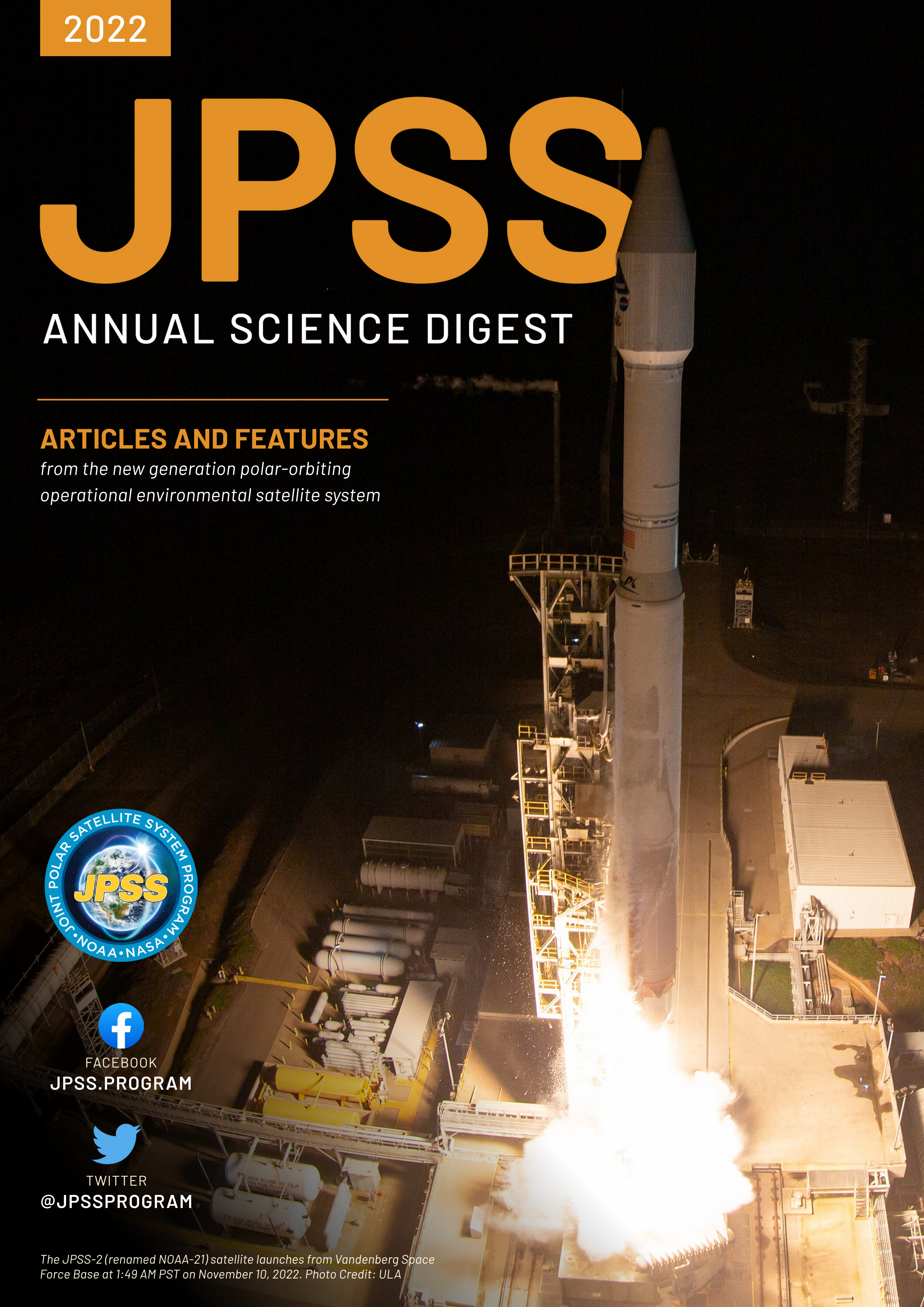
2022

JPSS

ANNUAL SCIENCE DIGEST

ARTICLES AND FEATURES

from the new generation polar-orbiting operational environmental satellite system



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The JPSS-2 (renamed NOAA-21) satellite launches from Vandenberg Space Force Base at 1:49 AM PST on November 10, 2022. Photo Credit: ULA

IN THIS DIGEST

4 2022 JPSS Annual Science Digest Contributors

6 A Message from the JPSS Program Director

10 A Message from the JPSS Senior Program Scientist

★ FEATURED ARTICLES

14 **FEATURE 1** Visualizing Clouds in Three Dimensions for Aviation Weather Applications

32 **FEATURE 2** Using Airborne Truth Data to Validate the Visible Infrared Imaging Radiometer Suite (VIIRS) Aerosol Detection Product

50 **FEATURE 3** On the Lookout for Bioluminescent Milky Seas: Using NOAA Satellites To Spot a Mysterious Natural Wonder

82 **FEATURE 4** Inspecting the Atmosphere's "Plumbing" With Multi-satellite Water Vapor Products

102 **FEATURE 5** The NOAA Unique Combined Atmospheric Processing System (NUCAPS): A Supplementary Tool for Forecasting Severe Storms

126 **FEATURE 6** Estimating Phytoplankton Size Class in the Northeast U.S. Continental Shelf Using Regionally Tuned Ocean Color Algorithms

150 **FEATURE 7** Fire Light at Night: Quantifying Fire Combustion Phase Using the Visible Infrared Imaging Radiometer Suite (VIIRS)

174 **FEATURE 8** Engaging with National Centers for Environmental Information (NCEI) Data Users

190 **FEATURE 9** Mapping and Monitoring River Ice With a Visible Infrared Imaging Radiometer Suite (VIIRS) Product Tool

220 **FEATURE 10** The Role of the Joint Center for Satellite Data Assimilation in Data Assimilation for Better Weather and Climate Prediction

242 **FEATURE 11** Exploring the Use of Ocean Biogeochemical Data in Marine Ecological Forecasting and Operational Weather Models

268 **FEATURE 12** Expanding the Use of VIIRS Aerosol and Fire Products Through a Customizable Hands-on Training Program

290 **FEATURE 13** Planning for the Next Generation of Satellite Sensors: Insights From NOAA Workshops

WEB FEATURES

300 *WEB FEATURE:* The Most Important Instrument You've Never Heard Of

314 *WEB FEATURE:* NOAA's Next Polar Orbiting Satellite Prepares For Launch

320 *WEB FEATURE:* JPSS-2 Satellite Gets Its Solar Array Installed

322 *WEB FEATURE:* Forecasting Weather For The Weather Satellite Launch

HIGHLIGHTS

326 *HIGHLIGHTS:* Social Media

330 *HIGHLIGHTS:* Public Outreach & STEM Engagement

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Feature 4—Inspecting the Atmosphere's "Plumbing" With Multi-satellite Water Vapor Products:
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Feature 5—The NOAA Unique Combined Atmospheric Processing System (NUCAPS): A Supplementary Tool for Forecasting Severe Storms:
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Feature 10—The Role of the JCSDA in Data Assimilation for Better Weather and Climate Prediction:
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FROM THE
JPSS PROGRAM DIRECTOR

It is an exciting time and great honor to share my first Science Digest message with you as JPSS Program Director. The year began with JPSS-2 entering and completing critical pre-launch testing milestones before being shipped from the spacecraft facility in Gilbert, AZ to its Vandenberg Space Force Base launch site in August. By year's end we saw the culmination of years of work with the spectacular launch of JPSS-2 on November 10 at 1:49 am PST from Vandenberg Space Force Base.

JPSS continued to provide life-saving data and valuable products to users in another year marked by significant hurricanes, tornadoes, droughts, floods, fires, and heat waves. In October, Suomi National Polar-orbiting Partnership (Suomi NPP) celebrated its eleventh year of operations. In November, NOAA-20 completed its fifth year in orbit, the same month JPSS-2 launched. We're seeing the first science being produced by JPSS-2, now renamed NOAA-21, as its four 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)—are being brought online and calibrated. NOAA-21 has already sent back data for ATMS and VIIRS first-light images. At the end of December, the VIIRS and CrIS cooler doors will open, followed by the CrIS detector power-on and the OMPS door opening, providing data for our teams to produce the first-light images from OMPS and CrIS. Our teammates at the NOAA Satellite Operations Facility are leading the commissioning process for NOAA-21 to be the primary satellite in the JPSS constellation while continuing to operate Suomi NPP and NOAA-20.

JPSS-3 and -4 are progressing well, with launch readiness expected for 2027 and 2032. JPSS-3's four main instruments cleared pre-ship reviews in the beginning of the year and are now beginning integration and testing at the spacecraft facility after their arrival in December. The new Libera instrument that will fly on JPSS-3 completed its Preliminary Design Review this year. Libera will continue the mission of the Clouds and the Earth's Radiant Energy System (CERES) Sensors on earlier JPSS satellites. CERES measures Earth's outgoing radiative energy and provides vital information on the state of Earth's climate.

In preparing for the future of Low Earth Orbit (LEO) observations to include a larger commercial component, we are progressing in developing a small sat microwave sounding mission known as QuickSounder. QuickSounder will be a risk mitigation mission we will implement and fly for NOAA within 3 years. This mission will include a NASA Rapid Spacecraft Development Office bus with the refurbished ATMS engineering development unit made available during the ATMS acquisition. QuickSounder will allow us to provide additional critical microwave sounding observations in an orbit different than our traditional early afternoon JPSS orbit. In December, a QuickSounder Milestone 2 review was successfully completed to baseline the project.

With QuickSounder leading the way, we are defining future LEO architecture beyond JPSS-3 and -4. We anticipate that architecture will include a disaggregated set of instruments, allowing us to provide, among other things, increased orbital diversity and faster refresh rates for critical data necessary to optimize numerical weather prediction. In December, the new Sounder for Microwave Brightness and Analysis (SMBA) team held an Industry Day for the Phase A Study to foster discussion on the SMBA instrument, which will serve as the backbone microwave sounder for the new proposed Low Earth Orbit – Environmental Observations System (LEOS) program. The team met with six vendors and answered questions pertaining to the Request for Information that was released, with Phase A study awards expected to be made in the 1st quarter of FY2024.

The success of our satellite programs, both ongoing and emerging, is a direct result of extensive collaboration and the work done by the satellite developers, our NOAA corporate partners, and our national and international stakeholders. JPSS continues to emphasize global collaboration. Our extensive User Engagement activities have helped build a strong foundation of operational applications to meet users' mission requirements. The program also maintains 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 leverage existing and planned capabilities from other research and operational satellite programs to deliver more capabilities 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 patterns.

Weather and climate headlines in the news this year highlighted the need for these critical partnerships and programs. One example is the satellite capabilities used during the 2022 Hurricane Season. This hurricane season produced 14 named storms (winds of 39 mph or greater), of which eight became hurricanes (winds of 74 mph or greater) and two intensified to major hurricanes with winds reaching 111 mph or greater. Two major hurricanes, Ian and Nicole, made landfall in Florida. Hurricane Ian tied for the fifth-strongest hurricane ever to make landfall in the U.S., as a Category 4 with 150 mph maximum sustained winds, causing at least 137 fatalities. Hurricane Nicole became only the third November hurricane on record to make landfall in Florida. Nicole crossed the same region in Florida devastated six weeks earlier by Hurricane Ian. Despite being relatively weak, Nicole's large size produced widespread heavy rainfall and strong winds across the Greater Antilles, the Bahamas, and Florida, knocking out power and inflicting significant damage in many areas. The U.S. National Hurricane Center (NHC) used JPSS ATMS products and the AMSR2 sensor on the Japan Aerospace Exploration Agency (JAXA) Global Change Observation Mission - Water (GCOM-W) satellites to define the structure of these hurricanes and evaluate structure change as they developed and came inland.

According to NOAA Administrator Rick Spinrad, Ph.D., "Forecasters at NOAA's National Weather Service and its National Hurricane Center issued earlier forecasts with increasing accuracy this season. These improved forecasts coupled with critical NOAA data and services undoubtedly led to the better protection of life and property."

The JPSS Program can take great pride in doing its part helping in the response to these storms.

Thank you to the many contributors to this Science Digest, and to our JPSS science team and community for their contributions to the program. This Science Digest joins the other Digests dating back to 2014 in documenting the successful research and operational applications of our JPSS capabilities. Thank you to Satya Kalluri, JPSS program scientist, for his leadership.

Between the successful launch of JPSS-2 to our new formulation efforts to define the future of LEO observations, 2022 was a tremendous year for the Program. There is much to look forward in 2023 as we continue the success of JPSS and progress with QuickSounder and the proposed LEOS Program, offering this generation a rare opportunity to shape the future.

Tim Walsh
Joint Polar Satellite System (JPSS) Satellite and Information Services National Oceanic and Atmospheric Administration (NOAA)

FROM THE
JPSS SENIOR PROGRAM SCIENTIST

2022 has been yet another remarkable year in the history of the NOAA NESDIS Joint Polar Satellite System (JPSS) program with the successful launch of the JPSS-2 satellite, now renamed NOAA-21, from Vandenberg Space Force Base in the early morning hours of November 10, 2022. As of the publishing of this Science Digest, all NOAA-21 sensors have opened their doors and begun collecting Earth science data. The hardworking scientists at the NOAA Center for Satellite Applications and Research (STAR) and NASA have declared that the NOAA-21 instruments are performing as designed. The contributions of these scientists to the success of the JPSS mission are much appreciated. With almost identical sensors onboard three JPSS satellites in the same orbit, Suomi National Polar-orbiting Partnership (Suomi NPP), NOAA-20, and now NOAA-21, there is great resiliency in the JPSS program, and more to come with future JPSS satellites, JPSS-3 and -4.

While the JPSS engineers were hard at work pushing NOAA-21 to launch, the science and end user communities were busy as ever exploiting and innovating the science data from Suomi NPP and NOAA-20 instruments. The 2022 JPSS Annual Science Digest highlights some of the exciting accomplishments from the past year.

The applications and benefits of JPSS data are many. JPSS and Low Earth Orbit (LEO) data are critical to protecting lives and property and they provide critical inputs to ocean, land, and atmospheric models. One example is Numerical Weather Prediction (NWP), as described in Feature 10 that highlights the role of the Joint Center for Satellite Data Assimilation (JCSDA) in improving weather and climate prediction. Also, data from both LEO (JPSS) and geostationary satellites (GOES-R) are complimentary across many short-term forecasting applications, and Features 1, 4, and 5 provide excellent examples of how these data, used together, impact short-term weather prediction for aviation, atmospheric rivers, and atmospheric stability leading to severe weather and precipitation events. Over northern latitudes where cold weather leads to freezing of inland water bodies causing river ice, VIIRS data has been successfully demonstrated to detect and monitor changes in river ice conditions, helping emergency managers and flood forecasters assess the risks associated with rapidly melting river ice (Feature 9).

Over the oceans, JPSS and other LEO data are used in ocean biogeochemical models, like those described in Feature 11, that are important for marine ecological forecasting for coastal area management, weather prediction, and climate change adaptation and mitigation. Another example: VIIRS ocean color products are used to monitor phytoplankton, an important indicator of healthy oceans to support recreational and commercial fisheries (Feature 6). While the unique VIIRS Day/Night Band capability has contributed to a variety of applications in weather, as well as monitoring anthropogenic activity through detection of lights over land and water, it is still enabling new discoveries such as the mysterious "milky seas" bioluminescence phenomena described in Feature 3. VIIRS data are also extensively used for fire detection and characterization (Feature 7), aerosol detection (Feature 2), and air quality science (Feature 12), all of which are interrelated.

