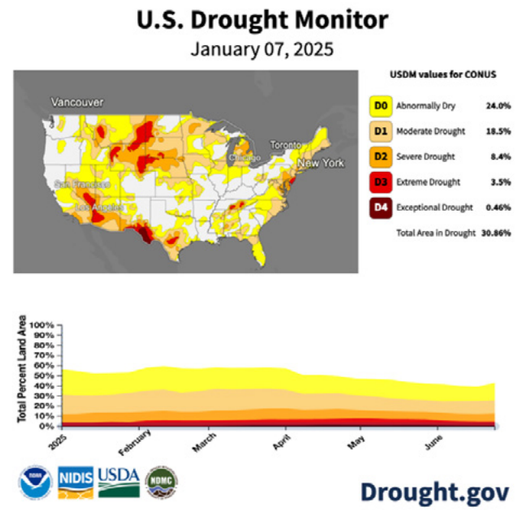
The U.S. Drought Monitor is a collaboration between NOAA, USDA, and the National Drought Mitigation Center at the University of Nebraska-Lincoln. Along with VIIRS-derived vegetation health data, the U.S. Drought Monitor incorporates data from VIIRS Vegetation Health products, along with many other data sources. In their Map Viewer, the U.S. Drought Monitor can be overlaid with other data to help users analyze connections between precipitation, temperature, and drought. The U.S. Drought Monitor also shows the percentage of major agricultural areas experiencing drought at a given time, as shown in the figures above.

Beyond the importance of drought conditions in wildland fires, understanding how farmland overlaps with drought areas is also important. This information can help inform crop yield estimates and can be used to adjust management practices. Farmers can adapt to drought conditions by altering their seasonal crop decisions, strategies for fertilizing, irrigation, harvest, and tillage. These decisions are essential to ensure there are enough harvestable crops to feed the American people and support the U.S. economy.

Droughts can heighten fire severity which further impacts the stability of the agriculture industry. Dry land and vegetation increase the rate, severity, and spread of fires, as they act as fire fuel. Fire fuel is material with low moisture content that makes it easier for vegetation burn, aiding wildfire growth. When looking at the NWS Storm Prediction Center's Fire Weather Outlooks, the areas of active wildfires tend to overlap with the highest



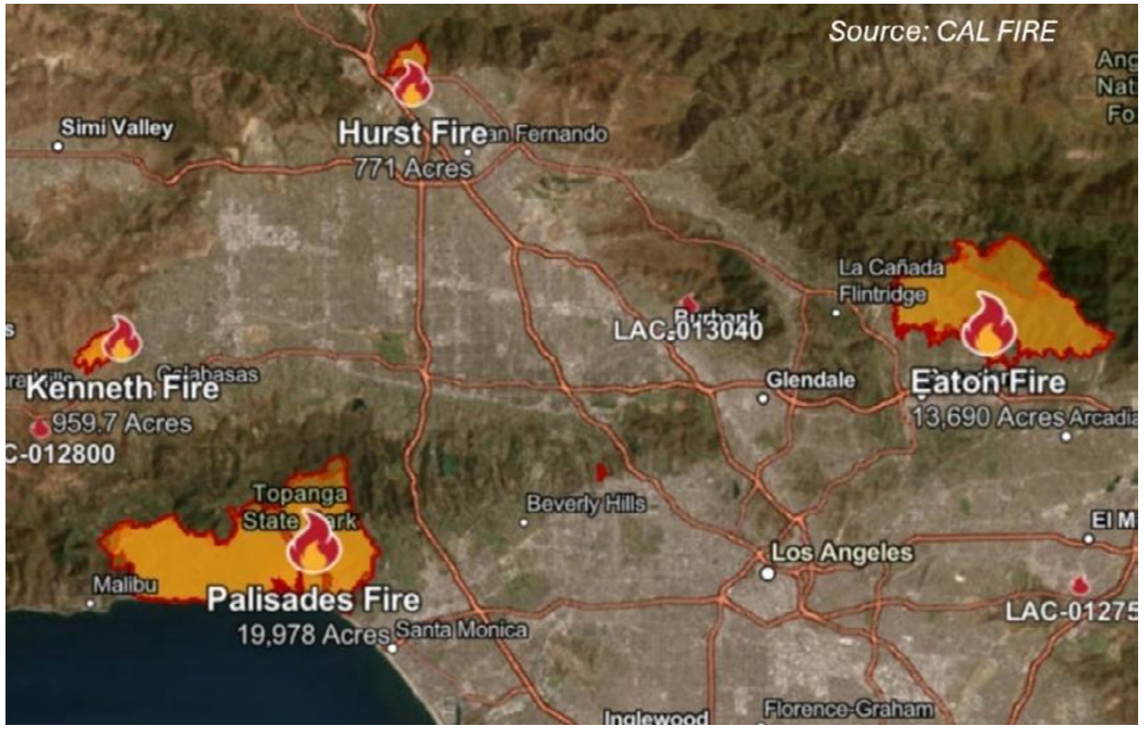
Click image to enlarge. *Active large wildfire map overlaid with U.S. Drought Monitor on July 30, 2025.*



Click image to enlarge.

severity areas on the U.S. Drought Monitor. This data can be visualized using the NOAA/National Integrated Drought Information System (NIDIS) interactive map for wildfire management and drought (an example is on the previous page), allowing clear connections to be made between drought, wildfire, and many other environmental conditions.

In early 2025, around 30 percent of the U.S. was experiencing drought. In Southern California, the drought conditions were largely due to a poor wet season in 2024 that led to suitable fire conditions in early 2025. The NWS issued a red flag warning for the Greater Los Angeles area on January 2nd, 2025, forecasting moderate to strong SAWs, with a potential for "extreme fire weather conditions" in the following days. A more urgent "Particularly Dangerous Situation" alert on January 6th forecasted the potential for extreme fire behavior, with anticipated damage to Los Angeles and Ventura Counties and isolated winds ranging from 80-100 miles per hour (mph) near mountain areas. The Palisades and Eaton fires began on January 7th, shown on the map below. The SAWs fanned the flames making them hotter and more intense and contributed to the spreading of the fire and smoke. Information on the location and spread of the fires was necessary for the emergency responders to



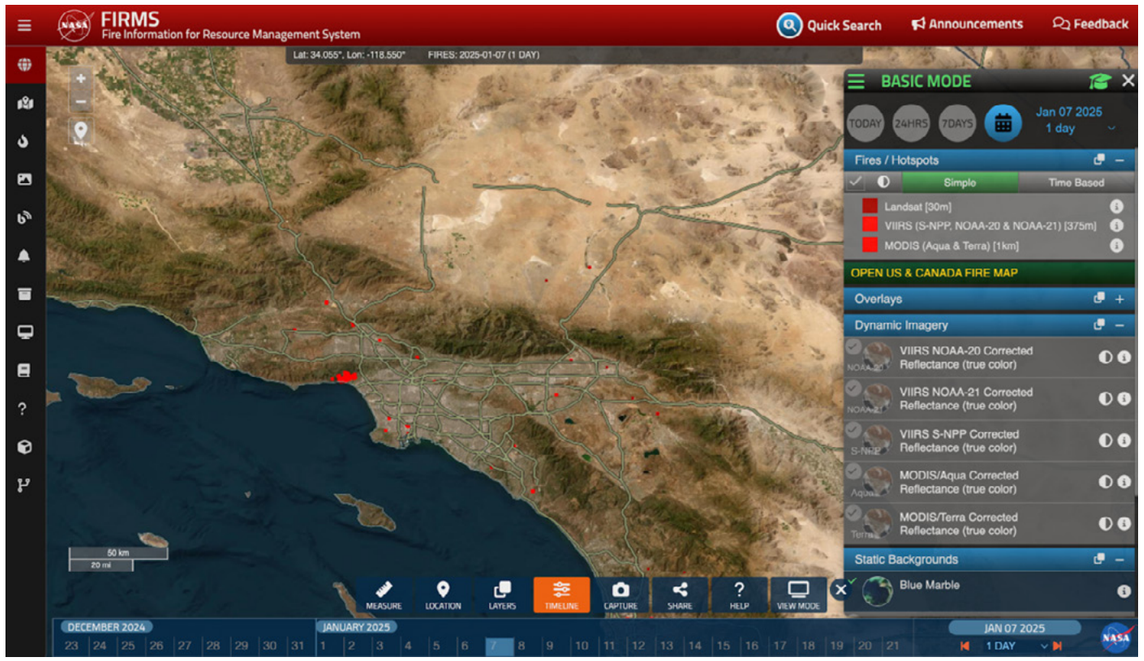
secure protection of people and lands. When fire conditions are unmanageable, one of the tools that CAL FIRE uses to approximate fire perimeters is LEO satellite data, notably, data from the VIIRS Active Fire product. It can be used day or night for detecting new and active fires and providing Fire Radiative Power (FRP) information. FRP is an estimate of the fire's intensity taken by measuring the energy released by the fire. This product provides emergency managers with situational awareness, helping them understand where the fires are most likely to spread, and helps to identify the most intense areas that should be targets for immediate response when it is too dangerous to use drones or boots-on-the-ground to assess conditions.

The Role of JPSS Observations in Wildfire Detection

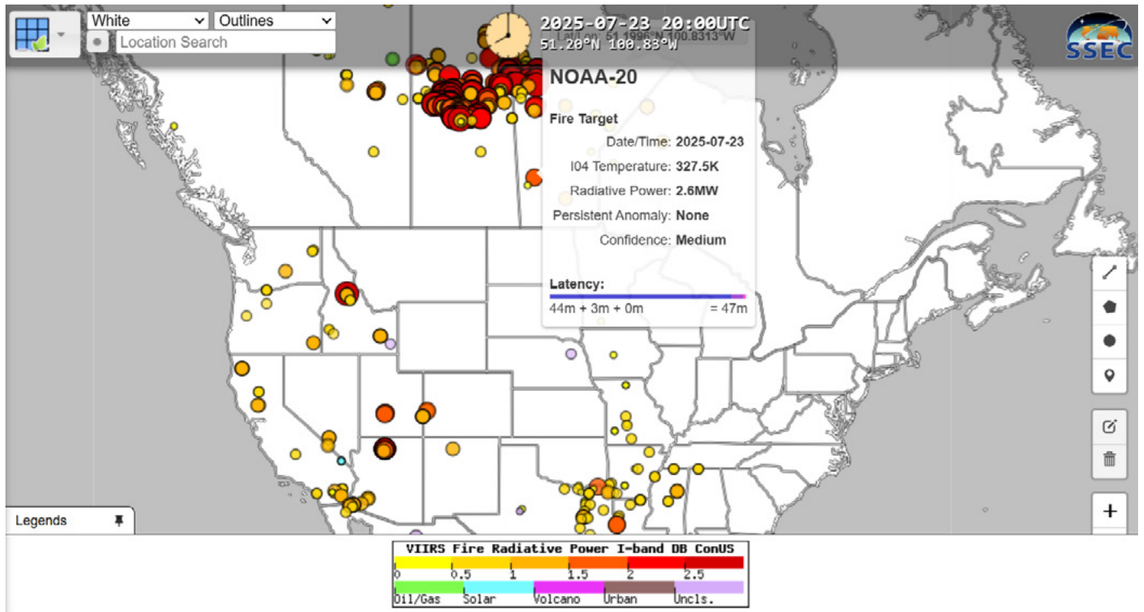
The NWS Fire Weather Program Incident Meteorologists (IMETs) use a variety of resources to monitor fires, including satellite-based fire products available through NOAA. In addition to the VIIRS Active Fire product mentioned above, IMETs and others also use the VIIRS Day Fire RGB product (RGB stands for red, green, blue spectra), which detects fire hot spots, monitors vegetation health, identifies burn scars, and captures daytime smoke plumes. The product is especially good at detecting small fires because of its 375-meter (m) spatial resolution and in identifying burn scars (explained below). In the image below, dark brown areas indicate burn scars, blue indicates smoke, red represents active fires, and green represents healthy vegetation.

Monitoring the intensity and distribution of fires is necessary for best allocation of firefighting resources by emergency responders. VIIRS FRP data is available at a spatial resolution of 375m, viewable using several data visualization platforms including SSEC/CIMSS RealEarth™ and the NASA Fire Information for Resource Management System (FIRMS). Organizations such as CAL FIRE, can use these fire detection mapping tools to target areas to deploy their emergency response teams to contain the fires as quickly as possible, saving both lives and valuable agricultural land and infrastructure.

Suomi-NPP VIIRS Day Fire RGB of New Mexico's Hermit's Peak/Calf Canyon fire from May 2nd, 2022. Source: NOAA/NASA JPSS.



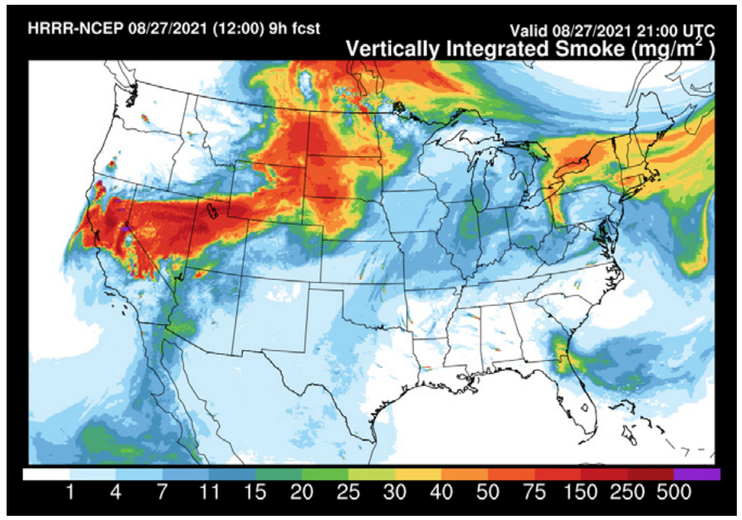
VIIRS Active Fire product displayed through the Fire Information for Resource Management System (FIRMS) on January 7th, 2025. Source: NASA FIRMS.

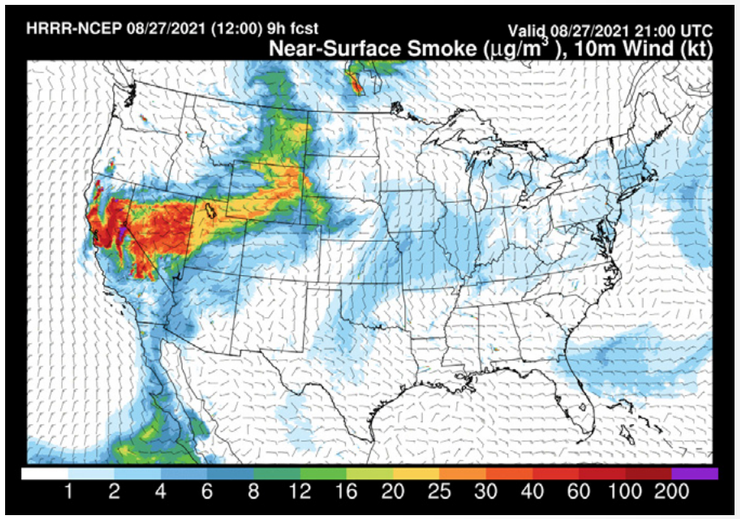


An example of VIIRS Fire Radiative Power I-band DB data displayed through RealEarth™ on July 14th, 2025 (January 2025 data was unavailable at the time of publication). Source: SSEC/CIMSS.