The JPSS program supports a variety of training opportunities through several initiatives and venues such as the University Corporation for Atmospheric Research (UCAR) COMET program and at scientific meetings, for example, the American Meteorological Society (AMS) annual meeting. These training programs are critical to the success of our program. Feature 12 highlights a training program developed by the NOAA STAR Aerosols and Atmospheric Composition Science Team that is designed to increase access to aerosol, fire, and trace satellite products from VIIRS and other sensors and promote their proper use in air quality applications. In addition to working with our core users, the JPSS program is committed to inspiring our next generation of budding scientists and engineers through STEM engagement at all education levels and public outreach activities. The Highlights articles at the end of this digest feature many of the activities and accomplishments of the JPSS Communications Team from the past year.

Understanding the impact of public engagement, who our users are, and how JPSS data are used are also priorities at NOAA and JPSS. Feature 8 gives a detailed look into the well-established user engagement process at the NOAA National Centers for Environmental (NCEI) and provides insights into the JPSS end user community. Such information is valuable in demonstrating the broad use of our data for societal benefits, as well as understanding what resources, products, and services are needed to support all sectors of the U.S. economy.

Looking to the future, this year NESDIS established a LEO Program tasked with managing all LEO observations. The program will include observations from NOAA satellites like JPSS, as well as from partner agencies like the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the Japan Aerospace Exploration Agency (JAXA). As part of the planning and formulation process of future LEO observations, the LEO Program Office held several workshops to understand how current observations are used, their impact, and future enhancements needed. Feature 13 provides a summary of these user workshops, which each focused on a different topic: microwave (MW) sounders; infrared (IR) sounders; ultraviolet/visible/near infrared (UV-Vis-NIR) instruments; and the Visible Infrared Imaging Radiometer Suite (VIIRS). It is hard to summarize the wealth of applications and societal benefits from these workshops in a summary report and I highly encourage our readers to visit the JPSS Workshops & Events webpage to appreciate the large number of applications and benefits resulting from the JPSS mission.

I would like to extend my gratitude to Ms. Amy Leibrand for composing the excellent articles in the 2022 JPSS Annual Science Digest and to Mr. Bill Sjoberg for seeking out the innovators to present their experiences at the monthly JPSS Science Seminars. I am indebted to the highly capable and motivated JPSS Communications Team whose contributions are evident in this publication. I am lucky to have science support staff who actively manage and engage with the JPSS science activities, including the JPSS Proving Ground and Risk Reduction activities. As we embark on the LEO program, we are excited to bring you a broader range of science applications and an unprecedented number of global observations from JPSS and our partner missions in the coming years.

Satya Kalluri
Joint Polar Satellite System (JPSS) Satellite and Information Services National Oceanic and Atmospheric Administration (NOAA)

FEATURE 1

Visualizing Clouds in Three Dimensions for Aviation Weather Applications

Image Credit: Photograph: Adam White. Clouds seen from the window of a Cessna P206C plane in Northwest Alaska along the Kobuk River. https://www.nesdis.noaa.gov/news/new-data-product-warns-alaska-pilots-of-clouds-dangerously-cold-weather

Weather is a frequent factor in aviation accidents. In Alaska, unpredictable weather contributes to an accident rate more than double that of the rest of the United States. Because most of Alaska is inaccessible by road, more than 80% of Alaskans rely on aviation to access goods and services. Clouds are visible indicators of weather, and pilots and aviation meteorologists rely on cloud information to assess weather conditions for flight planning. Clouds are made up of water droplets and ice crystals that can hamper visibility, produce turbulence, and cause ice to form on a plane's surface. Dense vertical cumulonimbus clouds often produce severe weather, such as lightning, hail, and dangerous winds, posing hazardous flight conditions.

Satellites provide crucial information about cloud properties as they offer a "big picture" view of cloud extent and type as well as other properties like a cloud "map" of a region. For example, observations from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument aboard the NOAA-20 and the NOAA/NASA Suomi National Polar-orbiting Partnership (Suomi NPP) spacecrafts are used to evaluate cloud phase and structure, such as whether a cloud is made up of liquid, ice, or a mix of both, and at what altitude clouds are located. Cloud information plays an important role in aviation meteorology, especially in regions like Alaska where conditions can change rapidly, and data is sparse.

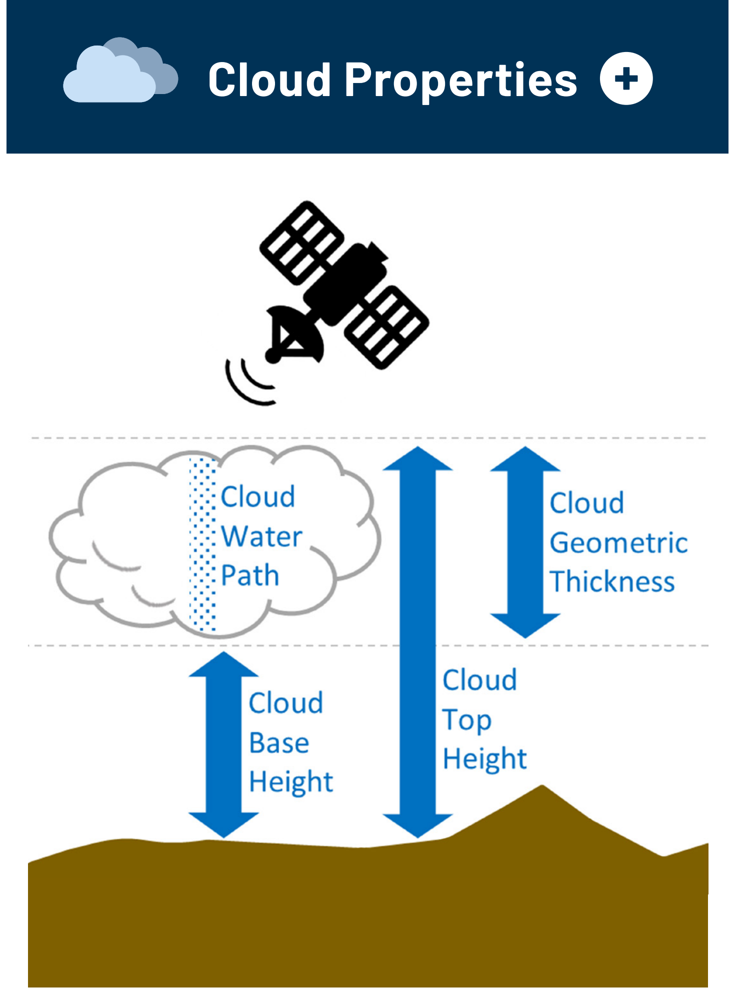
THE MORE INFORMATION THE BETTER

Recognizing a need for improved forecasting of aviation hazards, in 2018, NOAA established the JPSS Aviation Initiative with a focus on engaging pilots and aviation forecasters in Alaska. The initiative helps the polar aviation community by providing new and improved satellite products and collaborating with end users. In support of the initiative, research scientist Yoo-Jeong Noh and others at the NOAA Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University are working on new approaches to enhance satellite cloud information.

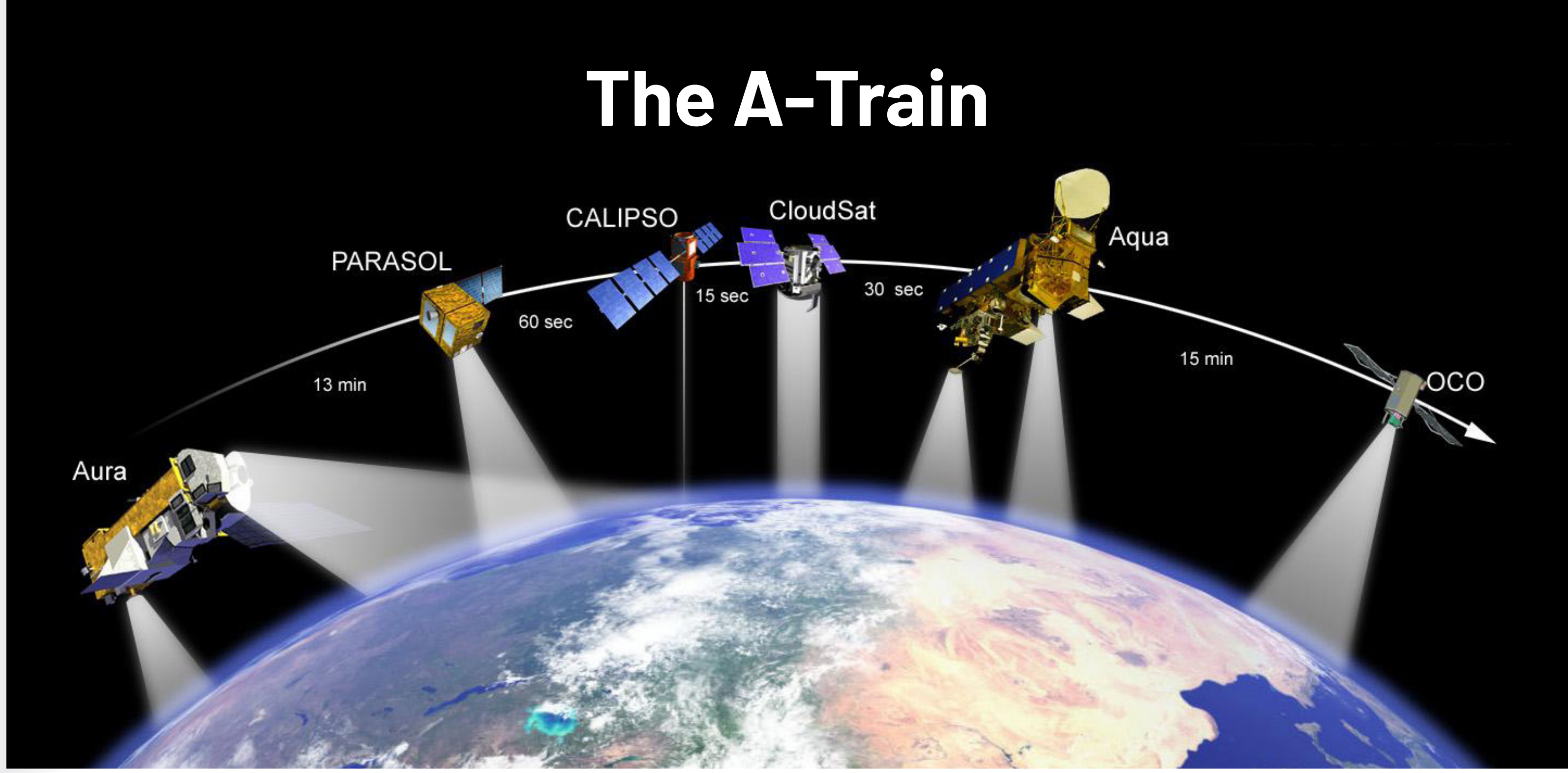
Traditionally, the aviation community uses 2D weather charts to assess conditions prior to flight, but 2D maps lack information about vertical cloud structure. Vertical cloud formation is difficult to evaluate in two dimensions but is important to pilots because what happens inside of a cloud—between its highest and lowest boundaries—often dictates flight conditions. One solution developed by Noh and her team uses cloud properties retrieved from satellites to build 3D cloud structures. Like the name implies, 3D cloud structures allow pilots to see cloud conditions in three dimensions along a vertical path within a cloud cross-section. However, obtaining cloud properties from satellites to build a 3D cloud is tricky.

THE ELUSIVE CLOUD BASE HEIGHT

Key components in constructing a 3D cloud structure include cloud top height, cloud water path, cloud geometric thickness, and cloud base height. Cloud information from visible and infrared satellite instruments, like VIIRS, is mostly biased toward the cloud top because their wavelengths cannot pass through clouds. Clouds reflect or absorb visible and infrared light, so on a cloudy day these instruments will only see the tops of clouds, meaning that knowledge is limited about what lies beneath. While visible and infrared satellite instruments reliably estimate cloud top height and vertical water content (cloud water path), they cannot easily measure cloud base height. Cloud base height—the part of the cloud closest to the ground—is critical for building a 3D cloud structure.



To tackle this challenge, Noh and her team developed a Cloud Base Height (CBH) algorithm using a new method to determine cloud geometric thickness to help estimate cloud base height. These enhancements led to the launch of an experimental 3D cloud product that enables aviation users to visualize weather conditions as a vertical cross-section along a flight path. In November 2021, Noh presented research and development highlights at the JPSS monthly science seminar.

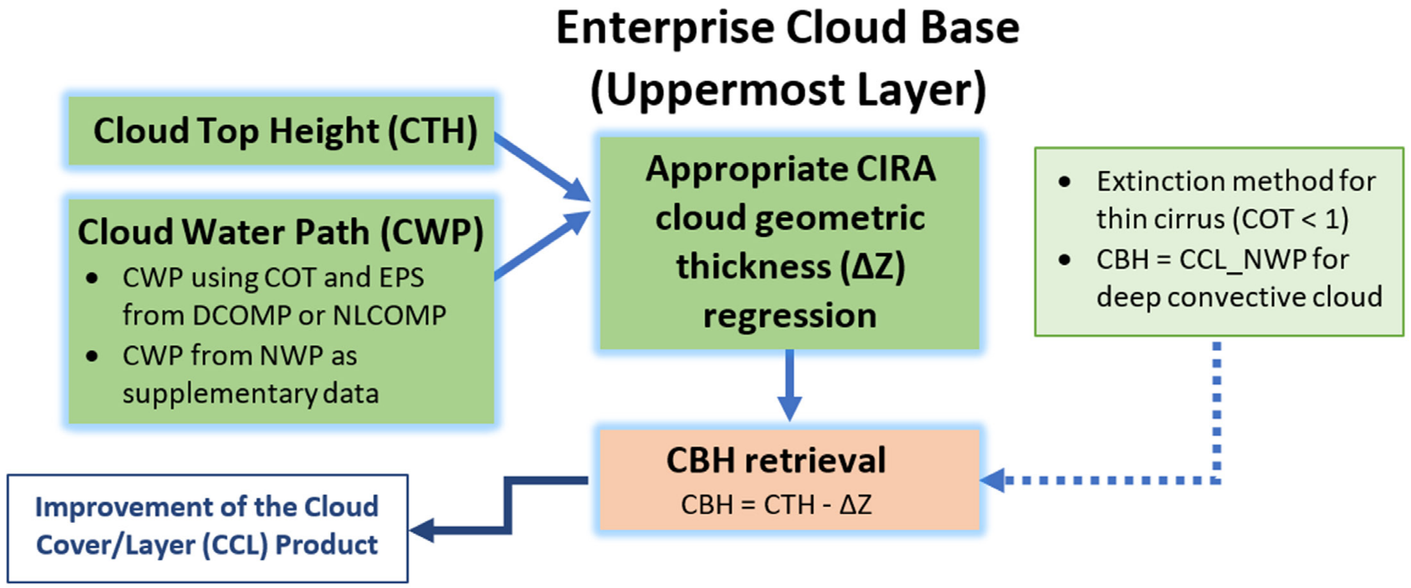


The Afternoon Train, or "A-Train" for short, is a constellation of NASA satellites that travel one behind the other, along the same track, as they orbit Earth. Source: NASA Jet Propulsion Laboratory.
https://www.jpl.nasa.gov/images/pia03010-a-train-artists-concept