VIIRS-Derived Smoke Products

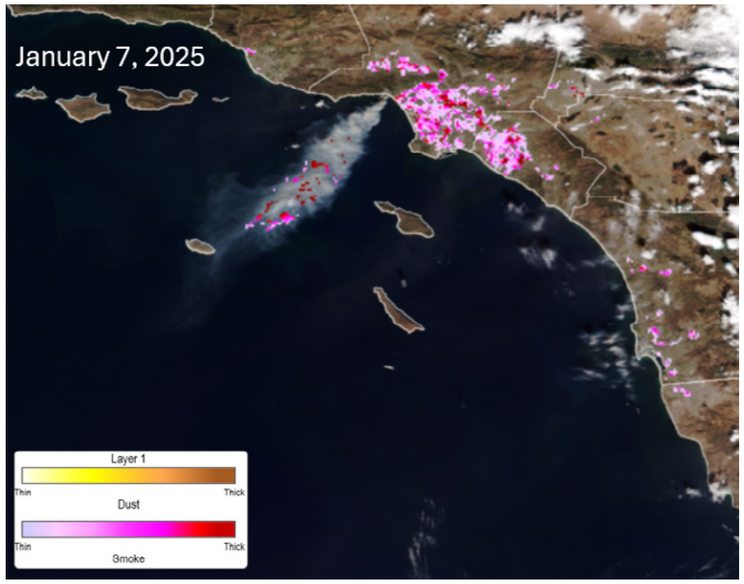
Smoke can negatively impact crops due to high levels of particulate matter, and often travels great distances from its source. Wildfire smoke can harm California wineries through the drying of grapes and smoke-taint which alters the taste of the grapes, making them unusable. Smoke-taint can have varying effects on crops depending on the location, age, and composition of the smoke. Smoke plumes can be monitored using information obtained from NOAA's High Resolution Rapid Refresh (HRRR)-Smoke model. Based on VIIRS FRP data, the HRRR-Smoke model forecasts smoke transport, total biomass burning, and plume rise up to 24 hours in advance. The model provides products such as Near Surface Smoke and Vertically Integrated Smoke. The Vertically Integrated Smoke product forecasts the total smoke mass approximately 25 kilometers (km) up into the atmosphere. The Near Surface Smoke product is created by incorporating wind data in order to forecast the movement of smoke at surface level. Products generated by the HRRR-Smoke model are valuable to farmers because they can help them evaluate how smoke plumes may move and impact agricultural lands.

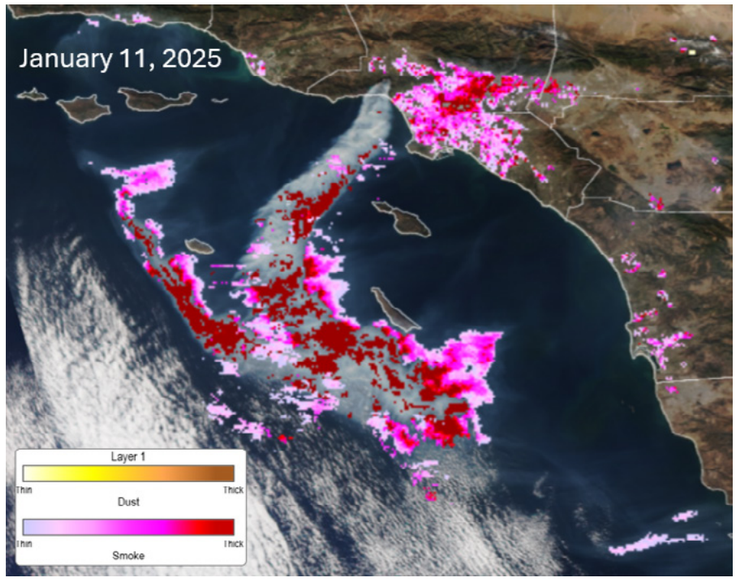




The HRRR-Smoke Vertically Integrated Smoke product (above) and Near-Surface Smoke product (right) show the 9-hour forecast for smoke from the Caldor Fire, valid August 27th, 2021, at 21:00 UTC. The Caldor Fire started near Sacramento, California. In both products, yellow, orange, reds, and purple indicate high concentrations of smoke. The dashed lines in the right image indicate the wind direction and speed (knots). Note that January 2025 maps were unavailable at the time of publication.

Another JPSS product for visualizing smoke is the VIIRS Aerosol Detection Product (ADP), which can be accessed using NOAA's interactive AerosolWatch tool. The VIIRS ADP product is generated using a retrieval algorithm that distinguishes smoke and dust in the atmosphere. The VIIRS ADP, or Smoke/Dust Mask, provides near real-time data on the presence and thickness of smoke and aerosols over the course of a day, making it valuable for issuing smoke advisories. Archived VIIRS ADP imagery is also available from NOAA through the JSTAR Mapper visualization tool. The VIIRS ADP imagery below shows the Smoke/Dust Mask on particular days of the 2025 Palisades and Eaton wildfires in California with red representing areas with the thickest smoke. The fires were centered in the Los Angeles area, starting January 7th and most were contained by January 31st. The smoke levels rose and fell throughout that time with the worst smoke on January 11th.

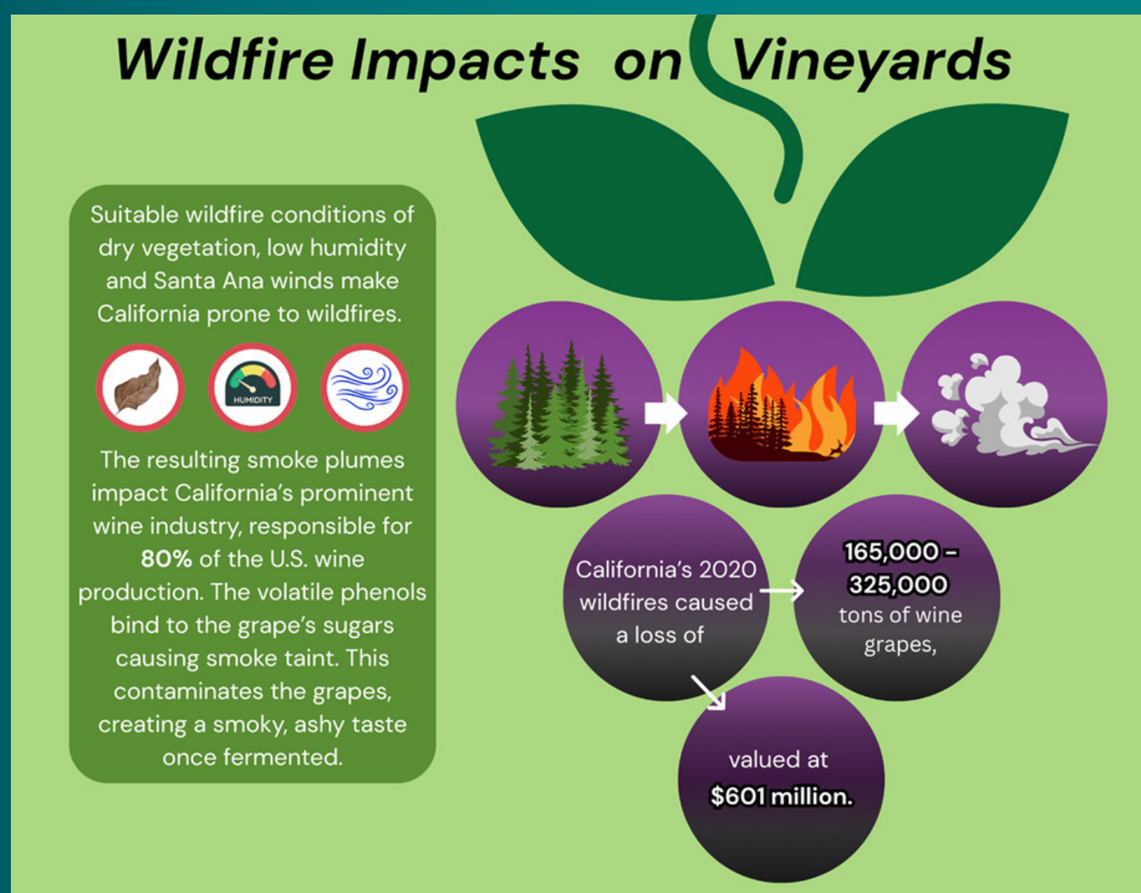




The NOAA-20 Smoke/Dust Mask on January 7th, 2025, (above), and January 11th, 2025 (right) shows thin (light pink) to thick (dark red) smoke from the Palisades and Eaton fires in Southern California. The product overlays VIIRS True Color imagery, where blue-gray smoke is visible drifting southwest. By January 11, thick smoke had spread westward over the ocean. Source: JSTAR Mapper.

Vineyards and Smoke

When smoke infiltrates the skin of grapes, it causes the resulting wine to carry a smoky or ashy taste. The volatile phenols in smoke bind to the sugars in grapes and remain undetectable until fermentation when the smoky taste becomes apparent. Grape growers can do tests to determine if their grapes have been contaminated through sensory analysis of smoke traces through a grape sampling protocol or micro-fermentation protocol. However, growers often have to determine grape crop decisions quickly and with limited data. California experienced significant wildfires in 2020, and its effects have been analyzed by a report by the California Association of Winegrape Growers (CAWG). They determined that wildfire smoke exposure caused an estimated loss of 165,000-325,000 tons of wine grapes, valued at $601 million. While there are not any current barrier technologies recommended for protecting grapes from smoke damages, smoke forecasts can help wineries anticipate potential smoke exposure so they can adjust vineyard operations, such as harvesting schedules, to reduce the amount of time grapes are exposed. The West Coast Smoke Exposure Task Force (WCSETF) is working to make advancements in this research to find solutions for protecting smoke impacts on wineries.

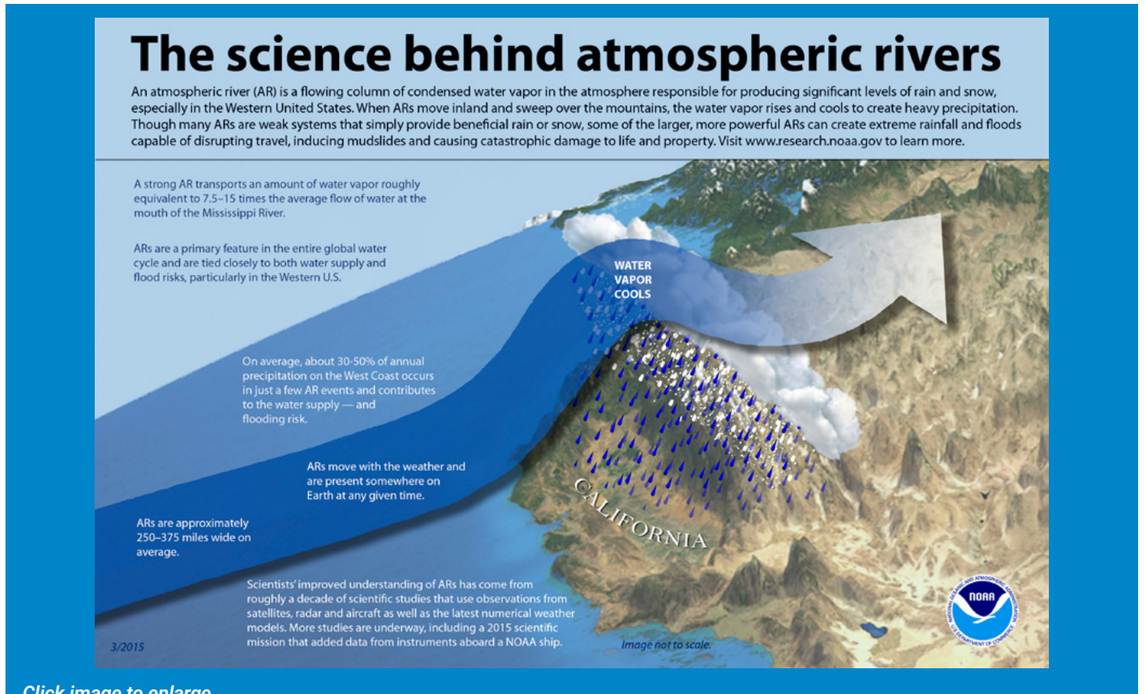


The Role of Atmospheric Rivers After Wildfires

Flooding is a cascading effect of wildfires in California. Fires leave behind burn scars where the ground is barren of vegetation, and the soil is charred and chemically altered. These scars make the soil water repellent, decreasing water percolation and increasing runoff. Since the soil becomes water repellent, even less precipitation is required to cause flash flooding, landslides, mudslides, or debris flow. Debris flow is a kind of landslide that brings a mix of sediments and rocks as well as large objects such as boulders that can significantly disrupt transportation, destroy infrastructure, and affect drainage patterns, causing damage to agricultural land and infrastructure.

The burn scars in Southern California depicted in the VIIRS Fire Day RGB image above on the right often occur in areas of higher elevation. High mountain tops make it difficult for emergency responders to contain fires, making it easier for fires to expand and create large burn scars after they are extinguished. Downhill lands are prone to flash flooding and debris flow due to the change in elevation, making those communities susceptible to large scale damages, particularly after the landscape is left scarred by wildfire. The dangers of flash flooding after a fire may persist for years after, as it takes time for the vegetation to reestablish after fires. Atmospheric rivers are a common occurrence along the West Coast, and can contribute to serious flood events, as they can deposit large amounts of precipitation in a short time frame.

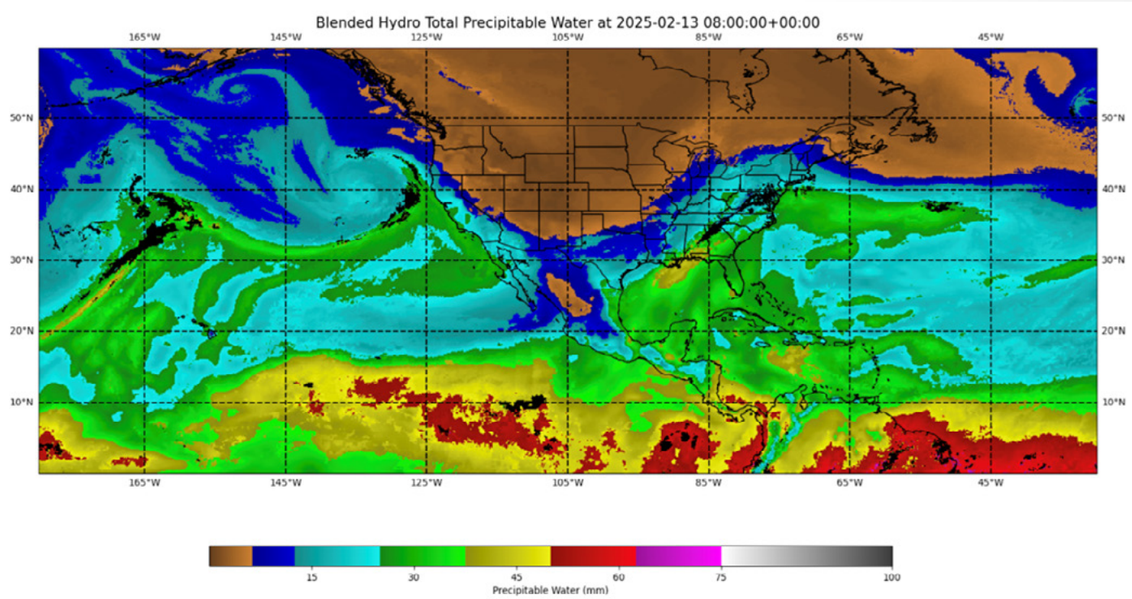
Click image to enlarge. *S-NPP VIIRS Fire Day RGB burn scar imagery of Southern California, January 13th, 2025. Source: CIRA Satellite Library.*



Click image to enlarge.