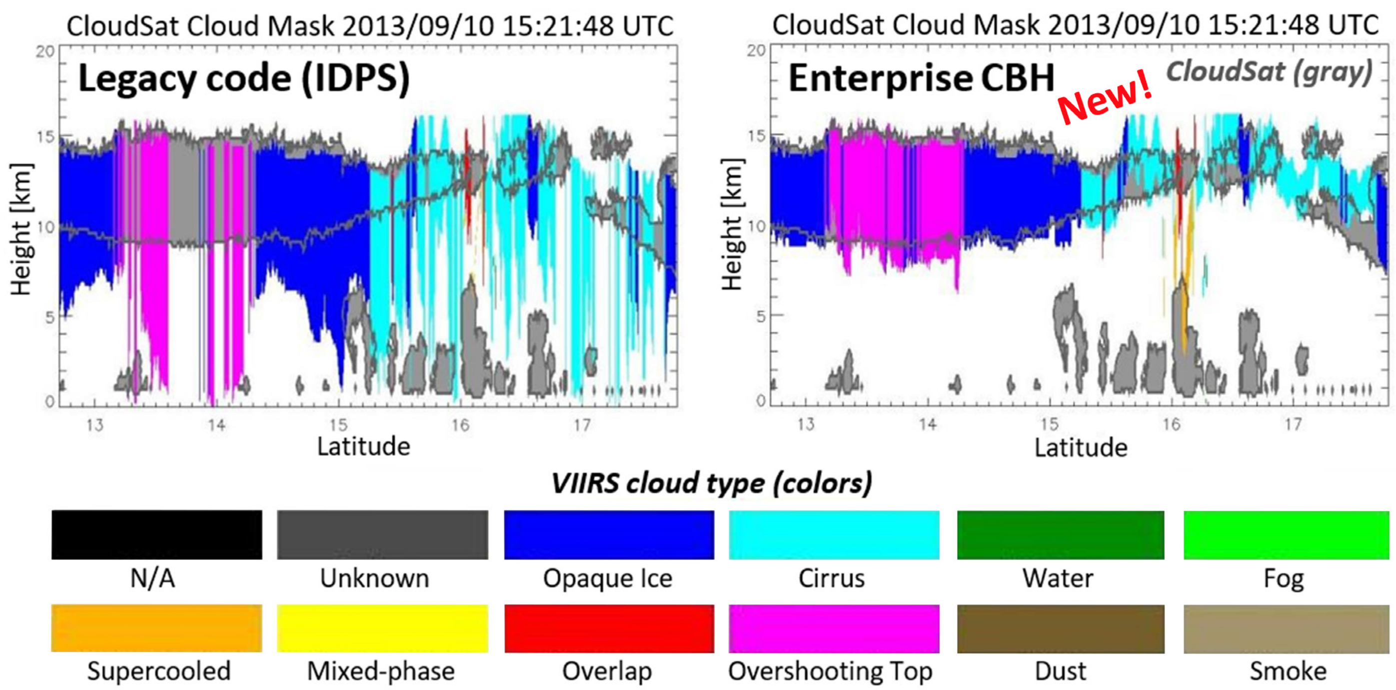
AN IMPROVED APPROACH TO CLOUD BASE HEIGHT RETRIEVAL

The new CBH algorithm uses sensor observations from three of NASA's A-Train satellites: CloudSat, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), and Aqua. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard Aqua provided cloud cover, cloud top height, and cloud water path information. CloudSat and CALIPSO data were used to identify vertical structure and cloud geometric boundaries. With this information, Noh and her team performed statistical analysis to retrieve cloud base height, providing the necessary information to convert 2D cloud information into a 3D cloud structure.

Retrieval of cloud base height with the new CBH algorithm has its limitations. Noh notes that "the relationship between cloud geometric thickness and cloud water path is constrained by [the



accuracy of] cloud top height." Also, because nighttime satellite cloud data without visible information is relatively unreliable, nighttime collection requires additional data from numerical weather models. Numerical weather models are computer simulations of weather that have drawbacks (accuracy and data gaps) but provide adequate supplementary information when data is sparse. Further, the CBH algorithm performs best on single layer clouds (or uppermost layers), neglecting characterization of complex multi-layer clouds for a more complete understanding of cloud conditions. The cloud base height in multi-layer cloud scenes may not be what is considered a 'ceiling' in the aviation community (that is, the height of the base of the lowest clouds).



Comparison between the new NOAA Enterprise Cloud Base Height Product (right) and the previous cloud base height product (left) showing improvements with the new CBH algorithm.

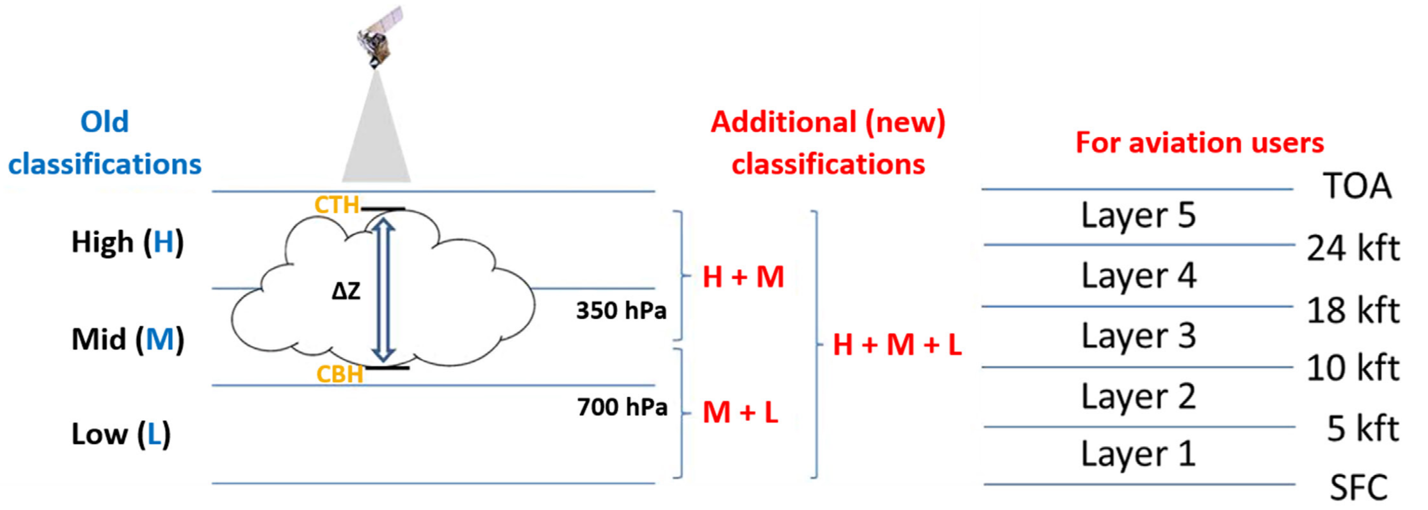
So far, the new CBH algorithm is operational for VIIRS as part of the NOAA Enterprise Cloud Algorithm (VIIRS Cloud Base Height Product). The CBH algorithm is also undergoing testing for Geostationary Operational Environmental Satellite (GOES) Advanced Baseline Imager (ABI) operations. Validation using independent CloudSat and CALIPSO data shows sizable improvement compared with the previous algorithm.

PUTTING THE CLOUD BASE HEIGHT ALGORITHM TO WORK

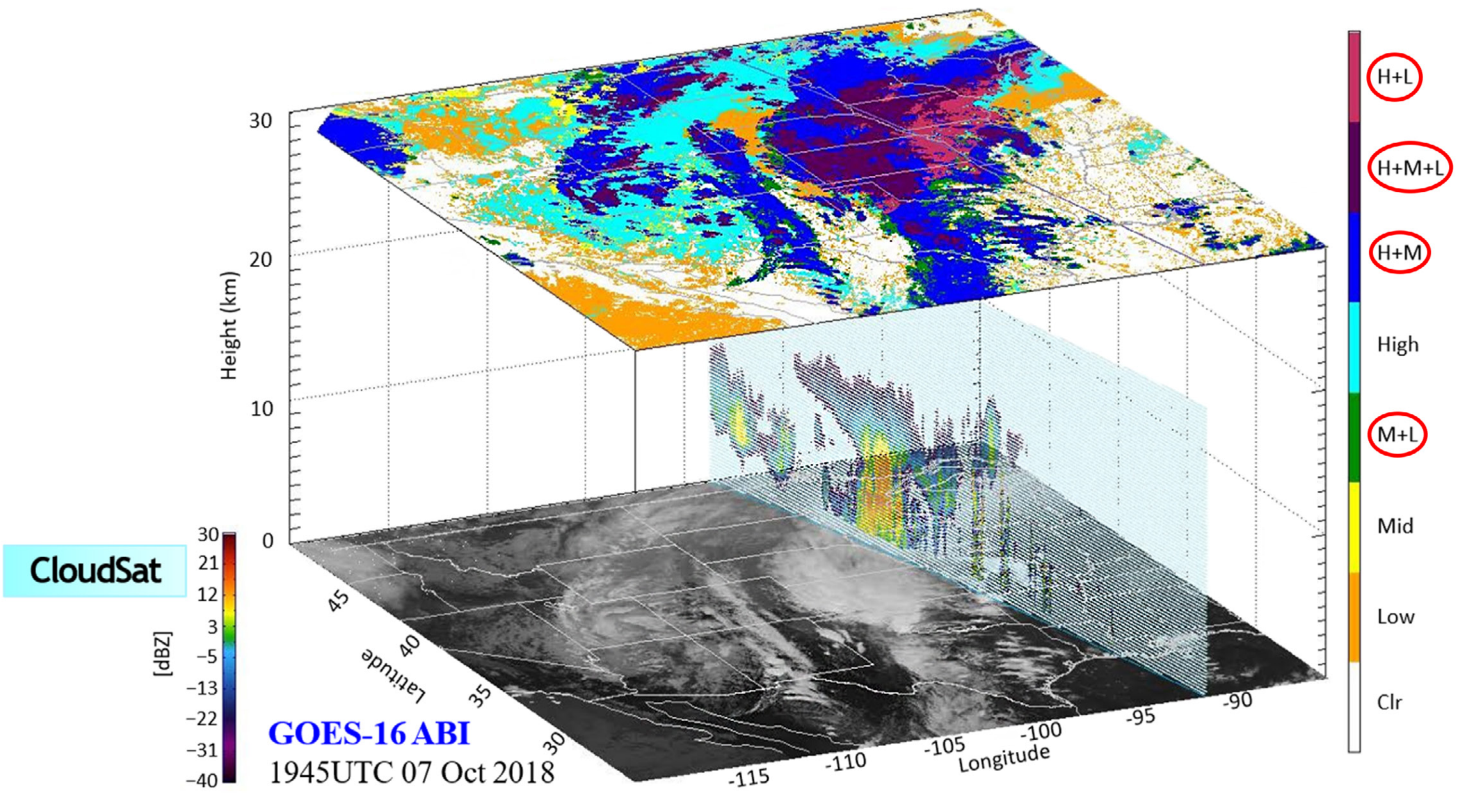
Improving the NOAA Enterprise Cloud Cover Layer Product to Support Aviation

Cloud cover layer information provides insight into the lower parts of clouds that are typically hidden from satellites—essential parts for visualizing cloud properties in three dimensions. By using the cloud geometric thickness retrieved from the new CBH algorithm "we can enhance lower cloud layer fractions by introducing additional cloud coverage hidden below cloud top," says Noh.

For aviation users, this means having more information about what is happening inside clouds they might encounter at their flight level. Pilots must follow Federal Aviation Administration (FAA) rules to operate their planes in different weather conditions. Visual Flight Rules (VFR) restrict pilots from flying through clouds because they must maintain horizontal visibility of three to five miles. VFR requires that they go under and around clouds or divert if clouds are blocking their route ("see and avoid"). Instrument Flight Rules (IFR) allow pilots



Expansion of cloud classifications from three to five flight-based level layers.

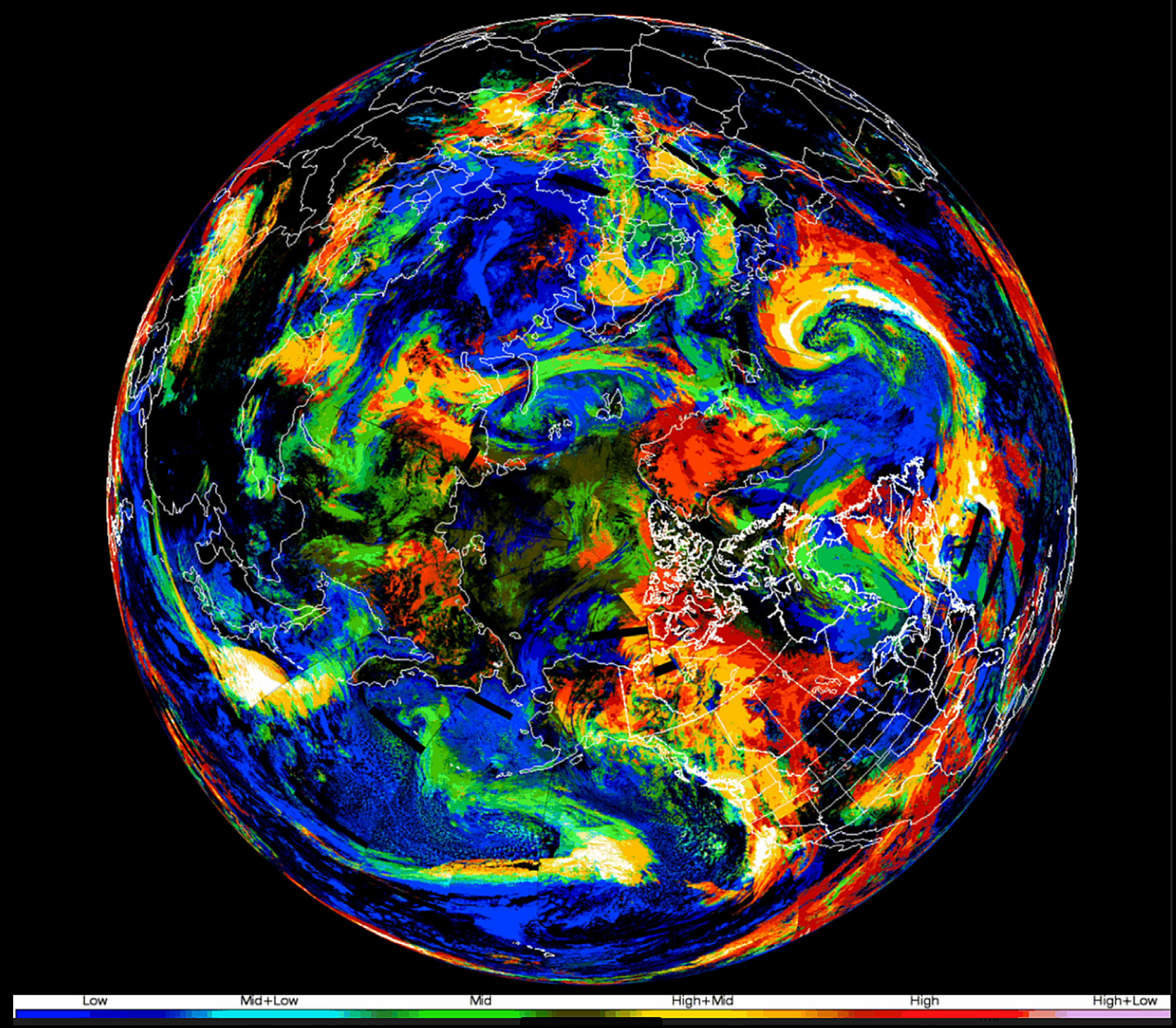


CloudSat overpass showing the addition of cloud top, cloud base, and vertically extended layer information as part of the improved NOAA Enterprise Cloud Cover Layer Product. Newly enhanced layers are circled in red.

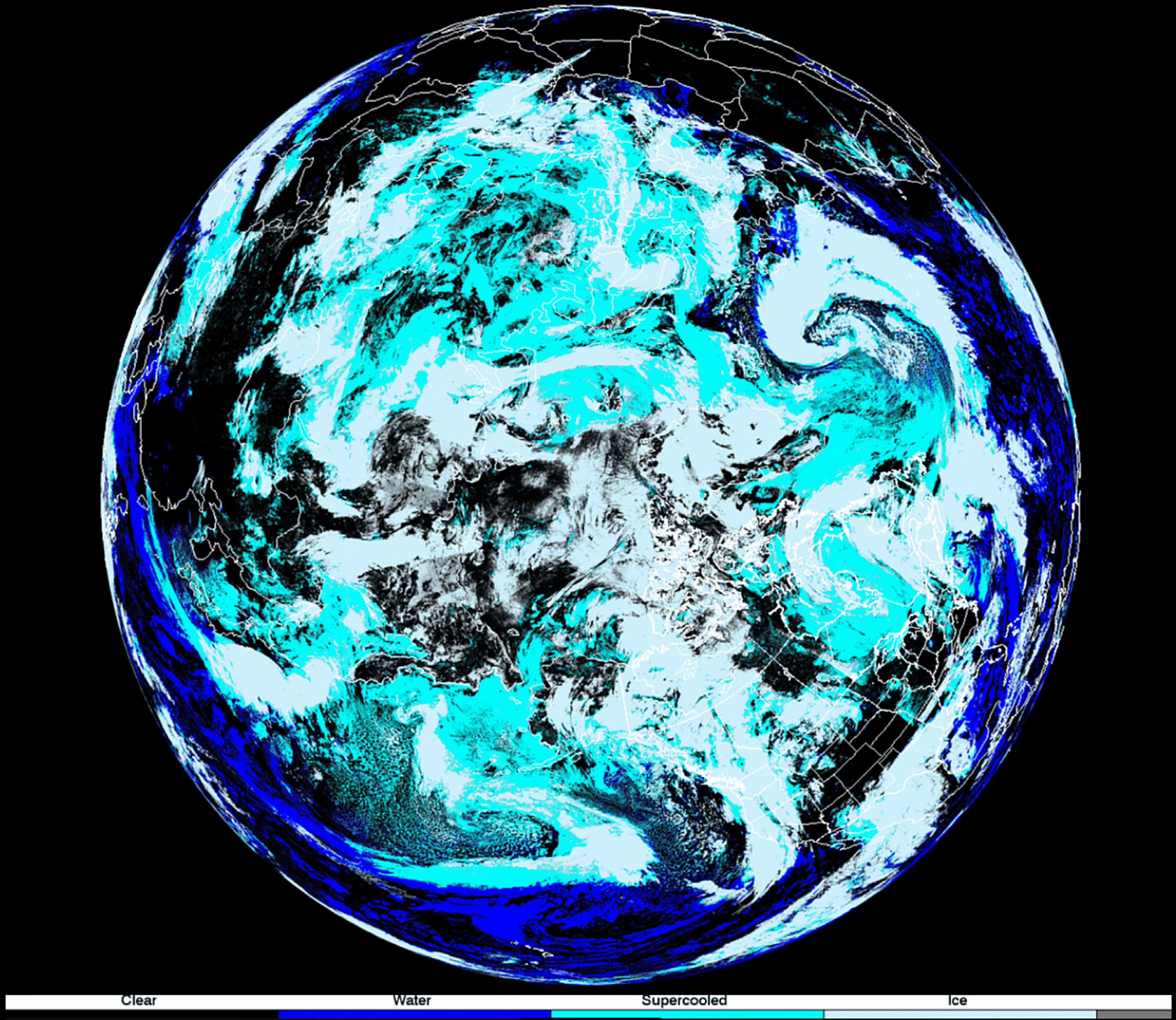
to use cockpit instruments to navigate a plane through clouds and rough weather conditions. Cloud cover layer information enables pilots to anticipate areas of clouds that could turn a VFR flight into an IFR one, which is important for flight planning. Understanding cloud layer conditions also helps pilots anticipate problems with terrain that are hidden in the clouds and may not be visible to the pilot.

The improved Cloud Cover Layer Product provides new information about the deep parts of a cloud, like convective cloud layers that indicate turbulence. Additional cloud layers are shown as vertically extended layer scenes, for example "H+M+L" means high, mid, and low layer information is combined, and so on. The previous Cloud Cover Layer Product only produced high, mid, and low cloud information, leaving out important data that can impact flight planning and safety.

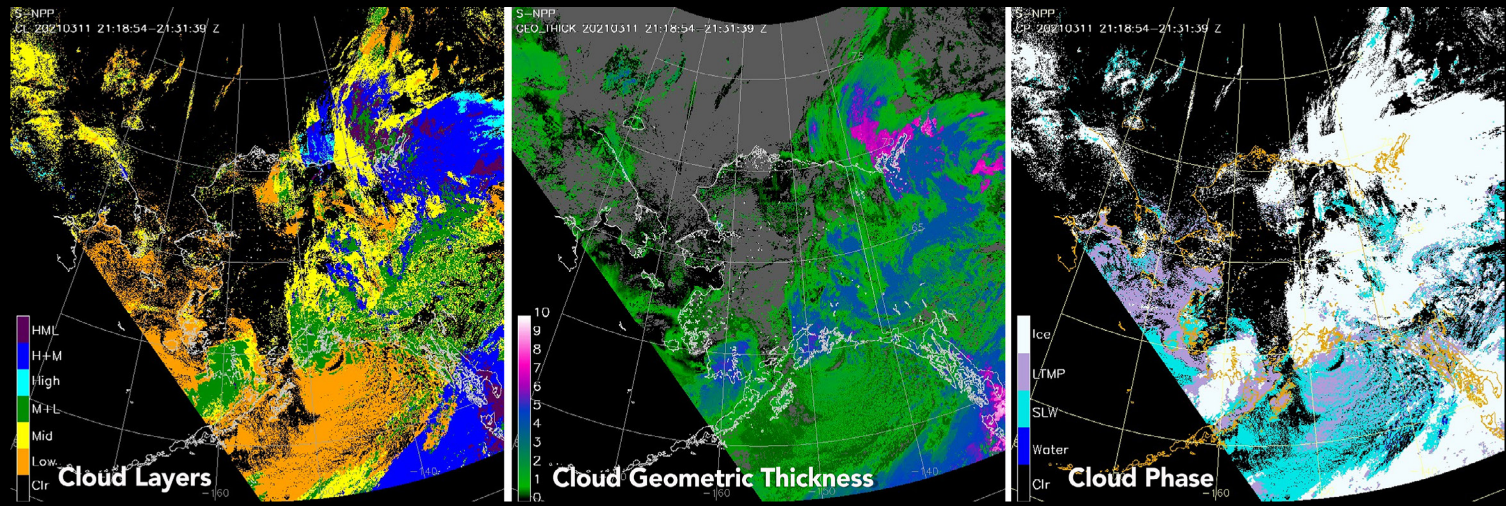
Cloud cover layer and cloud base products from VIIRS are available in near-real-time with a 4-week archive on the CIRA VIIRS Imagery and Cloud Products website for Alaska (https://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_arctic.asp). These and other products for polar regions



Flight Level-based Cloud Layers RGB. This screenshot of the CIRA Polar SLIDER tool shows flight level-based cloud layers from the improved NOAA Enterprise Cloud Cover Layer Product, including newly expanded Mid+Low, High+Mid, High+Low, and High+Mid+Low (H+M+L) layers.



Cloud Phase. This screenshot from the CIRA Polar SLIDER tool shows cloud phase from the improved NOAA Enterprise Cloud Cover Layer Product. Black represents clear sky, dark blue represents water, turquoise represents supercooled, and light blue represents ice.



Example of cloud layer, cloud geometric thickness, and cloud phase imagery available on the CIRA VIIRS Imagery and Cloud Products website.

can also be viewed in the CIRA Polar Satellite Loop Interactive Data Explorer in Real-time (Polar SLIDER) tool (https://rammb-slider.cira.colostate.edu). The Polar SLIDER displays real-time satellite imagery for the polar environment, including flight level-based cloud layers on a loop.

SO MANY CLOUD PRODUCTS!

NOAA offers a great number of cloud products in their Enterprise Cloud Product Package. With so many, Noh realized that aviation users need focused cloud data delivered in a more user-friendly way.

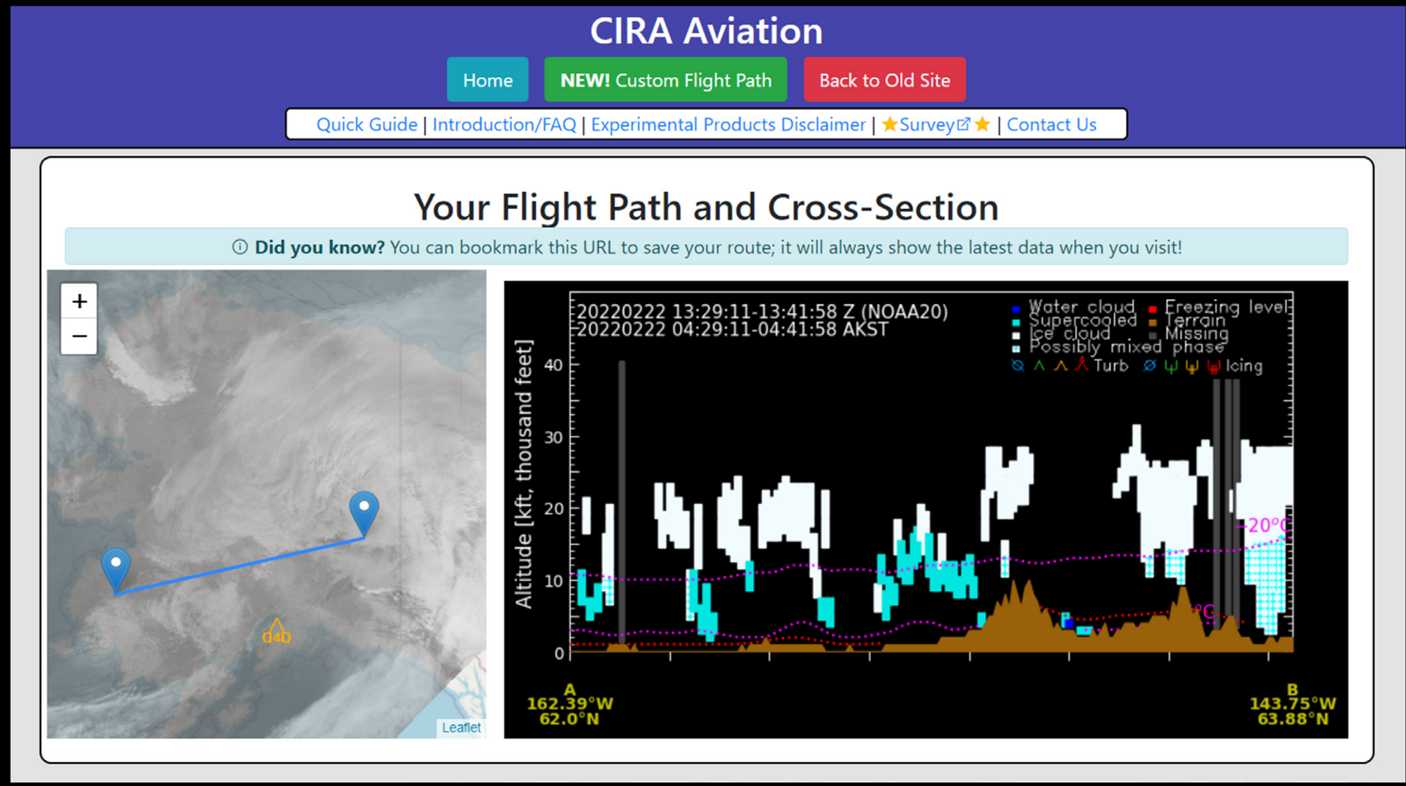
Her team introduced an experimental Cloud Vertical Cross-section product that provides a comprehensive 3D cloud data set for aviation. Minutes after Suomi-NPP and NOAA-20 satellites pass over, VIIRS data is extracted and used to create cross-sections of cloud information along selected flight paths, which are then linked to a website (https://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_arctic_aviation.asp). The product graphically displays a vertical view of cloud properties along routes, including cloud boundaries, cloud conditions, and terrain. Turbulence and icing

NOAA Enterprise Cloud Product Package

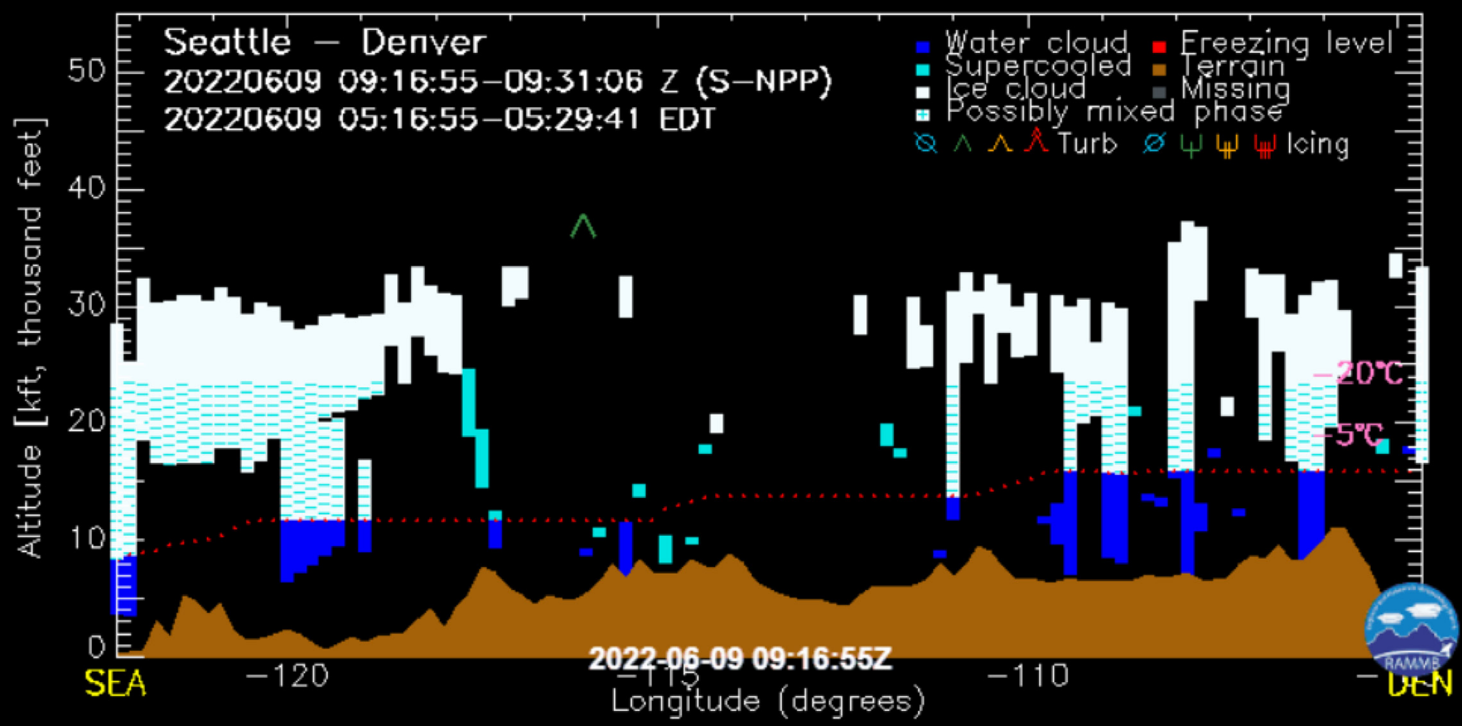
> While there is some weather reporting at these airports and a weather observer at Bettles [Alaska], there is a still a lot of distance between these locations with no data and very hostile terrain features. The test product [Cloud Vertical Cross-section product] was helpful to get an idea of what I might encounter.
>
> Adam White,
> Alaska Airmen's Association

conditions from real-time pilot reports (PIREPs) and temperature data from the NOAA Unique Combined Atmospheric Processing System (NUCAPS) are added to cross-sections when available. The cloud cross-sections help pilots understand how far down clouds go and the hazardous conditions in their path.