Forecasters monitor atmospheric rivers using precipitable water products that allow for the analysis of atmospheric moisture over land and ocean. Precipitable water products help forecasters see where atmospheric rivers are and how much moisture they contain, allowing them to anticipate potential heavy precipitation that could lead to flash floods, debris flows, and mudslides, thus allowing for more timely warnings and evacuations. One example is the operational Blended Total Precipitable Water product (bTPW) developed by Cooperative Institute for Research in the Atmosphere (CIRA)/University of Colorado with support from the JPSS Program.

The bTWP product blends atmospheric data from multiple geostationary (GEO) and LEO satellite sensors, including the Advanced Technology Microwave Sounder (ATMS) onboard JPSS satellites, to provide a continuous, global view of atmospheric moisture. The product aids in forecasting heavy rain, flooding, and other weather events. Looking at the mid-February 2025 flood event in California, the bTPW product shows an atmospheric river as it approaches the coast (below). This atmospheric river was observed by the NWS before rains started to fall. On February 5th, warnings for "life threatening flooding" were issued by NWS as heavy rains from the atmospheric rivers started to hit the California coast. The resulting debris flows and flash flooding caused evacuations and destruction of property, which were exacerbated by burn scars caused by the Palisades and Eaton fires. To mitigate flooding impacts, tactics such as debris basins, reinforced drainage systems, and stabilized slopes can be applied by mapping areas known to be prone to flooding or affected by burn scars.



The bTPW product showing Total Precipitable Water for North America on February 13, 2025, at 08Z. Precipitable water amounts in the 30-millimeter (mm) range, indicated by green, can be seen along the coast of California.

Summary and Future

Forecasting weather events and environmental conditions that can fuel wildland fires and prompt cascading effects is essential for the protection of lives, agricultural land, infrastructure, and the economy. Preventative measures can be taken to issue better warnings, contain fires, and limit flooding impacts and smoke exposure based on information from LEO satellite data products. Recognizing the connections between drought, precipitation, humidity levels, and vegetation health allows for enhanced hazard mapping and timely alerts.

Looking to the future, the Cooperative Institute for Meteorological Satellite Studies (CIMSS) is developing the Next Gen Fire System (NGFS) as the newest tool for fire detection, decision making, and analysis by integrating observations from multiple LEO and GEO satellites, as well as other data sources. JPSS VIIRS data is being tested in the NGFS by the Alaska Fire Service, in comparison to legacy VIIRS fire detection products to improve detection of active fires. The system's focus is early fire detection and near-continuous monitoring. The NGFS also limits the amount of atmospheric obstruction such as clouds and aerosols like smoke, improving upon past products. These improvements will enhance the accuracy of detection and support faster emergency response, which helps limit fire spread and its subsequent impacts. Monitoring wildfires and their cascading effects is important for disaster planning, to lessen impacts when these incidents do occur. Support from LEO satellite imagery and data products is imperative for safeguarding Americans, our lands, and the U.S. economy.

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HIGHLIGHTS

Meet the LEO Summer Interns

NOAA offers a wide range of internship programs for students interested in science, technology, engineering, and mathematics (STEM). Opportunities range from short-term experiences to full summer internships and are open to students from high school through graduate school. These internships inspire our nation's next generation Earth scientists and engineers.

In the summer of 2025, the NOAA NESDIS Office of Low Earth Orbit (LEO) Observations welcomed several undergraduate and high school interns to its office at NASA's Goddard Space Flight Center, where they contributed to a variety of engaging projects. Along with their research and technical work, they took part in a summer filled with learning and connection. They met with NOAA and NASA leaders, joined "lunch and learn" sessions, toured the Goddard facility, and attended career fairs to connect with industry partners. Throughout the summer, they also engaged with experts in a wide range of fields, including ground communications and CubeSat engineering, to explore potential career paths.

The following spotlights highlight LEO's 2025 interns and their reflections on the experience.

Right: LEO summer interns pose beneath "Orbits Interweave" at the NASA Goddard Space Flight Center Visitor Center. The exhibit by the Joint Polar Satellite System (JPSS) and the Geostationary Operational Environmental Satellite (GOES) R Series programs features a kinetic sculpture accented by three polished stainless steel spheres that symbolize Earth-observing satellite orbits.

Charlotte Krisetya

NOAA William M. Lapenta Intern
University of Maryland
Major: Environmental Science & Policy

During the summer of 2025, Charlotte Krisetya participated in the NOAA William M. Lapenta Internship Program as a rising junior at the University of Maryland-College Park, where she studies Environmental Science and Policy with a concentration in Marine and Coastal Management. Her internship offered a chance to bridge her academic studies with hands-on experience that connects satellite observations to real-world challenges.

Charlotte's project examined how data from the Joint Polar Satellite System (JPSS) supports wildfire detection and helps to forecast cascading environmental impacts. Her study culminated in a guest contribution as Feature 10 in the 2025 LEO Science Digest, titled *Cascading Impacts: LEO Insights into the Effects of Wildfires on California Agriculture*.

Working alongside LEO Science Writer Amy Leibrand and LEO Internship Coordinator Julie Hoover, Charlotte explored JPSS data products, consulted with experts in agriculture and wildfire science, and gained valuable insight into how NOAA and NASA collaborate to advance Earth observations.

Reflecting on her experience, Charlotte said, "This internship has been an exciting opportunity to expand on my foundational knowledge of remote sensing and explore its real-world applications. I've enjoyed learning about how JPSS impacts people's lives, and it has strengthened my interest in pursuing a career in the environmental field to help people."

Raeed Kabir

NOAA Ernest F. Hollings Scholarship Intern
University of Alabama
Major: Pre-Med Mathematics and Economics

Raeed Kabir joined the Office of LEO Observations as a research intern through NOAA's Ernest F. Hollings Scholarship Program. Then a rising senior at the University of Alabama, Raeed is a Mathematics and Economics major on a Pre-Med track. His 10-week internship concluded in late July 2025 and provided an opportunity to combine his interests in data science, economics, and environmental science.

Raeed's research focused on integrating JPSS observations with individual-level decision data to examine how environmental exposure influences human behavior. His project, titled *Leveraging Remote Sensing Data to Estimate the Effect of Short-Run Temperature and PM2.5 on Consumption*, analyzed how exposure to temperature fluctuations and air pollution affects purchasing choices that offer short-term comfort and relief.

Reflecting on his experience, Raeed shared, "I am excited about continuously learning to handle large volumes of satellite grid data and understanding the time-series nature of weather."

Lapenta Internship

The NOAA William M. Lapenta Internship Program is a competitive 10-week paid summer internship for undergraduate and graduate students majoring in STEM fields. Interns are placed across NOAA Line Offices and work on projects under the guidance of NOAA scientists and mentors. The program aims to provide hands-on experience with NOAA's mission, helping students develop skills, professional networks, and a clearer vision of potential career paths.

Hollings Scholarship

NOAA's Ernest F. Hollings Undergraduate Scholarship recognizes outstanding students pursuing studies in NOAA mission fields. In addition to financial assistance, Hollings Scholars complete paid summer internships at NOAA facilities across the country. Many alumni say the program shaped their academic and career paths, expanded their professional networks, and strengthened their skills for work in NOAA-related disciplines.

Conner Timario

NOAA Ernest F. Hollings Scholarship Intern
California State Polytechnic University, Pomona
Major: Electrical Engineering

Conner Timario participated in the NOAA Hollings Scholarship Program, where his internship focused on researching spacecraft compatible with potential instruments that will fly onboard Near Earth Orbit Network (NEON) Series-2, NOAA's next-generation LEO mission that will succeed JPSS. His mentor, Valerie Mikles, is a NOAA scientist who works on weather satellites at the system level.

A student at California State Polytechnic University-Pomona, Conner is majoring in Electrical Engineering and expects to graduate in 2026. During his May through July internship, he developed a government reference tool to support spacecraft selection for NEON Series-2. His work involved contacting spacecraft vendors, researching their platforms, and compiling technical information to compare instrument compatibility across multiple spacecraft options.

During his time interning with LEO, Conner said, "What excites me most about this internship is the opportunity to explore both the electrical and structural aspects of satellite systems, and to see how they influence overall spacecraft performance. It's been a valuable experience that's deepened my understanding of electrical engineering in a real-world, interdisciplinary context."

Solomon Glavach

LEO Intern
Carnegie Mellon University
Major: Mechanical Engineering

In the summer of 2025, Solomon Glavach returned for a second year as an intern with the Mission Operations Support Team (MOST). His internship ran from May through August while he was a rising junior at Carnegie Mellon University, majoring in Mechanical Engineering.

The MOST team prepares code to communicate with the JPSS satellites in orbit and coordinates with the JPSS Flight project team to prepare for upcoming satellite launches. Under the mentorship of Brian Thibaudeau, Deputy Flight Operations Readiness Lead for JPSS-2, -3, and -4, Solomon gained firsthand experience in mission readiness and satellite operations.

Reflecting on his work, Solomon shared, "I think the most exciting part of being on the JPSS team is knowing that I am contributing to the launch of the satellites that are responsible for a lot of our weather predictions and research."

National Space Club Internship

The National Space Club and Foundation Scholars Program offers summer internships for up to 55 high school students to work alongside space scientists and engineers. Sponsored by NASA's Goddard Space Flight Center in Greenbelt, Maryland, and the Wallops Flight Facility in Wallops Island, Virginia, the program gives students firsthand experience in how research and development organizations operate in support of NASA's mission to inspire the next generation of explorers. Each participant is paired with a technical professional in a field that matches their interests and skills.

Laila Aziz

National Space Club High School Intern

Laila Aziz participated in the National Space Club high school internship at NASA's Goddard Space Flight Center during the summer of 2025. Mentored by Dave Campbell and Will Conn, she was a rising senior at Centennial High School and plans to pursue a college degree in Aerospace Engineering or Astrochemistry.

As a Supply Chain intern, Laila met with engineers and quality managers, learned about the scope of different missions, and researched and analyzed factors that influence operations. JPSS is one of the missions that Laila's mentors support at Goddard.

Laila shared, "What excites me about my internship is blending engineering aspects with business management and being able to explore a lesser-known side of NASA through mission assurance management. At the Supply Chain, we support several different missions and get to be involved in a little bit of everything."

Dessa Haavik

National Space Club High School Intern

Dessa Haavik was a 6-week summer National Space Club intern for the LEO office working on a JPSS tabletop model project. Her mentors were Julie Hoover and Wes Harvey on the LEO Communications Team and Michael Cabrera, a LEO Deputy Project Lead. During her internship, Dessa was a rising high school senior at Carver Center for the Arts and Technology in Towson, Maryland. In college, she plans to major in Mechanical Engineering and Physics.

As part of her internship, Dessa collaborated with fellow intern Elisabeth Min to design and build interactive, scaled models of the JPSS-4 and QuickSounder satellites. The models feature realistic instruments and solar arrays that rotate and deploy just as they do in orbit. These hands-on projects provide a tangible way to demonstrate how the satellites function and communicate complex concepts in an engaging, visual format.

Sharing her thoughts about her internship, Dessa said, "I have always liked doing woodworking and mechanical projects at home, so it's exciting to expand that passion in a different direction and build circuits, wire together motors, and write code to program the model's interactive pieces. I am excited for the challenge of designing both the mechanical and electrical elements to work cohesively in one model."

Elisabeth Min

National Space Club High School Intern

Elisabeth Min joined the LEO office as a National Space Club engineering intern. Mentored by Julie Hoover and Wes Harvey from the LEO Communications Team, along with Michael Cabrera, a LEO Deputy Project Lead, she spent six weeks onsite at NASA's Goddard Space Flight Center, concluding her internship on August 8. A rising senior at Mount Hebron High School in Maryland, Elisabeth plans to study Computer Science in college after graduating in 2026.

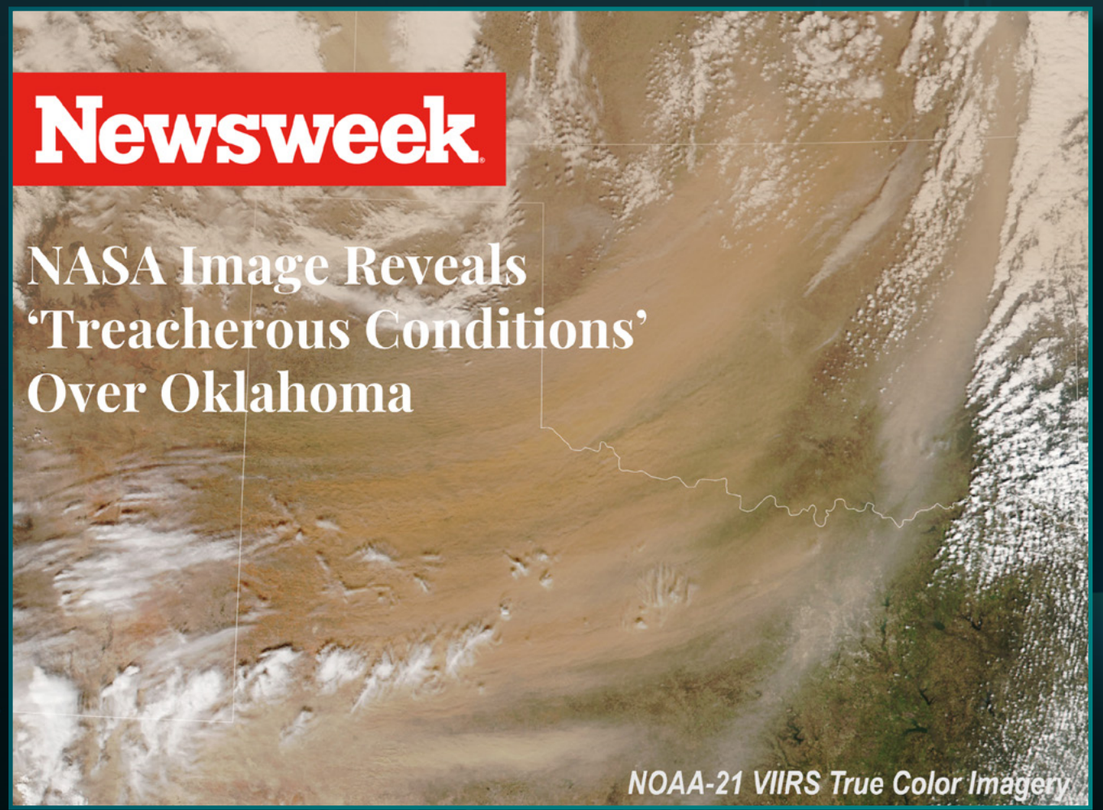
Throughout her internship, Elisabeth learned about LEO's JPSS and NEON programs. She applied her new knowledge and creative skills to design scaled 3D models of the JPSS-4 and NEON QuickSounder satellites, incorporating interactive features to enhance visualization and understanding.