Initially, the Cloud Vertical Cross-section product was only available along popular routes in Alaska (https://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_arctic_aviation.asp) and the lower 48 states, like Seattle to Denver (https://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_conus_aviation.asp). Recognizing the value of this information, aviation users requested the option to select custom routes. In response, CIRA launched an interactive website that allows users to pick two or more points on a map and create a cloud vertical cross-section for that route. Data is updated with every JPSS satellite overpass so users can watch for changing conditions. Archived cross-sections going back four weeks are available for select routes. The custom cross-section product is available for Alaska, but other U.S. regions are planned (https://aviation.cira.colostate.edu/define-custom-cross-section).



Screenshot of CIRA's Cloud Vertical Cross-section product website that allows users to select routes of their choice on a map to create a custom cross-section displaying cloud phase, altitude, terrain, turbulence, and icing information.

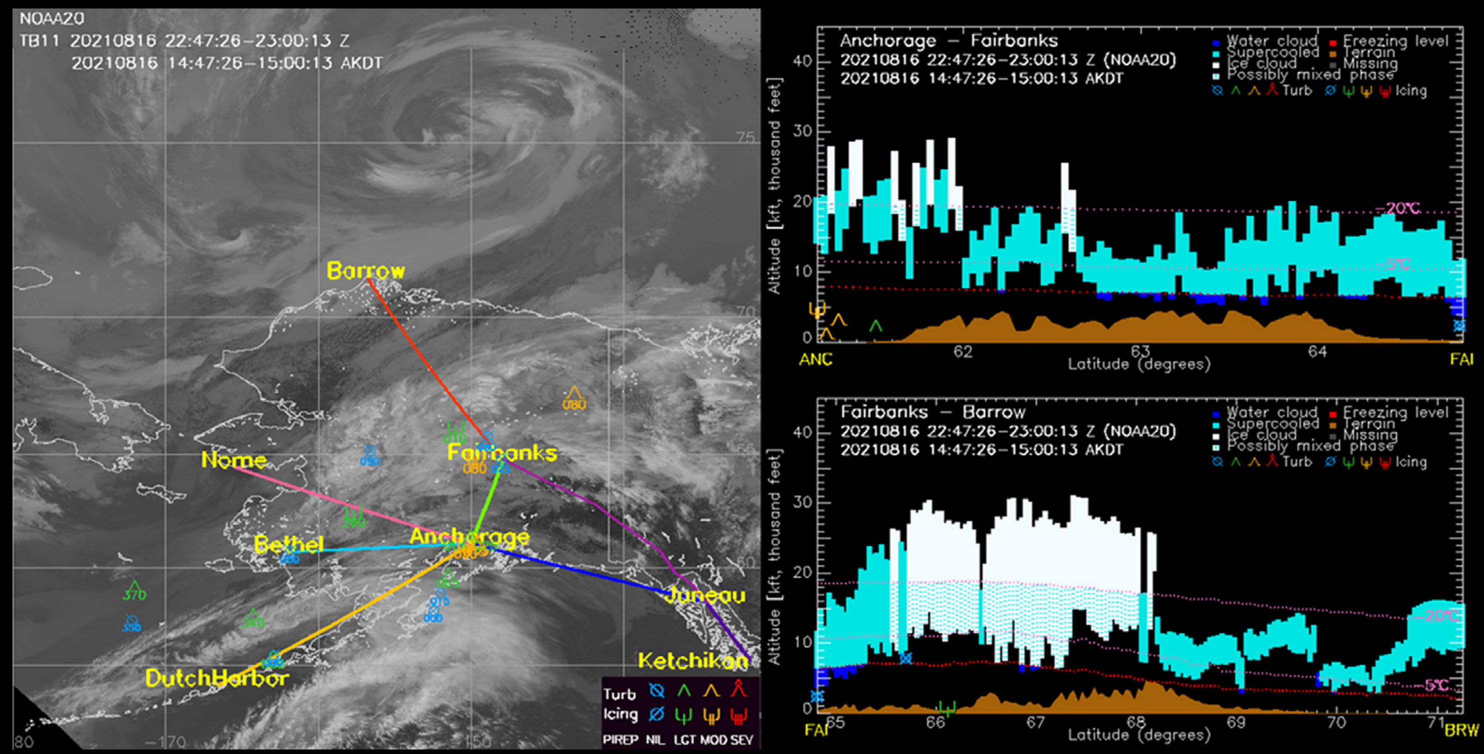


A screenshot of the CIRA's Cloud Vertical Cross-section product along the Seattle to Denver route on June 9, 2022.

DEMONSTRATING VALUE

"User feedback is essential to improve the products," says Noh. For CIRA, this means engaging users of aviation weather products, such as pilots and aviation meteorologists, through direct communication, social media, and online surveys. Working with end users is necessary to improve and evaluate new satellite products and to transition products from research to the real-world.

> I took off from FAI at 2300Z Sept 21 and landed at MRI (Merrill Field Anchorage) at 0100Z Sept 22 (3 pm to 5 pm AKDT). I observed no ceiling from FAI to the Alaska Range foothills, which is basically in agreement with the cross-sections. By the time I was over Totatlanika River strip (9AK) I was under scattered to broken clouds with bases around 5,500 ft MSL. Basically, I flew under a broken to overcast ceiling that was at about 5,500 to 6,000 ft nearly all the way from McKinley Park (PAIN) to about Willow (PAOU). These bases were considerably lower than shown on the cross-sections for most of the route...
>
> A Report from an Alaskan Pilot



NOAA-20 Infrared imagery (left) and flight path cloud cross-sections from VIIRS (right) used in the NTSB accident investigation.

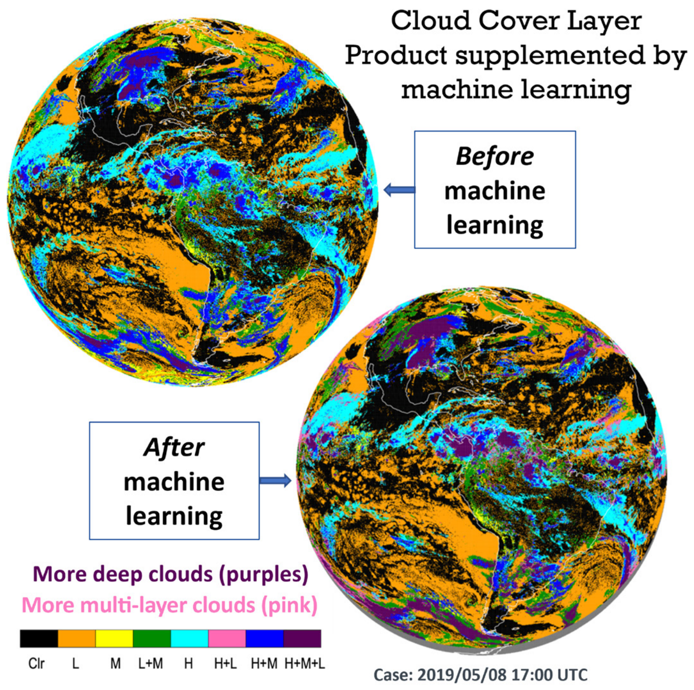
Investigating Aviation Accidents

In August 2021, a small plane carrying eight passengers and a pilot encountered severe turbulence that caused flight control issues. The pilot landed safely with no reported injuries, but the aircraft's wing was significantly damaged. During its investigation, the National Transportation Safety Board (NTSB) used archived Cloud Vertical Cross-sections and NOAA-20 VIIRS Infrared imagery to assess flight path conditions along the route and found that wing ice contributed to the accident. Icing conditions along the route are shown in light blue (supercooled liquid cloud) on the archived cross-sections in the figure above.

INNOVATIVE IMPROVEMENTS

Using Machine Learning

Noh explains that "algorithm improvement for low cloud layers, especially for aviation, is challenging when we have thick top layers." Yet, detection of low clouds is important for pilots to assess weather as it happens. The CIRA team is using machine learning to get new cloud classifications from multi-layer clouds, which are challenging to retrieve from satellite observations alone. The approach applies Random Forest and Artificial Neural Network methods to GOES ABI data and Numerical Weather Prediction (NWP) model humidity data trained using "truth" data from CloudSat and CALIPSO. Using this method, "the probability of detection of low clouds under cirrus [high altitude clouds], one of the most difficult situations, increased from 21% to 72% with a false alarm ratio of 21%," said Noh. This approach offers a more complete picture of the vertical distribution of clouds by expanding available cloud classifications. The team is working on translating the method from GOES ABI to use VIIRS inputs, as well as building a nighttime machine learning model to improve cloud data retrieved at night. The figure shows the addition of deep cloud layers (purple) and

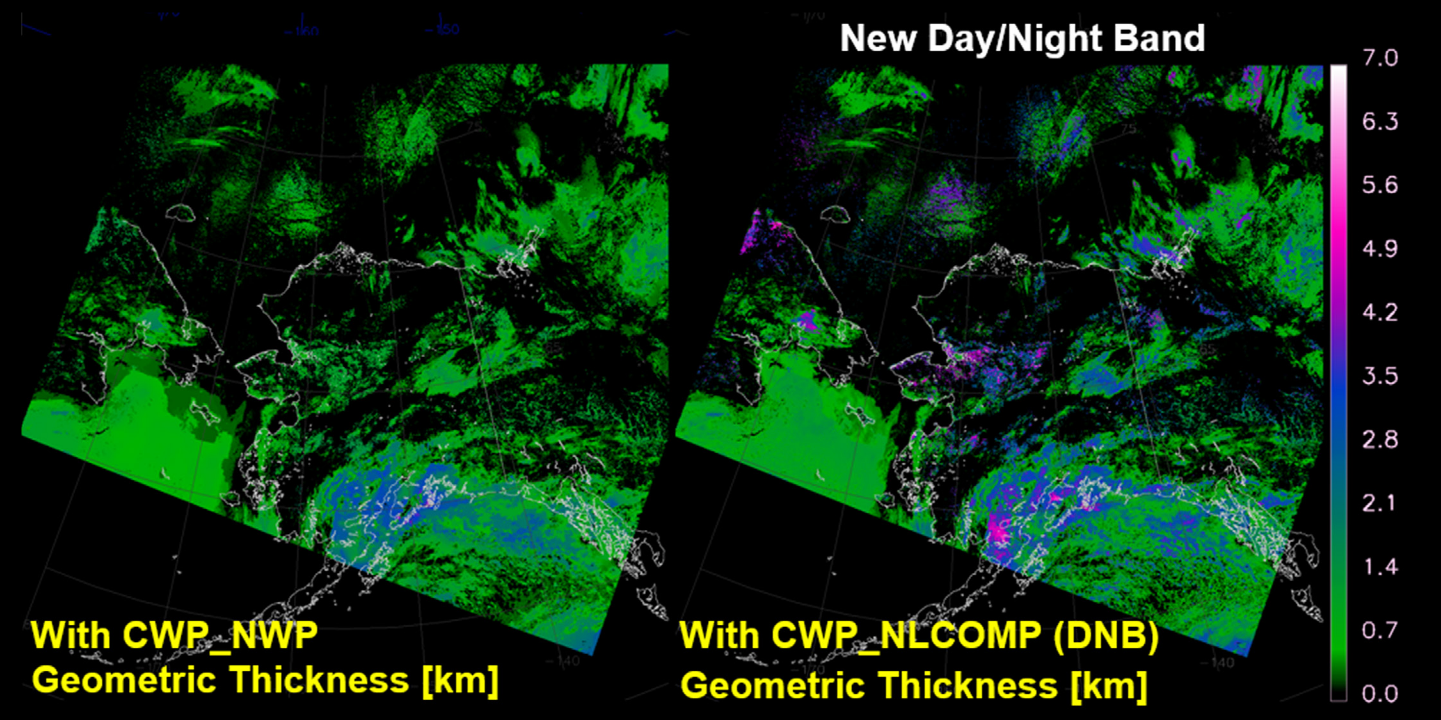


CLICK IMAGE TO ENLARGE. Comparison between Cloud Cover Layer product before (left) and after (right) applying machine learning to enhance cloud layer classifications.

multi-layer clouds (pink) after machine learning was applied to the Cloud Cover Layer product.

Clouds By Way of Moonlight

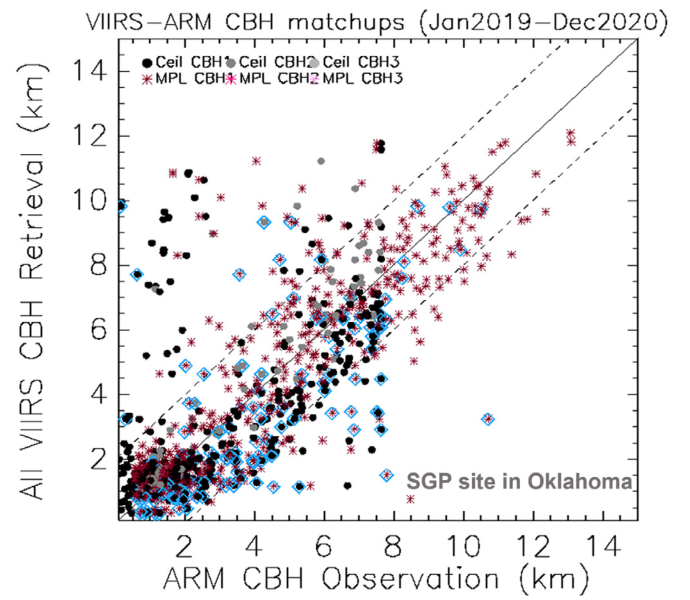
Accurate vertical cloud information is unavailable during nighttime. Some satellite cloud data, such as cloud water path, is not reliable at night because of the lack of bright visible light needed by conventional satellite cloud algorithms. To fill this gap, CIRA is testing the VIIRS Day/Night Band for nighttime retrieval. The VIIRS Day/Night Band uses moonlight (lunar reflectance) as a substitute for sunlight to make observations in low light conditions. This approach, enhanced with statistical analysis, has improved nighttime cloud imagery, as shown by the



Comparison of cloud geometric thickness imagery that shows improved data retrieval using VIIRS Day/Night Band (right) over conventional nighttime retrieval (left).

addition of pinks and purples in the figure above. Ongoing refinement is underway using supplementary data from numerical weather models and the Advanced Technology Microwave Sounder (ATMS) aboard JPSS constellation satellites.