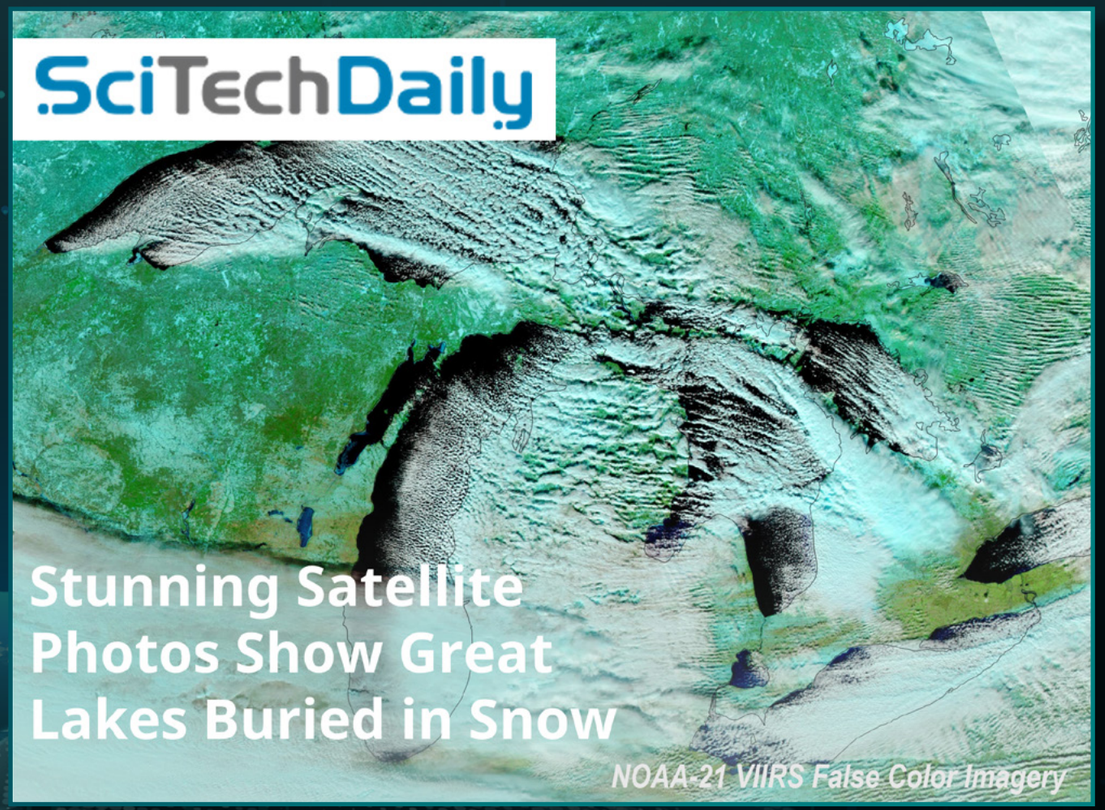
About her experience, Elisabeth shared, "I am very excited about combining aspects of design and programming into one project. This is because I greatly enjoy both subjects and have never done a project which requires this degree of complexity."

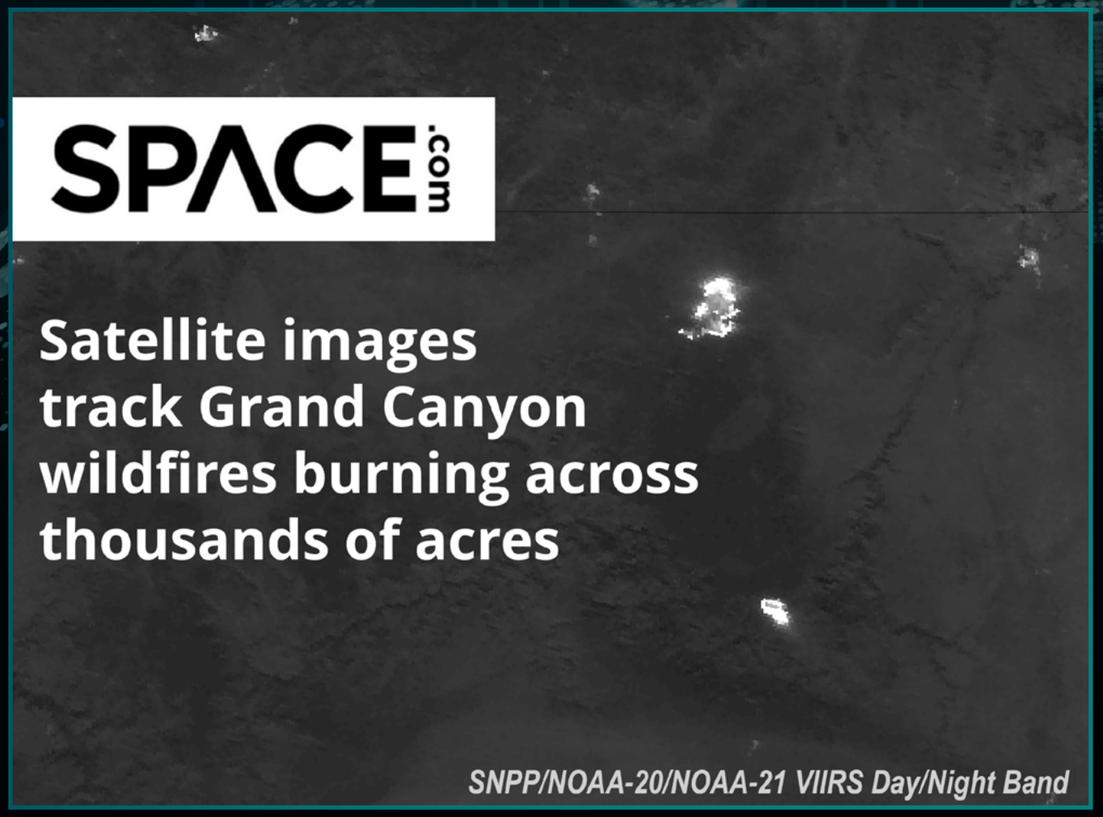
HIGHLIGHTS

JPSS in the News

From major weather events to environmental discoveries, imagery from the Joint Polar Satellite System (JPSS) often makes headlines for its striking visuals and scientific value. News coverage highlights how JPSS data informs the public, supports forecasters, and deepens our understanding of Earth's dynamic systems. The following pages show some recent examples of JPSS in the news.


Newsweek
NASA Image Reveals 'Treacherous Conditions' Over Oklahoma
NOAA-21 VIIRS True Color Imagery


SciTechDaily
Stunning Satellite Photos Show Great Lakes Buried in Snow
NOAA-21 VIIRS False Color Imagery

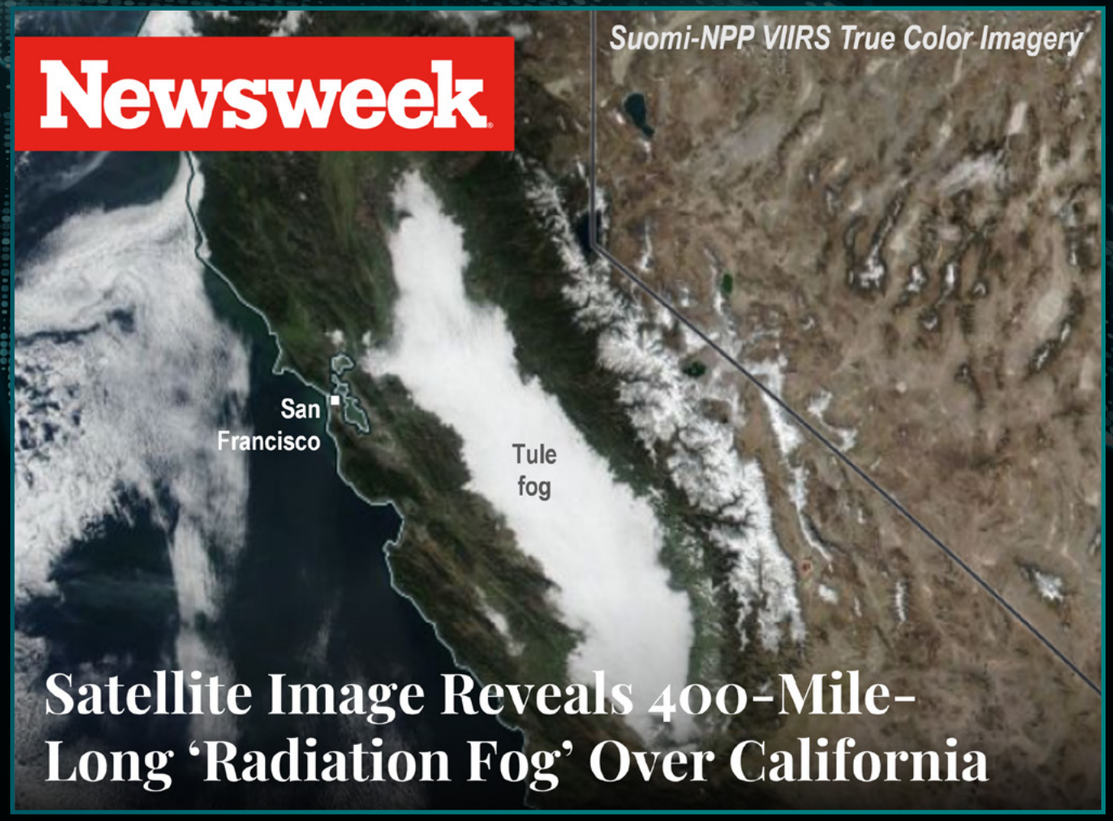

SPACE.com
Satellite images track Grand Canyon wildfires burning across thousands of acres
SNPP/NOAA-20/NOAA-21 VIIRS Day/Night Band

earth.com
NATURE · SCIENCE · LIFE
Two Atlantic storms collide in a rare tug-of-war
SNPP VIIRS True Color Imagery

Newsweek
Michigan's Majestic Fall Leaf Display Captured From Space
NOAA-20 VIIRS True Color Imagery

BBC Sky at Night MAGAZINE
Spain and Portugal blackout from space, captured by satellites orbiting our planet, pole-to-pole
SNPP/NOAA-20/NOAA-21 VIIRS Day/Night Band; NASA Black Marble

Reuters
In India and Pakistan, a shared blight: smog
NOAA-20 VIIRS True Color Imagery


Newsweek
Suomi-NPP VIIRS True Color Imagery
San Francisco
Tule fog
Satellite Image Reveals 400-Mile-Long 'Radiation Fog' Over California

HIGHLIGHTS

LEO Web Stories from NESDIS

WEB FEATURE: JUNE 30, 2025

A Silent Threat: How NOAA Satellites Help Save Lives in Low Visibility and Fog

View on the NESDIS Website

Hurricanes, tornadoes, and blizzards are well known for their destructive impact to life and property, but fog is a silent, often underestimated threat. Fog is a low-lying cloud made up of tiny water droplets suspended in the air near the Earth's surface that can drastically reduce visibility, posing serious hazards for drivers, pilots, and mariners. Sea fog, which forms when warm, moist air moves over cooler water, can bring entire ports and airports to a standstill. Dense fog, where visibility drops to a quarter mile or less, can trigger transportation shutdowns and cause ripple effects that result in millions of dollars in economic losses.

Unlike rain or snow, fog droplets are usually too small to be detected by radar. Weather stations and balloon-borne instruments called radiosondes can detect fog locally, but lack the coverage needed to track widespread or fast-changing events. That's where satellites come in. NOAA's Joint Polar Satellite System (JPSS) satellites (Suomi NPP, NOAA-20, and NOAA-21) carry advanced sensors that help forecasters detect, track, and predict hazardous conditions such as fog, dust, snow, smoke, and heavy precipitation that can reduce visibility across vast regions, including oceans and rugged terrain where ground-based observations are scarce.

Fog poses major risk for drivers

Each year, an average of 38,700 vehicle crashes occur in foggy conditions, according to the U.S. Department of Transportation. In 2024 alone, more than 600 people were killed and over 16,300 were injured in fog-related collisions. Most of these accidents occur during the winter, when changing weather conditions and sublimation from snowmelt—where snow directly transitions from a solid to water vapor—can increase the likelihood of fog formation. In October 2023, a dangerous super fog developed when smoke from marsh fires combined with fog near New Orleans, Louisiana. The thick fog reduced visibility to less than ten feet, which led to a mile-long pileup on Interstate 55 that resulted in multiple fatalities.

Fog can disrupt aviation and maritime operations

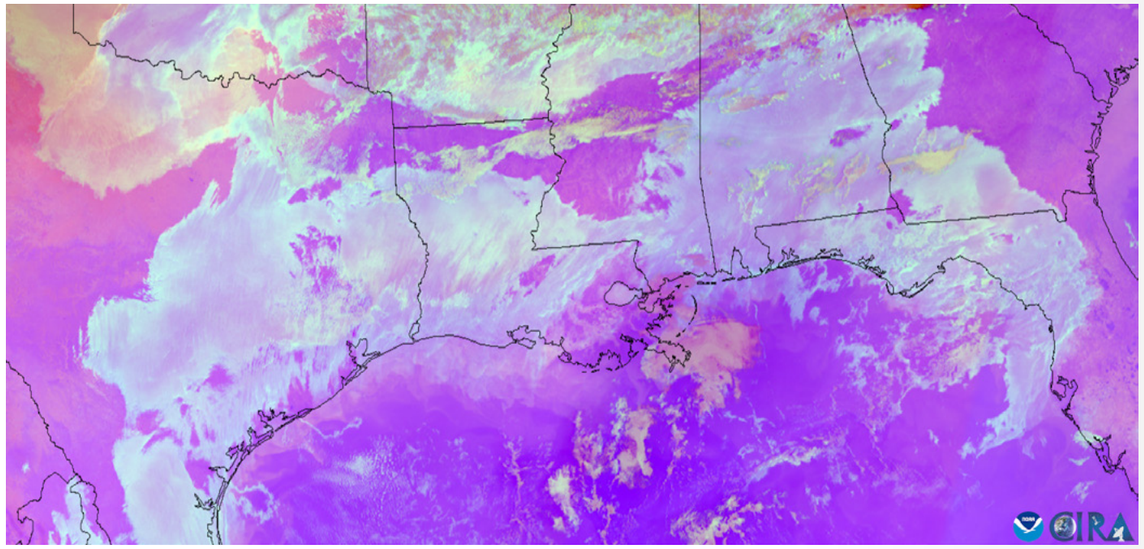
Fog isn't just a highway hazard—it has been a contributing factor in major transportation disasters throughout history. One example was the 1977 Tenerife airport disaster, where two Boeing 747 passenger jets collided on the runway, becoming the deadliest plane crash in airline history. Additionally, fog is responsible for 70% of ship collisions at sea. Despite advances in modern radar and navigation systems, accidents involving small fishing boats are on the rise. These boats largely rely on traditional foghorns to navigate when visibility is low, an approach that may be insufficient in busy harbors.