"Product evaluation is important," emphasizes Noh. Comparing satellite data with ground-based measurements is one way to validate satellite information. The plot to the right shows a two-year comparison between VIIRS satellite-based cloud base height estimates (blue) and cloud base height ground observations from ceilometers (black and gray) and ground-based lidar (red) at a site in Oklahoma. While multi-layer clouds caused outliers, the VIIRS data matched about 84% of surface lidar data and about 67% of ceilometer ground observations (within a 2 km error range). Noh and her team are applying a machine learning approach to improve the satellite-based results.



CLICK IMAGE TO ENLARGE. Validation of VIIRS Day/Night Band cloud base height estimates (blue) against ground-based data from Micro-Pulse Lidar (red) and ceilometer measurements (black and gray) collected from an Atmospheric Radiation Measurement (ARM) site in Oklahoma from January 2019 to December 2020.

SUMMARY AND FUTURE WORK

For decades, the aviation community has relied on pilot reports for real-time information about cloud conditions hidden under the cloud top. The lack of vertical data from standard cloud products is a challenging but important issue because clouds can cause severe weather. Understanding their properties from top to bottom is essential for pilots to avoid hazardous situations.

Visualizing a cloud in three dimensions requires accurate cloud base height and cloud cover layer data. While cloud top height and other properties can be estimated from satellite data, cloud base height is difficult to obtain. Previous attempts to retrieve cloud base height from VIIRS often failed to meet performance standards and impacted the accuracy of cloud cover layer products.

CIRA's new CBH algorithm improved the NOAA Enterprise Cloud Cover Layer product so that 3D cloud structures could be built. Their experimental Cloud Vertical Cross-section product is the first to offer pilots the ability to see what is happening inside a cloud along a flight path of their choice. These products not only benefit the aviation community, but they are also useful for weather and climate modeling.

Building on positive feedback, additional features and improvements to the Cloud Vertical Cross-section product and website are ongoing, including extending to global coverage. The cloud base height product is currently operational for JPSS VIIRS but is expected to be expanded to GOES ABI operations. Noh and her team continue to hone their machine learning approach to improve multi-layer cloud retrievals for day and night, with the hope to provide all vertical information using the advanced technique in the future. ✦

STORY SOURCE

The information in this article is based, in part, on the November 15, 2021, JPSS science seminar presented by Yoo-Jeong Noh, NOAA Cooperative Institute for Research in the Atmosphere (CIRA)/ Colorado State University, with contributions from John Haynes, Mattie Niznik, Steve Miller, and Curtis Seaman from CIRA. Additional collaborators and Alaska users include Andy Heidinger[1], Mark Kulie[1], Jeff Weinrich[2], William Straka[3], Yue Li[3], Steve Wanzong[3], Tom George[4], Adam White[5], Becca Mazur[6], Carl Dierking[7], Jay Cable[7], Jen Delamere[7], Amanda Terborg[8], Ty Higginbotham[8], Nadia Smith[9], Rebekah Esmaili[9], Jenny Colavito[10], and Paul Suffern[11].

1. NOAA/ National Environmental Satellite, Data, and Information Service (NESDIS)
2. National Weather Service (NWS)/Office of Science and Technology Integration (OSTI)
3. Cooperative Institute for Meteorological Satellite Studies (CIMSS)
4. Aircraft Owners & Pilots Association
5. Alaska Airmen's Association
6. NOAA Arctic Testbed
7. Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), University of Alaska Fairbanks/Geographic Information Network of Alaska (GINA)
8. NOAA Aviation Weather Center (AWC)/Aviation Weather Testbed (AWT)
9. Science and Technology Corporation (STC)/NOAA
10. Federal Aviation Administration (FAA)
11. National Transportation Safety Board (NTSB)

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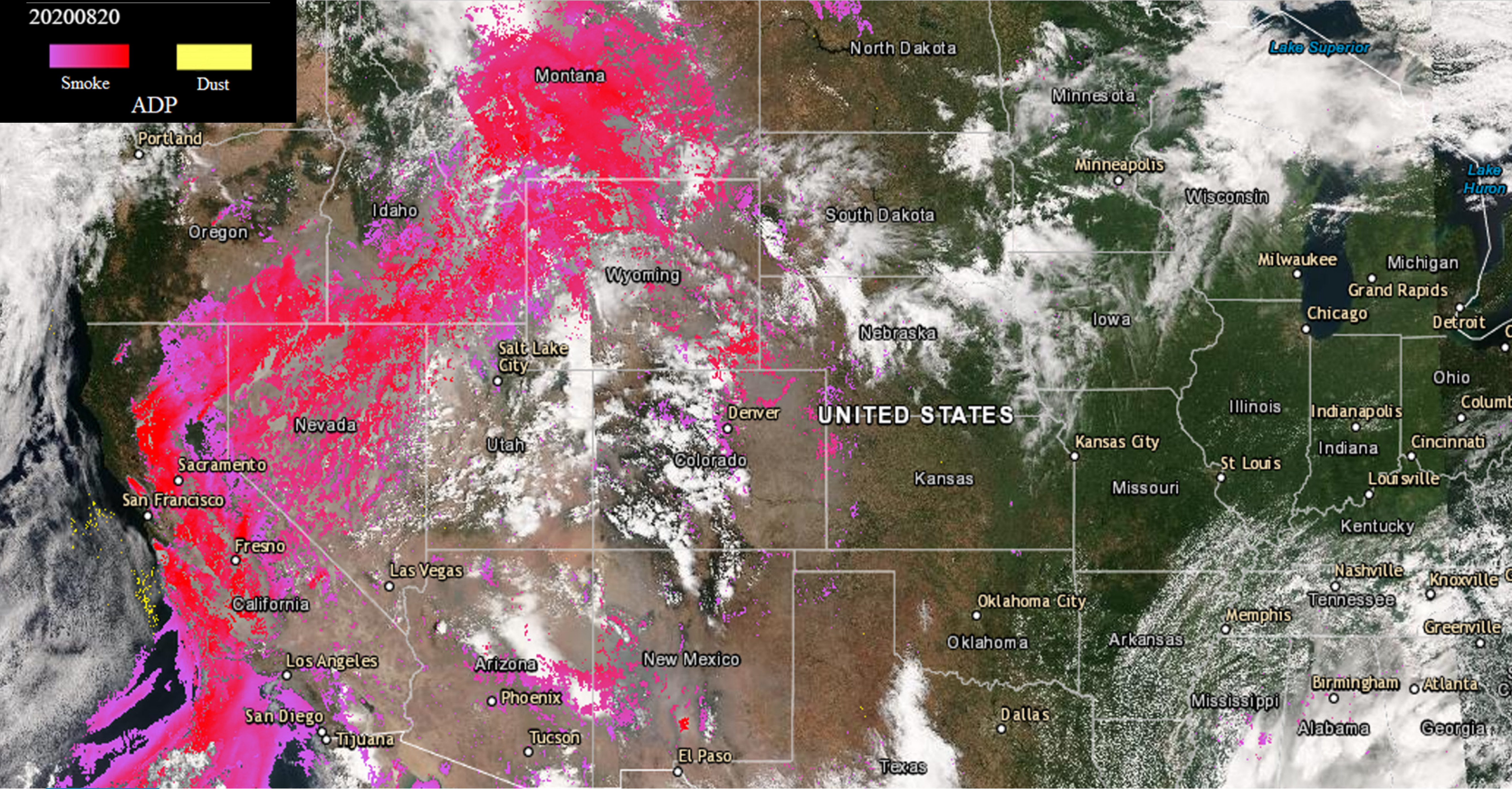
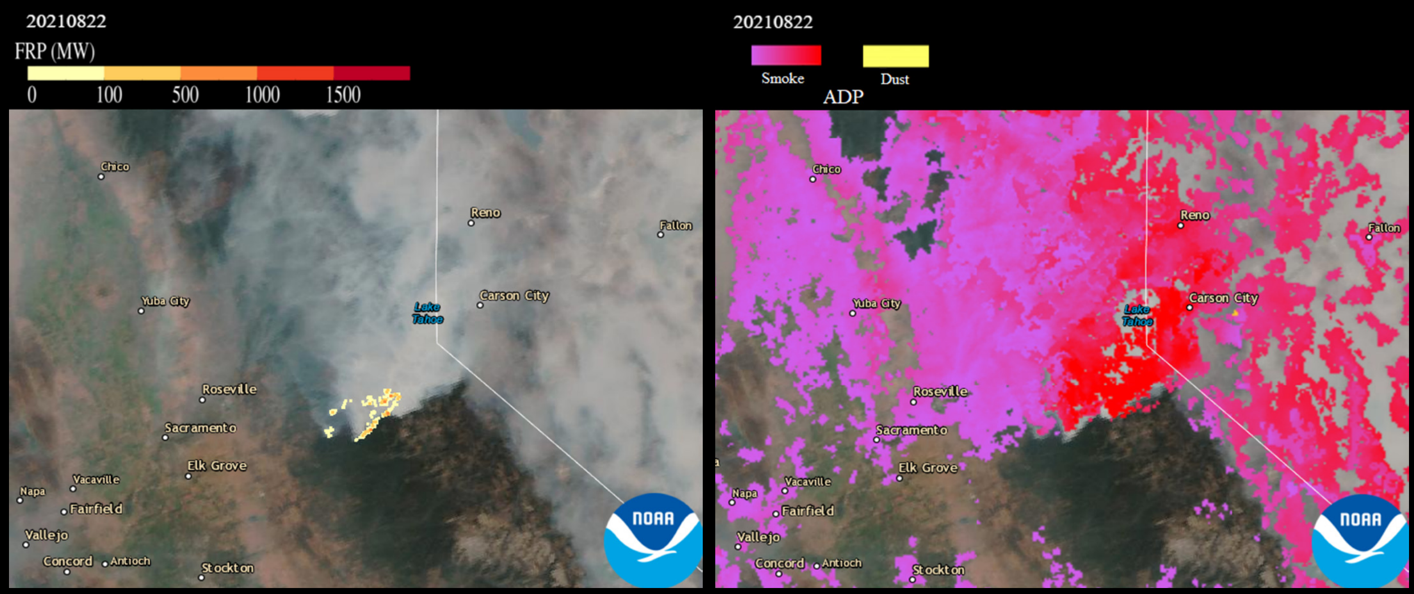


FEATURE 2

Using Airborne Truth Data to Validate the Visible Infrared Imaging Radiometer Suite (VIIRS) Aerosol Detection Product

VIIRS Aerosol Detection Product smoke/dust mask showing smoke plume transport from the August Complex fire in California on August 20, 2020, four days after the fire began. Source: NOAA AerosolWatch. https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/



CLICK IMAGE TO ENLARGE. VIIRS fire radiative power (FRP) overlaid on True Color (RGB) imagery (left), showing the location and intensity of the Dixie Fire in California on August 22, 2021; the fire began on July 13, 2021. The corresponding VIIRS Aerosol Detection Product (ADP) (right) highlights the regional smoke extent from the Dixie Fire. In the ADP image, light pink indicates thin smoke and dark red indicates thick smoke. Source: NOAA AerosolWatch, https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/.

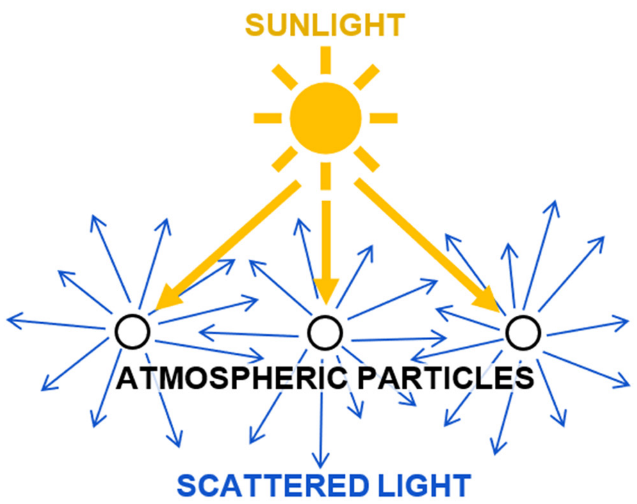
Smoke is one of the most visible features of wildfires. Wildfire smoke is made up of gas and tiny particles, 90% of which are 2.5 microns or less in diameter—about thirty times smaller than the width of a human hair. Particles this size can stay suspended in air for hundreds of miles, traveling long distances and causing poor air quality in areas far from where a fire started. Exposure to smoke can lead to eye and throat irritation, asthma, heart disease, and premature death, especially in sensitive populations like children, pregnant women, and older adults. Wildfire smoke not only impacts human health, but also the environment. Smoke particles block sunlight that can cause a drop in temperature, and they change the way clouds form, which can mean less rain. Smoke also reduces visibility, leading to potentially hazardous ground and air travel conditions.

Smoke detection is critical for warning the public about harmful air quality and poor visibility during wildfire events. Forecasters, emergency managers, and first responders rely on satellite instruments to identify smoke and track its movement. One example is the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Joint Polar Satellite System (JPSS) NOAA-20 and Suomi National Polar-orbiting Partnership (Suomi NPP) satellites. VIIRS collects data about how aerosols scatter

and absorb light, which are used in scientific algorithms to develop products like the JPSS VIIRS Aerosol Detection Product (ADP). The VIIRS ADP, also called the smoke/dust mask, is a qualitative indicator of the presence and relative intensity of smoke plumes.

THE STORY OF TWO ALGORITHM PATHS

Developed by Dr. Pubu Ciren and Dr. Shobha Kondragunta at the NOAA Center for Satellite Applications and Research (STAR), VIIRS ADP works by looking at the unique way atmospheric particles scatter and absorb light. Two algorithm "paths" have been developed to retrieve ADP: the Deep-Blue algorithm path and the Infrared (IR)-Visible algorithm path. Both paths generate ADP but with slightly different features. Each requires satellite measurements at specific wavelengths, shown in the table. The VIIRS ADP algorithm is the Enterprise Processing System (EPS) algorithm, that is, one set of algorithms that can be applied to observations from multiple sensors. This means the spectral coverage of the VIIRS sensor determines which ADP algorithm path or paths can be utilized, as shown in the table.