One notable example occurred in February 2025, when unseasonably warm air over cooler Gulf waters created dense fog in Houston, Texas that disrupted shipping operations at Port Houston, the busiest port in the U.S., for 14 consecutive days. "Weather challenges can be great disruptors for maritime operations, and in February we were hit hard," said Port Houston CEO Charlie Jenkins. Port Houston supports 200 facilities and contributes $906 billion annually to the national economy. That winter, fog and other weather delays caused a 29% drop in channel availability, compared to just 2.5% the year before.

NOAA satellites provide near real-time warnings

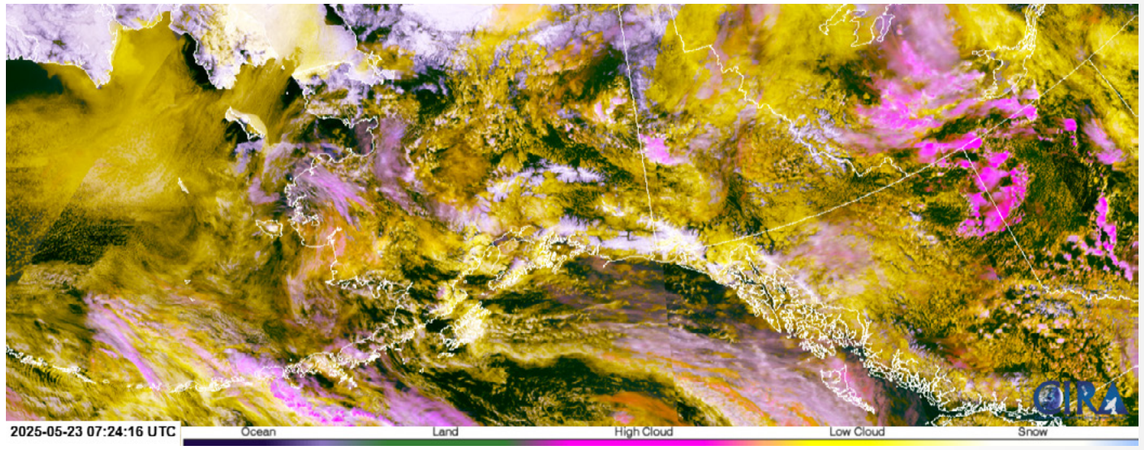
Fog detection and warning systems heavily rely on satellite observations, especially over oceans and in remote areas to see the full extent of the fog. The Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the JPSS satellites, is a key instrument collecting daily global observations of Earth's land, atmosphere, and oceans across 22 spectral bands in the visible and infrared wavelengths. The sensor's broad capabilities support forecasters in detecting and monitoring low-visibility conditions, both day and night, caused by low clouds, fog, volcanic ash, dust, and smoke.

One particularly valuable tool for nighttime fog detection is the VIIRS Nighttime Microphysics RGB (Red-Green-Blue) product. It combines multiple infrared bands to generate an image that distinguishes fog and low clouds from other cloud types. This is done by analyzing the unique infrared signatures, or spectral fingerprints, of various cloud types and color-coding them for easier identification.



Dense fog and low clouds infiltrated the Southeast US and Gulf Coast regions in February of 2025 as seen by NOAA-20, NOAA-21, S-NPP VIIRS Nighttime Microphysics RGB. Fog and low clouds appear aqua over warmer surfaces and yellow-gray in cooler conditions. Source: RAMMB/CIRA SLIDER. See the original web article to view an animation showing fog moving across the region.

Other popular VIIRS products for detecting low clouds and fog include the VIIRS Day Snow/Fog RGB product and the VIIRS Snow/Cloud Discriminator. Both use a combination of VIIRS bands to help forecasters distinguish between low-level clouds and snow or ice over land which can often look alike in air photos and imagery. The VIIRS Snow/Cloud Discriminator works both day and night, using the unique VIIRS Day/Night Band to detect very faint nighttime light, such as moonlight reflecting off clouds. This is especially valuable in regions like Alaska, where long winter nights limit the use of daytime satellite observations.



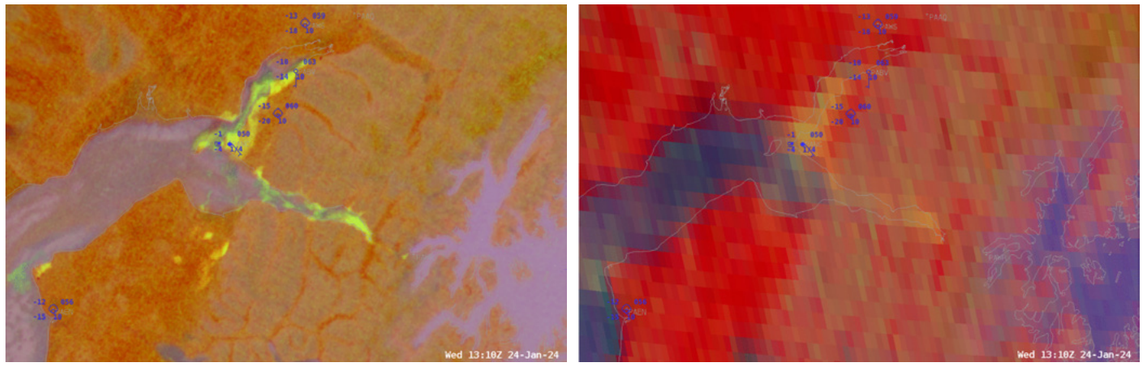
Widespread low-level clouds were detected on May 23, 2025, at 11:24 PM local time by the NOAA-20/S-NPP VIIRS Snow/Cloud Discriminator over Alaska and the surrounding waters, appearing as yellow making them easy to distinguish from the white snow and ice. Source: RAMMB/CIRA SLIDER.

These satellite capabilities are not just theoretical—they're actively used in operational settings. Christopher L. Smith of the Cooperative Institute for Satellite Earth System Studies (CISESS) emphasizes the value of VIIRS and uses its products to train meteorologists in fog detection and analysis. "My role as a satellite liaison," Smith explains, "is to infuse satellite products, both [geostationary] and LEO, into operations at [NOAA] Weather and Ocean Prediction Centers."

As part of this role, Smith trains forecasters to use satellite data effectively and gathers feedback to share with product developers, helping ensure the tools are practical for operational use. "The VIIRS Nighttime Microphysics RGB with its high spatial resolution really lets us see the detail of the fog," he says. "The Weather Prediction Center uses low Earth orbit (LEO) satellite data for a variety of forecasting purposes, mainly convection and heavy rainfall, and for drawing boundaries on the surface analyses to see phenomena like fog."

NOAA forecasters often use data from both LEO and geostationary satellites together to enhance coverage and offer a more complete view of atmospheric conditions. Geostationary satellites, like those in NOAA's GOES series, provide frequent updates—as often as every 5 minutes over the contiguous U.S.—which are essential for monitoring rapidly evolving weather conditions. However, their fixed position over the equator can cause features at higher latitudes, like Alaska, to appear distorted and displaced, making it more difficult to detect small-scale phenomena like low clouds and fog in these areas.

Polar-orbiting satellites like the JPSS series, can fill these gaps though. VIIRS passes over Earth's poles 14 times a day, providing direct overhead views that better capture features at high latitudes that geostationary sensors might miss. Such observations are crucial given the already high and growing volume of ship traffic in the Arctic region, which relies on accurate fog detection for safety and operational planning.



A comparison of imagery over Alaska on January 24, 2024, from the JPSS VIIRS Nighttime Microphysics RGB product (left) and the geostationary GOES-West ABI Nighttime Microphysics RGB product (right). While geostationary satellites provide more frequent updates than polar orbiting LEO satellites, their coarse resolution limits their ability to resolve localized fog. In contrast, the higher resolution VIIRS imagery clearly captures small-scale fog development (yellow shading) near Anchorage, offering critical detail for forecasters monitoring visibility hazards in the region. Credit: Bill Line, NESDIS/STAR.

Instruments onboard NOAA's JPSS satellites provide essential information that improve weather forecasts and help protect lives, property, and the national economy. Fog detection is just one example of how these observations support real-world decision-making. From aviation and highway safety to port operations and shipping routes, having timely and reliable information on low-visibility conditions is critical.

Looking ahead, JPSS-3 and JPSS-4—the next satellites in the JPSS constellation that are currently in development—will extend critical LEO observations well into the 2030s. ✦

WEB FEATURE: AUGUST 28, 2025

Twenty Years After Katrina: NOAA Satellite Advancements for Hurricane Forecasts and Tracking

View on the NESDIS Website

Twenty years ago, Hurricane Katrina devastated New Orleans and coastal Mississippi. It was one of the deadliest hurricanes on record and remains the costliest hurricane in U.S. history. The 2005 Atlantic hurricane season was record-breaking, with 27 named storms, 14 hurricanes, and three Category 5 storms. That record remained until 2020, when 30 named storms developed.

Hurricane Katrina flooded much of New Orleans, trapping many residents who did not evacuate.

Even then, NOAA provided an accurate forecast of Katrina's track three days in advance. Today, forecasters, local officials and first responders have even better tools to forecast a hurricane's path, estimate its intensity, and monitor storm conditions in real-time.

NOAA Satellite Technology in 2005

Geostationary Satellites

At the time, NOAA's Geostationary Operational Environmental Satellite-12 (GOES-12), operating as GOES East, monitored Hurricane Katrina as it organized into a tropical depression near the Bahamas on Aug. 23, strengthened into the 11th-named storm of the Atlantic season on Aug. 24, and made its first landfall as a Category 1 hurricane on the southeastern coast of Florida on Aug. 25. GOES-12 continued to closely track Katrina as it rapidly intensified into a Category 5 hurricane in the Gulf in less than 12 hours on Aug. 28, came ashore as a Category 3 hurricane near Buras, Louisiana, on Aug. 29, and eventually dissipated over the Great Lakes. The GOES satellites orbit 22,236 miles above the equator, at the same speed the Earth rotates, allowing them to constantly monitor a specific area. GOES-12 continuously tracked the storm throughout its lifespan.

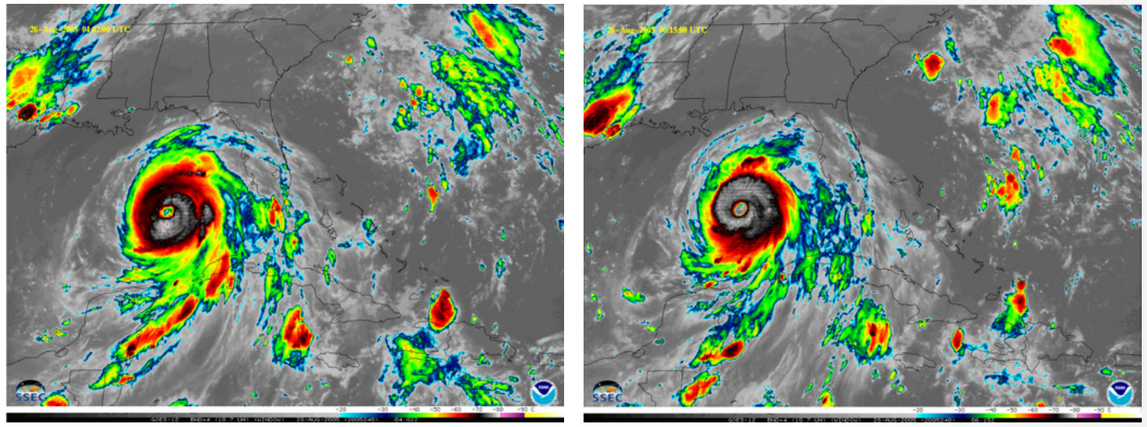
GOES-12 imagery of Katrina from August 27 to August 29, 2005. See the original web article to view an animation showing Hurricane Katrina from August 22 through September 1, 2005.

One advantage this generation of GOES satellites offered over the previous generation was the ability to temporarily suspend routine scans of the hemisphere and concentrate on a small area of quickly evolving conditions. GOES-12 was able to provide updates on Katrina every five minutes (compared to 30 minutes with previous GOES).

Another improvement this generation of GOES satellites offered was the ability to gather multiple measurements of weather phenomena using simultaneous imaging and sounding. This information increased the accuracy of forecasts and showed a more comprehensive picture of developing weather systems.

However, GOES satellites at the time had a limitation: they lacked the batteries to capture continuous imagery during satellite eclipses. When the satellites passed through the Earth's shadow in the weeks around the spring and fall equinoxes, their solar panels couldn't provide sufficient power.

As Hurricane Katrina strengthened in the Gulf on Aug. 28, 2005, the GOES-12 imager experienced a two-hour eclipse outage. GOES-12 imagery of the storm before and after the eclipse shows that the storm organized considerably during the time the satellite was unable to capture imagery.

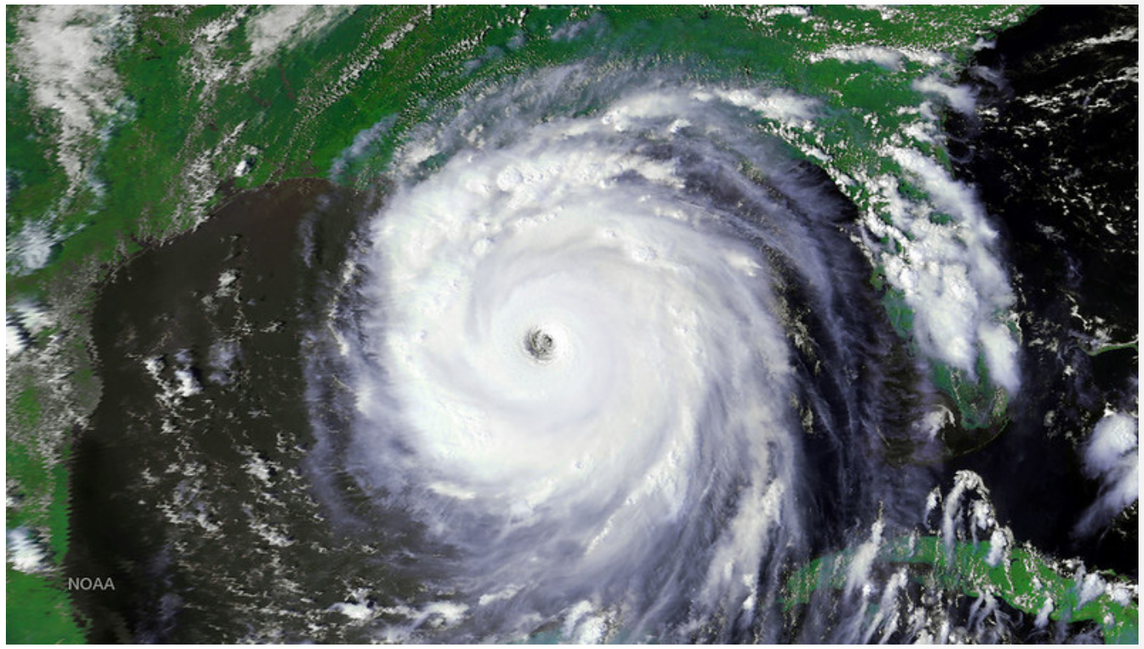


GOES-12 infrared imagery of Hurricane Katrina on Aug. 28, 2005. The left image shows the last pre-eclipse image (0402 UTC) and the right image shows the first post-eclipse image (0615 UTC). The storm had organized considerably in those two hours.

Starting with GOES-13, GOES satellites were equipped with greater battery capacity to eliminate this gap, providing imagery through eclipse periods without interruption.

Polar-orbiting Satellites

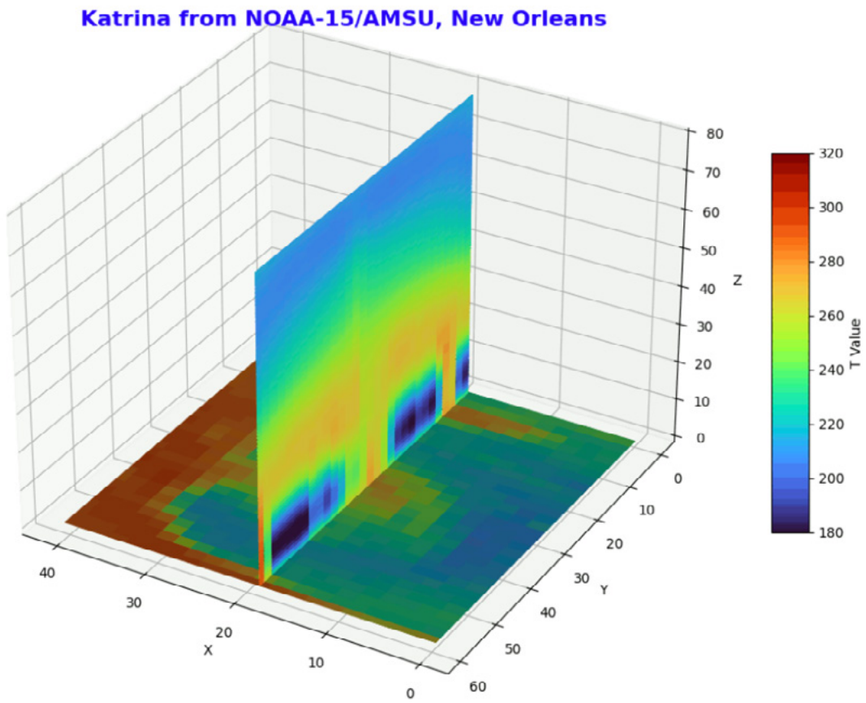
At the time of Hurricane Katrina, satellites from NOAA's Polar-orbiting Operational Environmental Satellites (POES) fleet, the predecessors to today's Joint Polar Satellite System (JPSS), also played an important role. Satellites, such as NOAA-16, captured critical observations of the storm as it moved across the southeastern United States. Flying about 520 miles above Earth, POES satellites completed orbits pole-to-pole 14 times a day.



This image of Hurricane Katrina was taken by the NOAA-16 AVHRR instrument on Aug. 28, 2005. Credit: NOAA

NOAA retired its NOAA-16 polar orbiting satellite, which operated in low Earth orbit (LEO), after the spacecraft exceeded its expected lifespan by ten years. The POES series, which began in 1978, provided decades of critical observations of Earth's atmosphere, surface, and oceans.

Early POES satellites like TIROS-N, NOAA-6, and NOAA-7 carried the original Advanced Very High Resolution Radiometer (AVHRR) instrument, which provided visible and infrared views of Earth's surface. Later generations, including NOAA-15 through NOAA-19, added instruments such as the Advanced Microwave Sounding Unit (AMSU), which measured atmospheric temperature and moisture, even through clouds and precipitation. These capabilities greatly improved forecasts for hurricanes, wildfires, floods, and other hazards, helping communities prepare for extreme weather.



Hurricane Katrina's vertical temperature profile and warm core captured by NOAA 15's AMSU instrument on Aug. 28, 2005. Credit: NOAA/NESDIS/STAR. See the original web article for an animation of the vertical temperature profile across the entire width of the storm.

Each POES satellite was originally designed to last five years, but most far outperformed those expectations. NOAA-16, for example, operated more than a decade beyond its intended lifetime, and the last operational POES satellite, NOAA-15, was only just decommissioned on August 19, 2025, almost 20 years after Hurricane Katrina made landfall. The AMSU instruments onboard these satellites directly fed into NOAA's numerical weather prediction models, advancing 3- to 5-day forecasts and helping to protect lives and property. Building on that legacy, today's Advanced Technology Microwave Sounder (ATMS) onboard NOAA's JPSS satellites delivers similar functionality, but with even better performance thanks to technological advancements.

Today's Tools for Forecasting and Monitoring Hurricanes

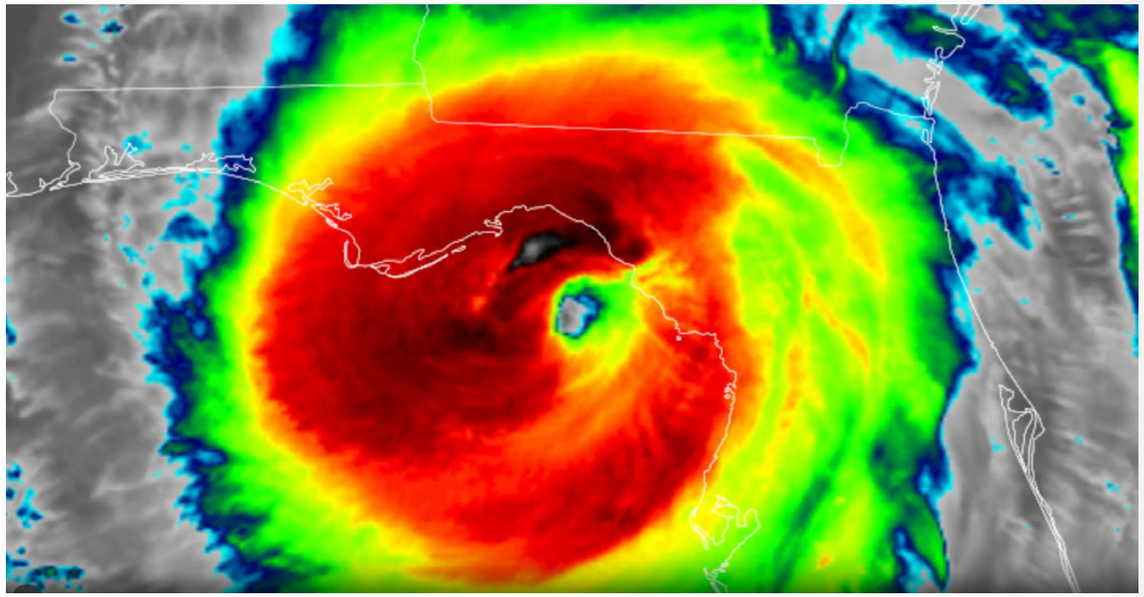
Geostationary Satellites

Today, NOAA's geostationary and polar-orbiting satellites continue to work together as a powerful team, and they have even more advanced technology that feeds more sophisticated and accurate forecast models. Today, forecast accuracy has improved so much that a five-day forecast is now better than that of a three-day forecast in 2005.

NOAA's newest geostationary satellites, called the GOES-R Series, have brought revolutionary improvements to hurricane forecasting and monitoring. They monitor environmental conditions as they happen in high-resolution detail, identifying areas where a storm is likely to form and pinpointing storms as soon as they develop. Once a hurricane forms, the satellites' Advanced Baseline Imager (ABI) gives forecasters and emergency managers real-time situational awareness of what is happening within the storm and where it is headed.

ABI can scan a targeted area as often as every 30 seconds, providing unprecedented real-time monitoring of a storm from space. Rapidly updating imagery helps forecasters better monitor cloud features and more confidently estimate the center of a hurricane. The added confidence in locating a storm's center of circulation also helps guide reconnaissance aircraft, like NOAA Hurricane Hunters, to the correct location.

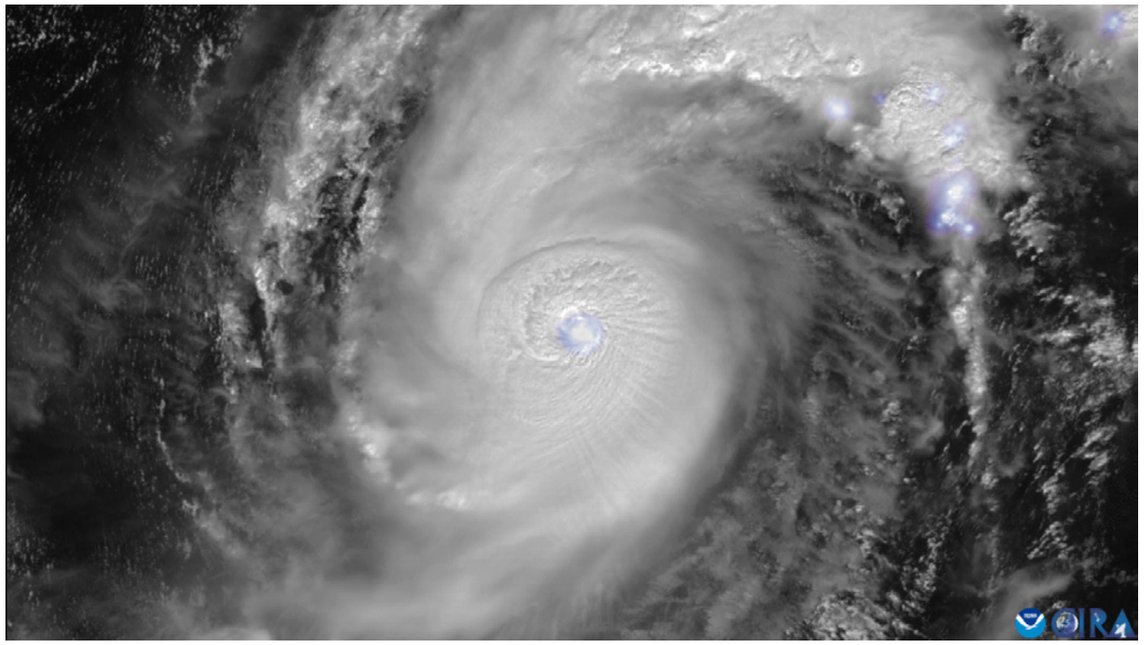
ABI also provides more measurements of the atmosphere than previous GOES imagers. New infrared channels help forecasters better determine the temperature of cloud tops and how fast they are cooling, which aids predictions of rainfall intensity and potential flash flooding associated with hurricane rain bands.



GOES-16 infrared imagery of Hurricane Helene nearing landfall as a Category 4 storm in Florida's Big Bend region on Sept. 27, 2024. See the original web article for an animation of the storm making landfall.

ABI provides much more detailed images than previous GOES. High-resolution imagery helps forecasters more accurately identify storm cloud patterns and analyze the intensity of a hurricane. Improved resolution along with frequent updates enables better wind estimates. More accurate wind data, used in numerical weather prediction models, leads to better hurricane forecasts.

The newest GOES satellites also carry the Geostationary Lightning Mapper (GLM), the first lightning mapper flown in geostationary orbit. GLM aids hurricane analysis and forecasting by clearly conveying convective patterns below the cloud tops. This information helps forecasters assess the structure and evolution of tropical storms. Rapid increases in lightning activity can indicate a hurricane is strengthening.



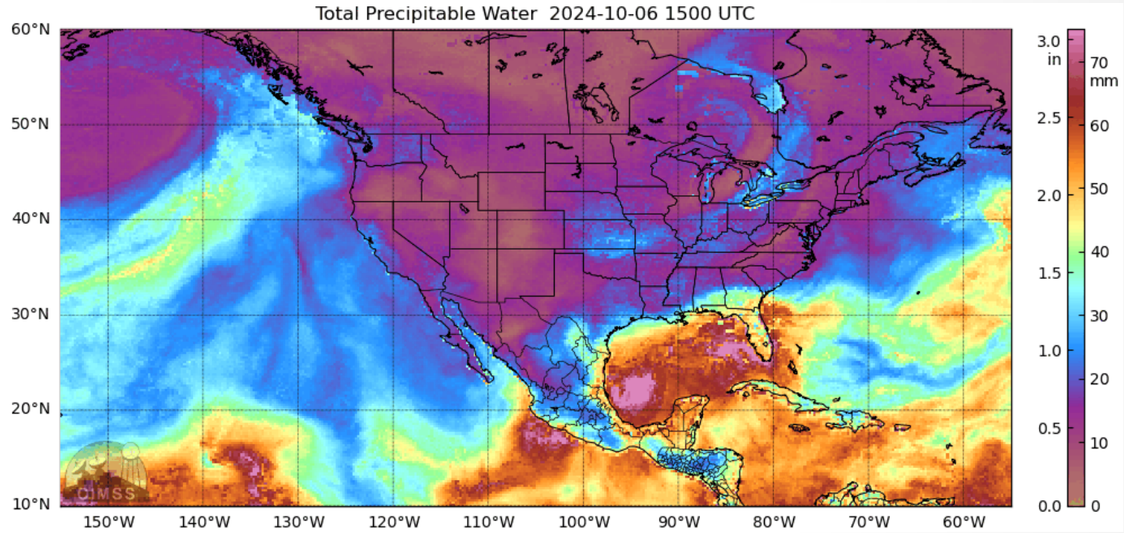
GOES-16 captured lightning activity within Hurricane Milton as it rapidly intensified on Oct. 8, 2024. See the original web article for an animation of the lightning.

Polar-orbiting Satellites

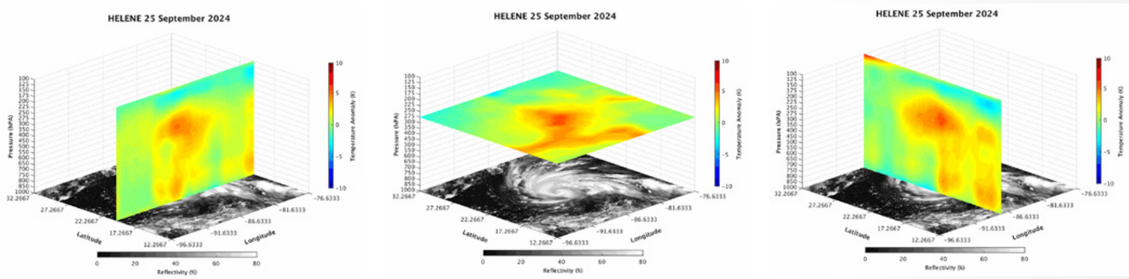
Today, NOAA continues the critical mission of collecting weather observations from a polar orbit with its current LEO constellation, JPSS. The first of five planned satellites launched in 2011, and three are now operational in orbit—NOAA/NASA's Suomi National Polar-orbiting Partnership (S-NPP), NOAA-20, and NOAA-21. Each is equipped with the Advanced Technology Microwave Sounder (ATMS) and a hyperspectral infrared sounder, the Cross-track Infrared Sounder (CrIS). Data from these sounders are used to derive vertical profiles of the atmosphere for assessing atmospheric conditions. The Visible Infrared Imaging Radiometer Suite (VIIRS) captures detailed, high-resolution visible (true color) and infrared images of storms, including at night. A fourth baseline instrument, the Ozone Mapping and Profiler Suite (OMPS), monitors the concentration of ozone and other aerosols in the Earth's atmosphere.