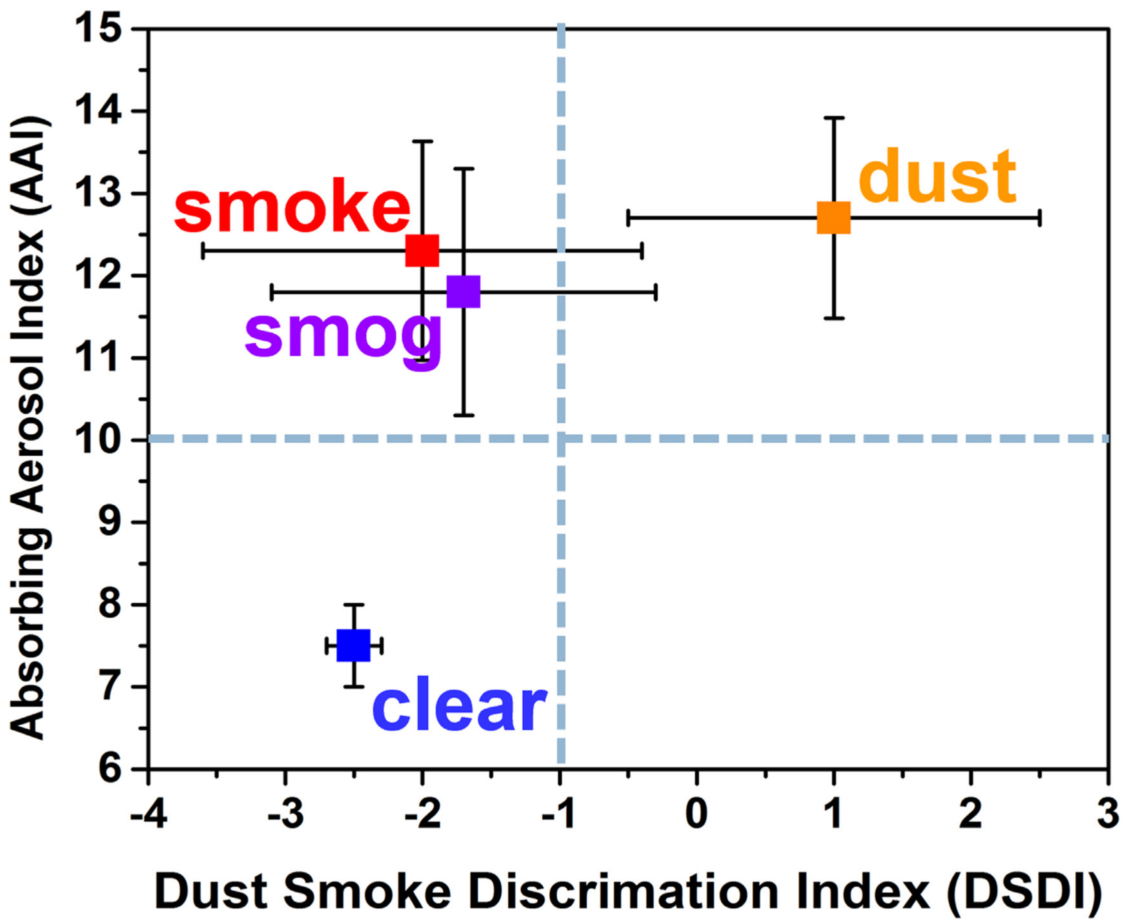


VIIRS Aerosol Detection Product

Central Wavelength, µm	Algorithm Path
0.412	Deep-Blue
0.445	Deep-Blue
0.488	Deep-Blue & IR-Visible
0.555	Deep-Blue
0.640	Deep-Blue & IR-Visible
0.746	Deep-Blue
0.865	Deep-Blue & IR-Visible
1.24	Deep-Blue
1.61	IR-Visible
2.25	Deep-Blue & IR-Visible
3.70	IR-Visible
4.05	IR-Visible
10.7	IR-Visible

The Deep-Blue Algorithm Path

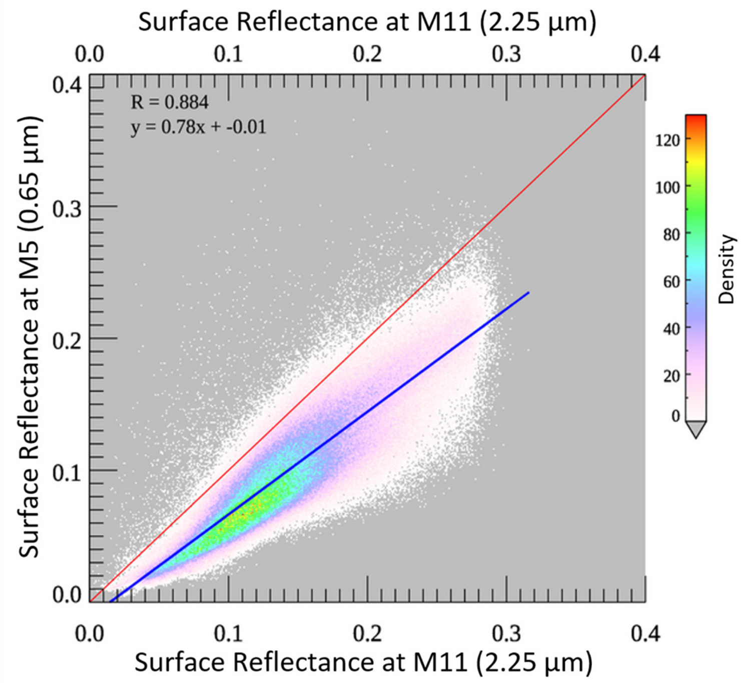
The advantage of the Deep-Blue algorithm path is that it identifies both the presence and the relative intensity (thick vs. thin plumes) of smoke and dust. The Deep-Blue path separates smoke from dust based on spectral threshold tests of two indices: the Absorbing Aerosol Index (AAI) that separates smoke/dust from clear sky and the Dust Smoke Discrimination Index (DSDI) that separates smoke from dust. Index values are calculated from the ratios of measured light at several wavelengths. For example, smoke and dust scatter light differently at shortwave infrared wavelengths (at 2.25μm, for example), so smoke has a lower DSDI value than dust. Also, as smoke concentration increases, so does its AAI value, making it easy to tell smoke from clear sky. The final output from the Deep-Blue path is the Scaled Absorbing Aerosol Index (SAAI), which expresses the presence of smoke and dust and its intensity (thick versus thin aerosol).

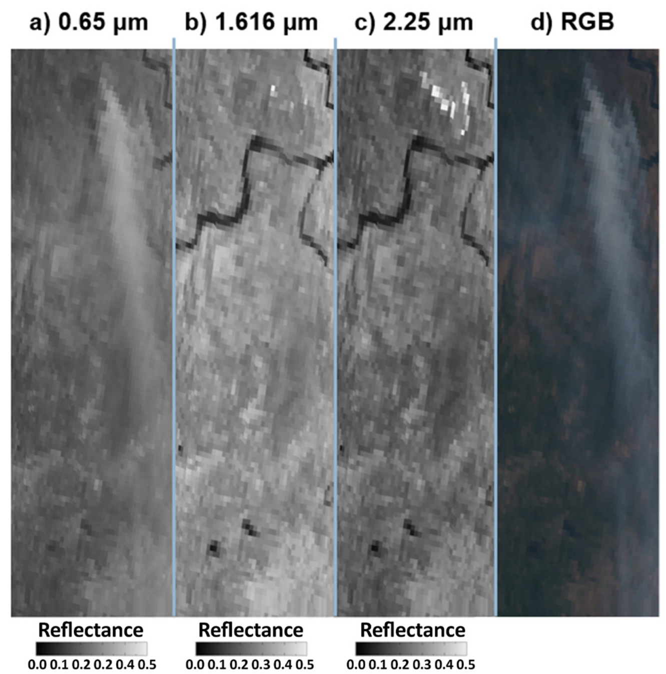


The IR-Visible Algorithm Path

Unlike the Deep-Blue path, which indicates both the presence and intensity of smoke and dust, the IR-Visible path only indicates the presence of smoke and dust. The IR-Visible path separates smoke from dust using spectral variability tests in the visible bands and the negative brightness temperature difference between two wavelengths in IR wavelength regions. Smoke detection over land draws on the linear relationship between surface reflectance in the visible range (0.67μm for VIIRS) and the shortwave IR (2.25μm for VIIRS), as shown in the plot below on the left.

Because smoke particles are relatively small, the smoke signal is extremely small in the shortwave IR wavelengths. This relationship is shown in the VIIRS images below (right), where smoke appears bright at 0.65μm (visible band) but gradually disappears as the wavelength increases, becoming transparent at 2.25μm (shortwave-IR band). A VIIRS true color (RGB) image of the smoke plume is included for reference. The final output from the IR-Visible path is a binary "yes/no" presence of smoke or dust.





CLICK IMAGES TO ENLARGE.

NASA ER-2 High-Altitude Airborne Science Aircraft "flying laboratory" that carried the enhanced MODIS Airborne Simulator (eMAS) used in the FIREX-AQ field campaign. Source: NASA.

HOW DO WE TRUST VIIRS FOR SMOKE DETECTION?

For satellite instruments to provide value to society, it is important to have confidence in the accuracy of their measurements. VIIRS orbits the Earth more than 500 miles above its surface, so how can users be sure that it correctly reflects ground conditions? Validating the VIIRS ADP has historically been challenging because of a lack of "truth" data—information accepted as true that is provided by direct observation. Up to now, the product had been compared to other satellite data and to Angstrom exponent data from the global ground-based AErosol RObotic NETwork (AERONET), but these data are often mismatched with the VIIRS ADP because of differences in space and time, which introduces uncertainty. The Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) field campaign provided a unique opportunity to assess VIIRS ADP smoke mask data. FIREX-AQ targeted fires and coordinated observations with VIIRS overpasses, which provided comparison data that matched the VIIRS ADP in time and space.

AERONET *is a network of ground-based sun photometers that measure atmospheric aerosol properties.*

The ***Angstrom exponent*** *describes how the optical thickness of an aerosol typically depends on the wavelength of the light.*

FIREX-AQ Field Campaign For "Truth" Data

FIREX-AQ, jointly led by NOAA and NASA, provides comprehensive observations about fire emissions for better forecasting and for improving satellite sensors that track smoke. During the 2019 wildfire season, FIREX-AQ observations were collected from hundreds of ground and airborne instruments. Airplanes carrying instruments, such as the enhanced MODIS Airborne Simulator (eMAS), flew over fires to measure emissions and study smoke plumes, providing "truth" data that can be used with confidence to evaluate measurements from satellite sensors.

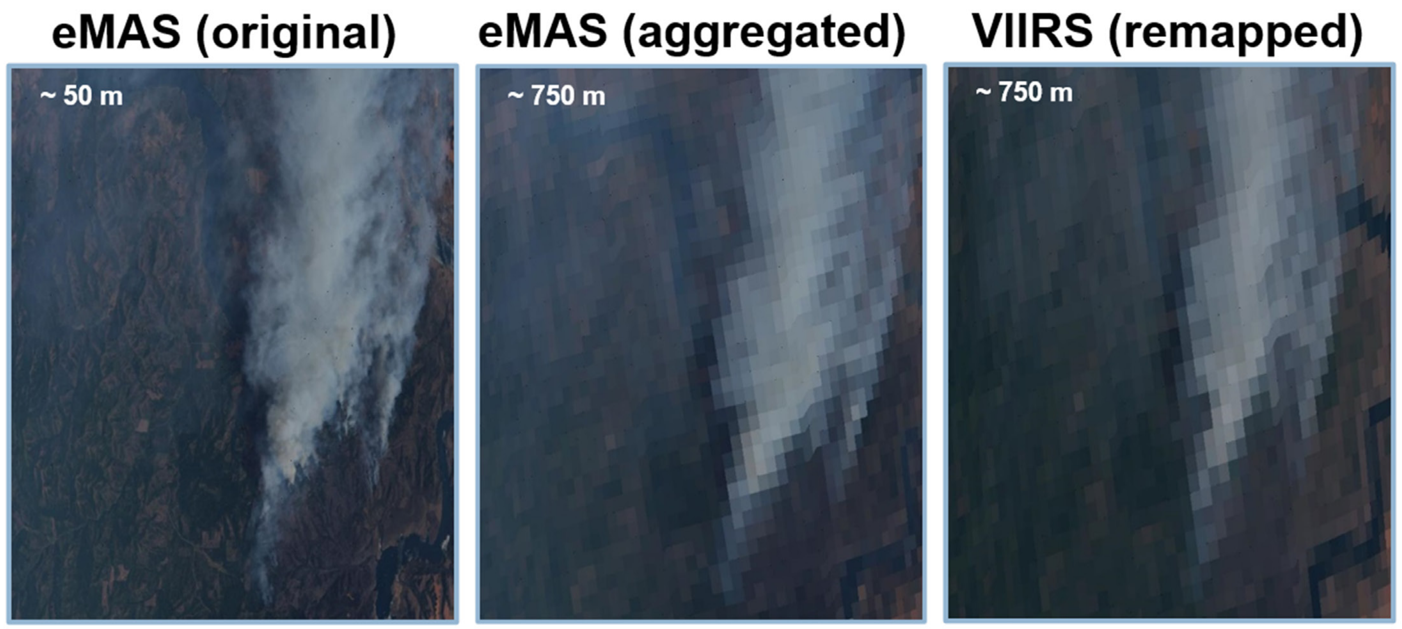
The eMAS instrument aboard NASA's ER-2 High-Altitude Airborne Science Aircraft, shown above, flew under VIIRS' orbital track collecting observations along nearly the same track at about the same time, a method called collocation. Collocated data provided a unique opportunity to match measurements from eMAS and VIIRS, and because eMAS operates at wavelengths that overlap with VIIRS wavelength channels (also called "bands"), their measurements are similar enough to compare. According to Dr. Ciren, "Observations from FIREX-AQ and eMAS are valuable 'truth' data, which provide great opportunities not only for evaluating VIIRS Aerosol Detection Product performance but also its algorithms though deep-dive analyses."

Overlapping Bands

FIREX-AQ eMAS		VIIRS	
Band	Spectral Range	Band	Spectral Range
1	0.45-0.49 µm	M3	0.48-0.50 µm
3	0.63-0.69 µm	M5	0.66-0.68 µm
7	0.85-0.89 µm	M7	0.85-0.89 µm
10	1.59-1.65 µm	M10	1.58-1.64 µm
22	2.21-2.26 µm	M11	2.23-2.28 µm
26	3.64-3.82 µm	M12	3.66-3.84 µm

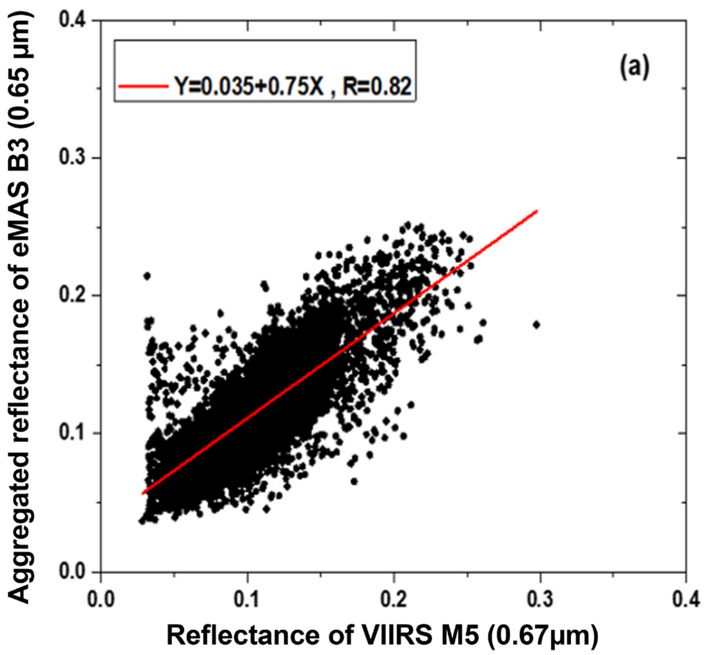
How Well Does eMAS Match Up With VIIRS?