As a microwave sounder, ATMS is able to see through clouds and precipitation, providing information that visible and infrared sensors cannot, making it a valuable complement to CrIS and VIIRS. CrIS and ATMS data are used to generate three-dimensional profiles of atmospheric temperature, moisture, and pressure. As their capabilities are complementary, they are often used together to enable a more complete picture of Earth's atmospheric conditions. ATMS and CrIS data also contribute to Total Precipitable Water (TPW) products, which provide an estimate of the total amount of moisture in a vertical column of the atmosphere from the Earth's surface to the top of the atmosphere. TPW data are valuable for tracking hurricane intensity and estimating rainfall potential days in advance. Higher TPW values suggest more moisture is available for rainfall, and can be an indicator of potential heavy precipitation and flooding.

During Hurricane Milton in October 2024, TPW values revealed areas of concentrated atmospheric moisture, helping forecasters monitor the storm's strength and the potential for heavy rains as it approached land.



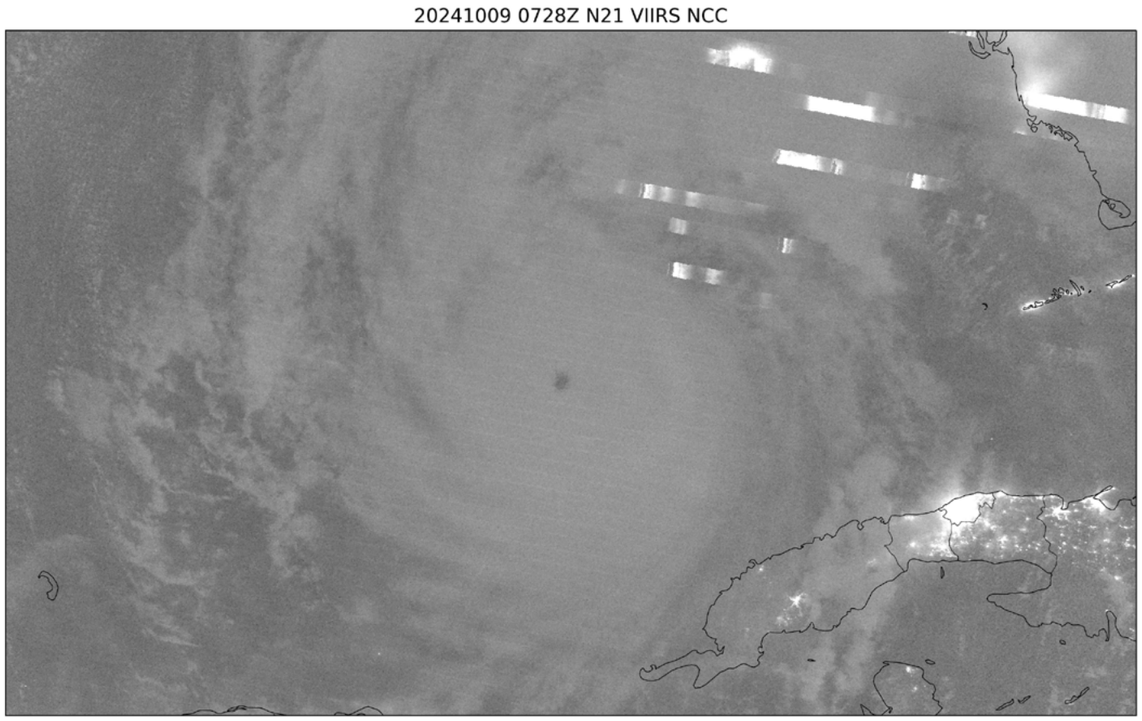
The operational TPW product, which relies on JPSS and other LEO data, shows total precipitable water (TPW) in excess of 70 millimeters (mm) associated with Hurricane Milton as it develops over the Gulf. Credit: Cooperative Institute for Meteorological Satellite Studies (CIMSS)/University of Wisconsin; NOAA NESDIS. See the original web article for an animation of TPW as the storm develops.



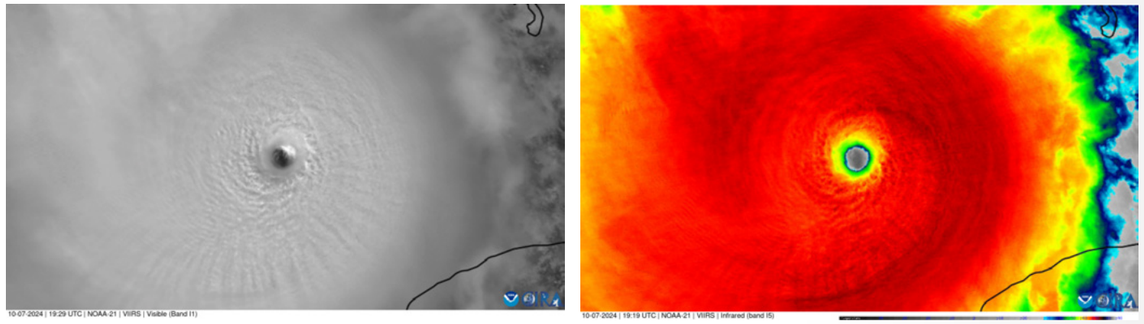
This three-dimensional view of Hurricane Helene on Sept. 25, 2024, combines satellite data derived from ATMS microwave soundings to show the storm's structure from the surface up through the atmosphere. Credit: NOAA NESDIS Center for Satellite Applications and Research (STAR). See the original web article for an animation of the vertical temperature profile across the entire width and height of the storm.

In addition, VIIRS captured high-resolution visible and infrared observations of Hurricane Milton, including a striking view of the storm's eye as a Category 5 hurricane. VIIRS also includes a highly sensitive Day/Night Band, which observes Earth's surface at night using reflected moonlight. This capability provides continuous monitoring of storms, allowing forecasters to track important changes in a storm's path that may occur overnight. When combined with model forecasts, these data improve predictions by helping meteorologists recenter storms in their forecast.

The NOAA POES fleet that observed Hurricane Katrina with its AVHRR instrument in 2005 provided imagery at 1 to 4 kilometers (km) resolution in 5 channels. By comparison, JPSS VIIRS delivers imagery at 375 to 750 meters (m) resolution in 22 different channels, which is several times sharper, along with many more channels to observe tropical cyclones. Similarly, the sounders on today's JPSS satellites represent significant advancements over the instruments carried on the legacy POES series. ATMS and CrIS offer much finer spectral detail, higher spatial resolution, and more channels, compared to their POES counterparts. These advancements in LEO capabilities allow forecasters to observe storms with greater clarity and accuracy than was possible two decades ago.



This NOAA-21 VIIRS Day/Night Band image of Hurricane Milton shows the storm at night near western Cuba, with its eye visible and numerous lightning streaks appvearing as bright white flashes. Credit: Cooperative Institute for Research in the Atmosphere (CIRA)/ Colorado State University; NOAA NESDIS.



The eye of Hurricane Milton when it was a Category 5 storm, captured by the NOAA-21 satellite on Oct. 7, 2024. The image rotates between VIIRS visible imagery (band I1) and VIIRS infrared imagery (band I5). Visible imagery is shown in grayscale. The infrared imagery measures temperature, where cold cloud tops in the eyewall appear in shades of red to dark red, while warmer clouds appear in green and blue color. Credit: CIRA/CSU; NOAA NESDIS.

While satellites can't prevent hurricanes from affecting communities, NOAA satellite data have dramatically improved over the years, providing forecasters with new and more accurate tools to measure atmospheric conditions, feed increasingly sophisticated forecast models, and monitor hurricanes in near real-time to understand their behavior. These advancements have collectively resulted in more timely and accurate forecasts and warnings, more precise landfall predictions, and a better understanding of hurricane dynamics, ultimately enhancing public safety and preparedness. ✦

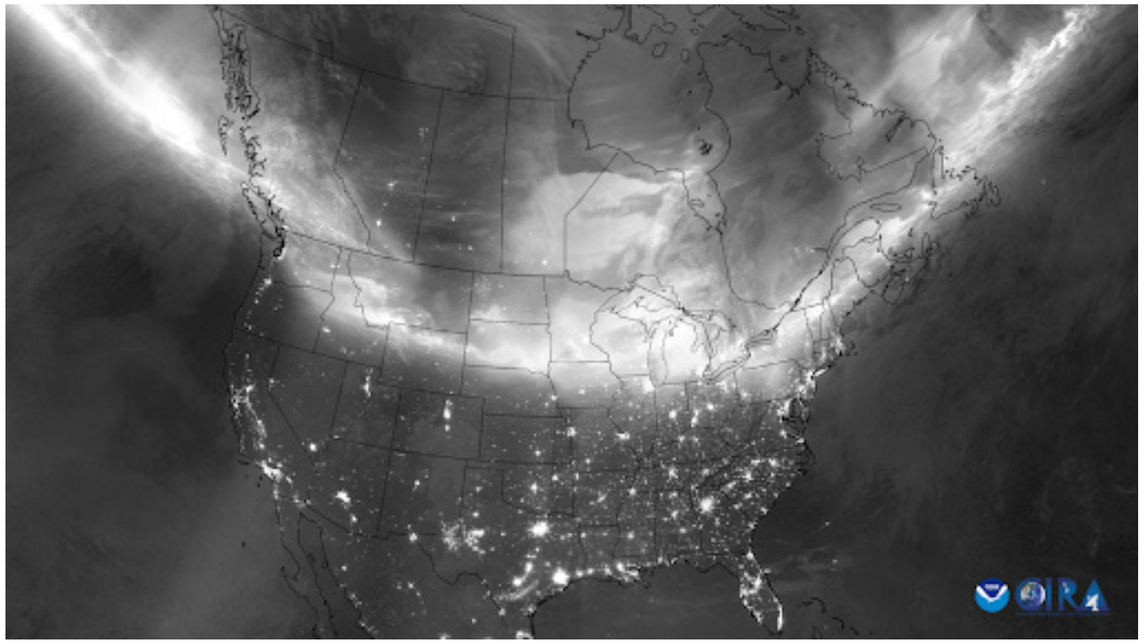
WEB FEATURE: MAY 20, 2025

Environmental Intelligence: Sensing Danger from Orbit *Part One: Worldwide Situational Awareness*

View on the NESDIS Website

NOAA satellites provide data that Americans use daily. Maintaining this "environmental intelligence" is critical to U.S. Armed Forces operations. As Space Force General David Thompson testified before the Senate Aviation and Space Subcommittee in 2019, "Every Department of Defense (DoD) operational mission begins with a weather briefing; either space weather, terrestrial weather, or both. The data required for DoD missions is often unique and necessitates 24/7 global ability to forecast weather in austere and denied environments."

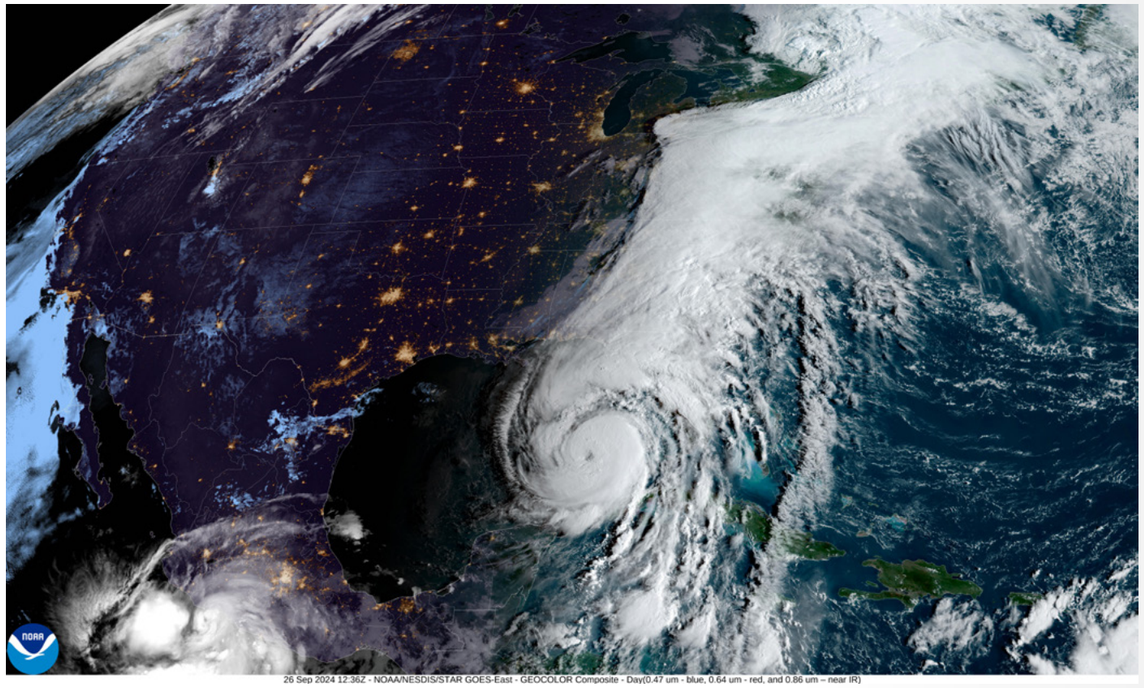
NOAA satellite data—whether used for monitoring erosion around deep-water ports, forecasting wind and air quality near airstrips, or sustaining reliable global positioning accuracy—is vital for defending national security. NOAA's information feeds weather prediction models used every day in the United States and around the world. Interagency collaborations are a force multiplier for observations of both Earth and space, as shown through agreements between NOAA, NASA, the Department of Defense, and other federal partners. Frameworks like these improve forecasts by sharing data and technology with operators.



This image from NOAA-20's VIIRS instrument shows the Northern Lights as part of an extreme geomagnetic storm that impacted Earth on May 11, 2024. Credit: Cooperative Institute for Research in the Atmosphere at Colorado State University

NOAA's Low Earth Orbit (LEO) Joint Polar Satellite System (JPSS) satellites record a complete picture of Earth twice per day. Their orbit over the north and south poles provides critical data about Earth's land, oceans, and atmosphere. Capturing a full global snapshot multiple times a day

is unique to satellites in this polar orbit. LEO sounding sensors can “see” deep inside clouds to help forecast models more accurately predict storms and keep aircraft safe. NASA launched the first polar orbiting weather satellite in 1960, founding a monumentally impactful environmental data record that NOAA has maintained since its formation in 1970. Over 65 years later, the JPSS satellites continue this effort, contributing to weather forecasting, research, and monitoring, and public safety. To a global operator like the DoD, NOAA’s LEO satellites are essential for mission planning and operational execution.



This composite image from GOES-East and the JPSS Visible Infrared Imaging Radiometer Suite shows Hurricane Helene impacting the East Coast of the United States on September 26, 2024.

NOAA’s geostationary satellites (GEO) are positioned to constantly watch over the Western Hemisphere, providing near-real-time maps of atmospheric conditions, lightning activity, weather patterns, and environmental hazards. They also provide information on solar activity and resulting space weather. Information from the Geostationary Operational Environmental Satellites (GOES) is essential for short-term weather forecasts, severe weather warnings, real-time situational awareness, and space weather forecasts and warnings.

NOAA’s Office of Space Weather Observations (SWO) develops, deploys, and sustains NOAA operational satellite systems that monitor space weather. Space weather is the variation in the space environment between the sun and Earth, primarily caused by solar events. This variation can impact assets in space, in the atmosphere, and on the ground. SWO’s programs bolster U.S. defense systems by ensuring their readiness for possible adverse effects of space weather, such as interfering with or blocking the high-frequency (HF) waves used for radio communication, triggering electrical malfunctions on satellites, and degrading satellite communications.

As mandated by the 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act, SWO provides real-time observational data to national authorities like NOAA’s Space Weather Prediction Center (SWPC) and the Air Force’s 557th Weather Wing. SWPC provides actionable space weather information for civil and commercial applications; the 557th handles operational space weather decision support services for national defense and intelligence applications.

Together, these satellite programs empower the DoD with indispensable information to protect personnel and assets.

Part Two: Front Lines & High Seas

Protecting Boots On The Ground

NOAA contributes 90% of the weather information used by the defense and intelligence communities. Satellites offer a view unrivaled by terrestrial technology. NOAA works closely with the Department of Defense (DoD) to contribute data that feeds forecasting models. The military relies on those models when planning, thereby protecting warfighters and assets both at home and abroad. From preparing for extreme temperatures to developing strategies for complex operations, situational awareness of the weather is key to success.

The DoD manages hundreds of military installations on U.S. soil alone. These bases house military personnel as well as aircraft, equipment, communications, and weapons systems that are subject to extreme weather at any time. Proper preparation and real-time environmental monitoring protects lives, property, and the American taxpayer’s investment.

Business owners in Asheville, North Carolina clean up the aftermath of Hurricane Helene. Credit: Melissa Sue Gerrits via Getty Images.

Accurate global weather data is essential to planning combat logistics as well as training operations. The microwave and infrared sounding instruments aboard NOAA's Low Earth Orbit (LEO) Joint Polar Satellite System (JPSS) satellites provide high-resolution input for forecasts globally, allowing personnel to plan military operations so that they use the weather to their advantage. Environmental conditions like cloud cover can aid in camouflage, but dust storms or severe weather could be dangerous for personnel, military equipment, and transportation plans. Rain, snow, and fog can jeopardize missions and risk lives. When the military is dealing with a time-critical target, inaccurate weather information could be catastrophic to the mission.

Extremely high temperatures on the ground are risks for military operations. NOAA satellites provide essential information for planning vehicle and troop movements in harsh environments. Heat exhaustion results in training and operations time being cut short. High temperatures harm infrastructure and equipment, from softening runway tarmac to reducing aircraft payload capacity and engine reliability.

NOAA space weather data is also used for land, air, sea, and space operations, where several types of space weather can affect radio communication. Solar flares, solar energetic particle (SEP) events, and geomagnetic storms can create atmospheric conditions that disrupt or block different parts of the radio spectrum. In December 2023, solar activity caused a complete blackout of both plane-to-plane and plane-to-ground VHF (very high frequency) communications for eight minutes, almost triggering Federal Aviation Administration (FAA) closure of most northwestern U.S. airspace. NOAA satellite data feeds into 3D models of atmospheric forecasts that inform the nation of communications blackouts, so radio operators know when to expect communications or scanning outages. Additionally, even moderate space weather effects can temporarily reduce GPS precision by dozens to hundreds of meters.

USS Tortuga (LSD 46) provided air evacuations and relief during the aftermath of Hurricane Katrina.

The Geostationary Operational Environmental Satellites (GOES) Data Collection System (DCS) supports the U.S. Army Corp of Engineers' flood risk management mission, which delivers, on average, over $200 billion of value to the country per year. DCS relays signals from 40,000 platforms on Earth that measure environmental information like water height, wave height, air quality, wind speed, and temperature. DCS provides eight million observations per day and monitors surface water, groundwater, stream flow, river levels, and precipitation to predict flooding and manage dams, locks, and levees. The DCS system provides ocean current information allowing vessels to plan travel to save fuel by traveling with the currents instead of against them. DCS also monitors ocean height for storm surge and tsunami warnings, aiding emergency response preparations. NOAA provides flood data to the Federal Emergency Management Agency (FEMA) and its partners, including DoD, for responses to domestic disasters like the April 2025 flooding of the Ohio and Mississippi Rivers. During one of the recent storms to hit Texas, the primary Army command for domestic disaster response prioritized their relief efforts using NOAA flooding maps. The Army National Guard also relied on Visible Infrared Imaging Radiometer Suite (VIIRS) data for coordinating the response to floods in 2019.

Surveying The Seas

The Navy, Marine Corps, and Coast Guard operate in high winds, punishing waves, and extreme temperatures. Maritime navigation requires environmental intelligence of potential risks and obstacles that would be impossible to see without satellite data. NOAA satellites provide data necessary for forecasting tropical cyclones, severe storms, wave heights, wind prediction, high-tide flooding, and visibility.

Accurate information helps protect tens of billions of dollars of American assets in personnel, weapons, systems, and vehicles. Proper weather forecasting is critical for preserving supply chains against disruption when time is of the essence. "Wars are won through logistics," Steven Morani, Acting Assistant Secretary of Defense for Sustainment, told the Worldwide Logistics Symposium. Extreme weather exacerbates the need for robust planning and access to supplies.

LEO satellites have a unique view of the polar regions due to their paths over the north and south poles. Satellites can survey ice thickness, which is of particular interest to submariners. JPSS tracks melting sea ice, which is hazardous for ships. In some areas, ice melt opens new routes, which increases international traffic through the Arctic Circle. In others, thinning ice packs shed more loose chunks. In the last 20 years, the safe transit season of the Beaufort Sea north of Alaska has halved as large sheets of broken-up ice choke shipping lanes.

USCGC Polar Sea on an expedition in the Beaufort Sea. Credit: Stocktrek Images via Getty Images.

Organizations like the Navy's 2nd Fleet and the Coast Guard's 9th District also use LEO and geostationary satellites (GEO) imagery to monitor shipping traffic, maintain border security, and enforce trade restrictions. The VIIRS onboard JPSS captures nighttime imagery used to track ships, particularly those fishing illegally. While nighttime often masks illicit activity, VIIRS sees fishing vessels through the veil of darkness.

Part Three: Air & Space

NOAA Prevents Pilots From Flying Blind

Despite the hazards inherent to air travel, U.S. civil and military aviation is by far the safest form of transit. This is in part due to complementary radar, command and control systems, and satellite-driven weather forecasting. Atmospheric conditions like dust, clouds, ice, and water vapor are a prime concern to aviators. NOAA's Low Earth Orbit (LEO) and geostationary satellites (GEO) satellites provide combined overwatch for potential atmospheric dangers, protecting valuable aircraft and human assets. Volcanic ash is a dramatic example: in 2010, the eruption of Eyjafjallajökull created a plume of heavy ash that interrupted enormous swaths of European airspace for almost a week. The microwave and infrared sounders flying on Joint Polar Satellite System (JPSS) work in conjunction to provide three-dimensional profiles of the physical properties of the atmosphere, revealing what pilots will find above, below, and even inside the clouds.

Accurate forecasts fueled by satellite data allow warfighters to plan operations with unprecedented efficiency and safety. Wind patterns, cloud cover, water vapor, and visibility measurements from satellites help meteorologists identify turbulence events. Flight planners use that information to plan routes to avoid the most dangerous turbulence.

Members of the Alaska Air National Guard training for a civilian rescue operation via helicopter. (U.S. Air National Guard photo by Staff Sgt. Edward Eagerton/released)

Take-off and landing are the most dangerous phases of flight, as lower speeds and altitude reduce safety margins. GEO satellites provide immediate detection of potential weather issues and threats. Real-time "eye in the sky" and model-driven forecasted conditions arm air traffic controllers with the environmental intelligence to select the safest flight paths as well as takeoff and landing approaches. This is particularly important for flight operations at sea, which require highly specific wind conditions to launch and recover aircraft, even requiring ships to change course and speed to create the correct conditions.

NOAA also supports the Department of Defense (DoD) mission by transferring Geostationary Operational Environmental Satellites (GOES) satellites that have completed their NOAA mission to the U.S. Space Force. Currently, the satellite that previously operated as GOES-15, renamed Electro-optical Infrared Weather System-Geostationary 2 (EWS-G2), operates over the Indian Ocean. In its new position, EWS-G2 provides critical weather data for planning and executing air, land, and maritime military operations across the region.

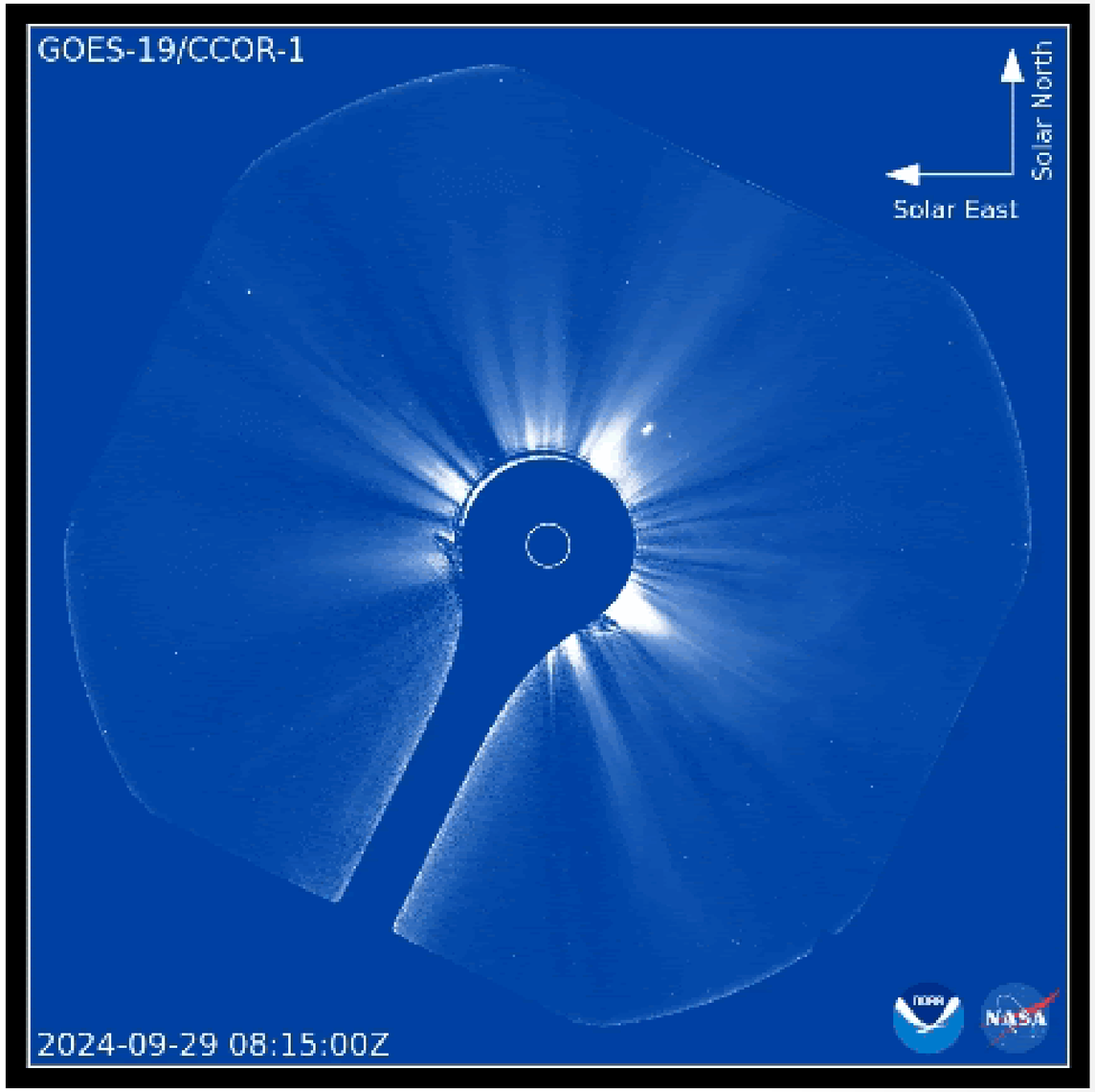
Solar activity can also disrupt any technologies that rely on radio or microwave transmissions, including radio communications and radar signatures, including GPS functionality. GPS radio signals pass through the Earth's upper atmosphere as they travel from the satellite to the receiver on the ground. When a space weather event disturbs that area, GPS receivers cannot properly determine position. Space weather also increases radiation in the upper atmosphere, which is especially hazardous to pilots and crew for polar flights. Finally, when disruptions do occur, space weather monitoring aids operators in satellite anomaly attribution, helping distinguish natural effects from other activity.

Keeping American eyes in the skies

Space weather disturbances influence our planet and nearby space environment enormously. In addition to affecting navigation and communications, space weather can shut down power grids. While extreme space weather events are far less common than extreme terrestrial weather events, they pose a substantial national security risk. Such an event would batter both civilian and military infrastructure. The Congressional Budget Office projects that damage from a severe solar storm would be astronomical; their 2020 analysis estimates costs in excess of a trillion dollars. The same report underlines the comparative scope of a major solar event, which would dwarf other worst-case scenarios such as a major conventional conflict with large-scale military operations or an electromagnetic pulse (EMP) attack.

Space weather heats Earth's upper atmosphere and causes expansion, known as atmospheric drag, that can significantly slow satellites and requires more fuel to maintain their orbit. In more extreme cases, the increased drag can even be destructive. During a period of moderate solar activity in February 2022, 38 Starlink satellites de-orbited shortly after launch due to atmospheric drag. Losses like this are dangerous as the debris can cause cascading risks to other important satellites.

NOAA's latest generation of GOES satellites carry an instrument that, while designed to map lightning, also detects bright meteors, known as bolides, when they enter Earth's atmosphere. Geostationary Lightning Mapper (GLM) data helps NASA's Planetary Defense Coordination Office



Energetic protons from solar radiation storms can cause profound damage to electronic circuits and biological tissue, creating danger for both uncrewed systems like drones and satellites as well as astronauts and high-altitude crews. See the original web article for an animation of the solar storm.

and DoD better understand and mitigate the threat posed by larger asteroids hitting Earth. GLM data helps improve impact prediction warnings by studying how asteroids fragment as they travel through the atmosphere. This information informs risk assessment models and strategies to deflect potentially dangerous asteroids away from Earth.

Both GOES-19 and the Space Weather Follow On at Lagrange 1 (SWFO-L1) carry sun-observing instruments such as the Compact Coronagraph (CCOR). CCOR provides operational monitoring of our sun to warn about its most energetic activity like coronal mass ejections (CMEs), shown below. CMEs pointed at Earth have caused the strongest space weather effects in recorded

history; continued CME monitoring is essential to national security. NOAA has a series of three CCOR instruments: CCOR-1 is onboard GOES-19 in geostationary orbit, while CCOR-2 and -3 will settle at distant points out in deep space. NOAA will combine images from the three instruments to paint a more complete picture of CMEs, improving detection and increasing warning time.

Worldwide situational awareness

Weather is a powerful force on Earth. Harnessing NOAA satellite data makes the U.S. military powerful. Missions like GOES and JPSS collect data used for comprehensive planetary modeling and high-resolution focus. Looking outward, solar monitoring gives the U.S. military forewarning against threats to communications, navigation, and equipment. In addition to all the direct observations afforded by the many complementary instruments, NOAA's archives, algorithms, and expertise are indispensable assets to military environmental intelligence. ✦

Thank you for reading the 2025 LEO Science Digest!

Learn more about the NOAA NESDIS Office of Low Earth Orbit (LEO) Observations by visiting our web page.