Out of a total of 60 match-ups between VIIRS and eMAS tracks, 25 contained smoke from wildfires but spatial resolutions were not a perfect match—the eMAS sensor has a finer resolution (50m) than the VIIRS sensor (750m). Dr. Ciren applied spatial aggregation to eMAS data, a "scaling up" process that changes the size of image pixels from fine to coarse spatial resolution and improves the similarity of data measured at different resolutions. Looking at RGB images from eMAS at 50m resolution, eMAS aggregated to 750m resolution, and VIIRS at 750m resolution (below), close agreement is seen between the sensors. Some detail from eMAS was lost at 750m because at coarser resolutions an image has fewer pixels.



Comparison between RGB images from eMAS and VIIRS sensors. The original resolution of eMAS is 50m and the original resolution of VIIRS is 750m.

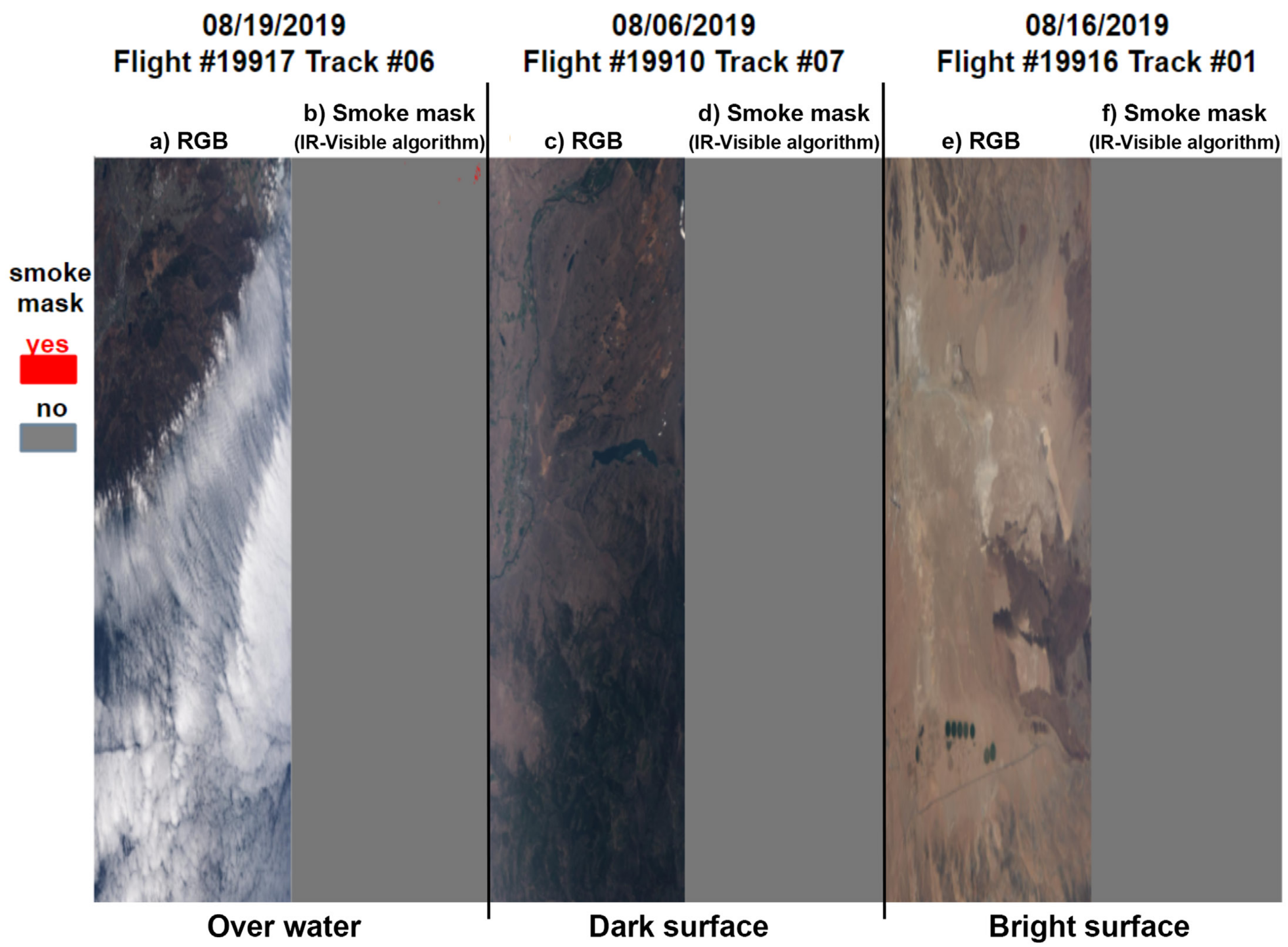
The scatter plot to the right confirms that the reflectance of the VIIRS M5 band (0.67μm) and eMAS B3 band (0.65μm) are well matched. This means that VIIRS "sees" smoke similarly to the eMAS "truth" data, making eMAS observations suitable for validating the VIIRS ADP.



Evaluating the ADP IR-Visible Algorithm Path Using eMAS Observations

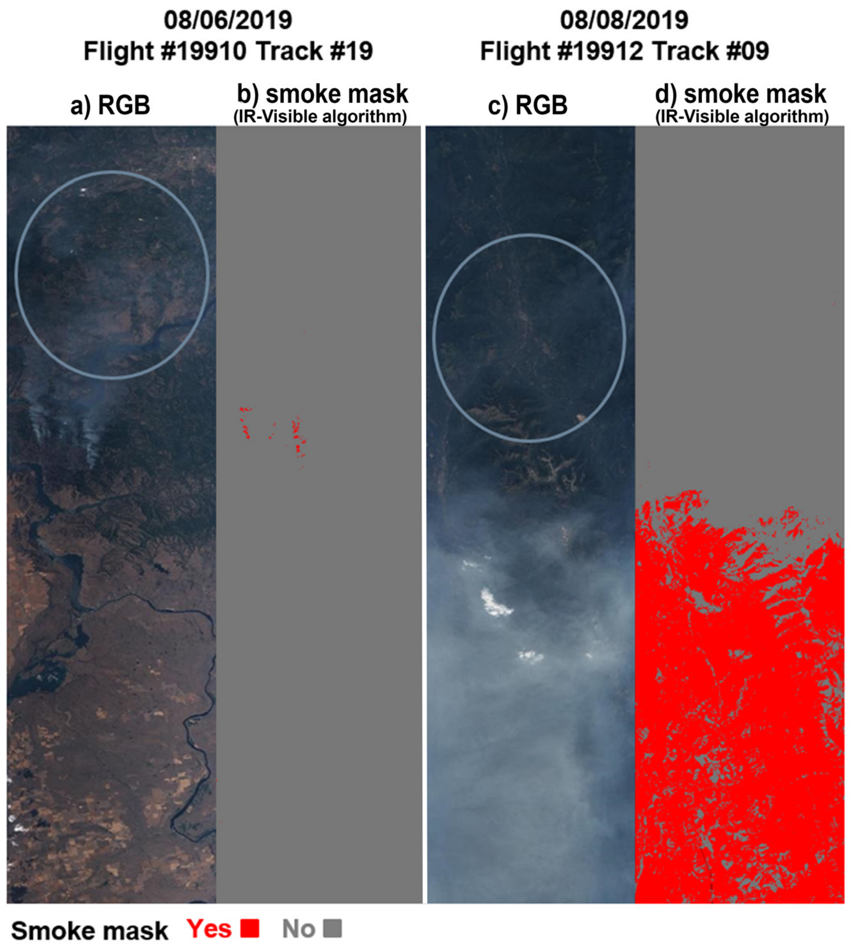
To evaluate the accuracy of the VIIRS ADP, Dr. Ciren ran the ADP algorithm on collocated data from eMAS and VIIRS and compared the results. True color (RGB) images were used for visual reference. Testing was limited to the IR-Visible path because the eMAS sensor does not have a deep-blue band (0.412μm) needed by the Deep-Blue path.

First, Dr. Ciren applied the IR-Visible algorithm path to eMAS tracks with no smoke plumes to set a baseline for algorithm performance. As shown below, the IR-Visible path performs well with very few false alarms when no smoke is present. Some false detection over thin clouds is expected because the eMAS sensor does not filter out clouds.



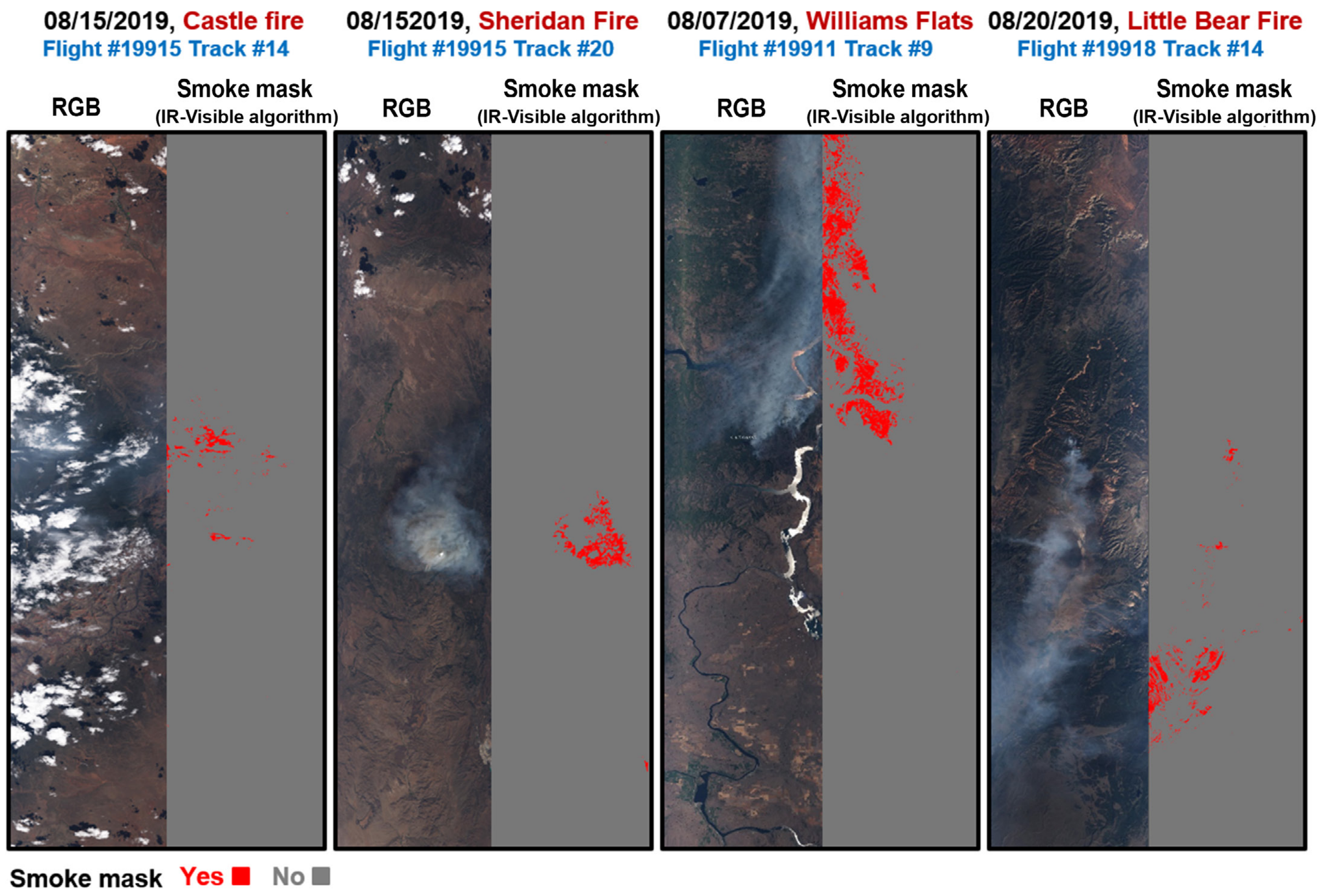
Performance of the Aerosol Detection Product (IR-Visible algorithm path) when applied to eMAS observation tracks that contained no smoke plumes.

Under smoky conditions, the IR-Visible algorithm correctly detects thick smoke close to its source (shown in red), but thin, dispersed smoke is missed (circled regions).



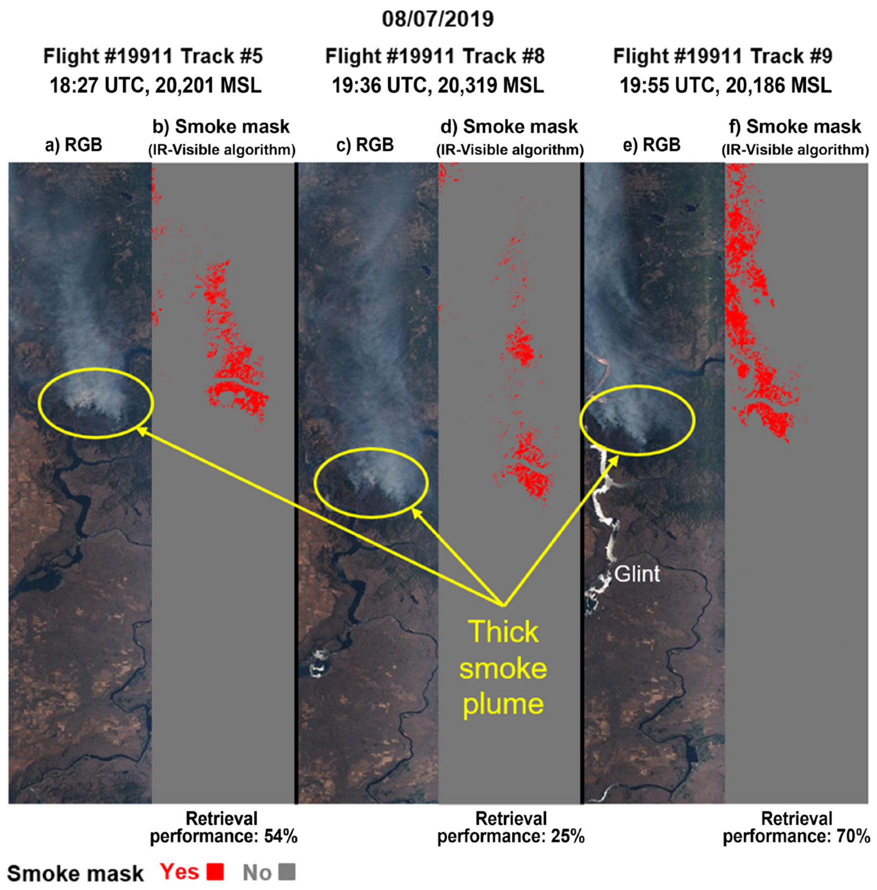
Performance of the Aerosol Detection Product (IR-Visible algorithm path) when applied to eMAS observation tracks that contained thick and thin smoke plumes.

Looking at eMAS observations from four wildfire events, below, Dr. Ciren again noticed that the IR-Visible algorithm detects thick smoke, but not thin smoke, and the quantity of smoke detected varies from event to event (shown in red).



Performance of the Aerosol Detection Product (IR-Visible algorithm path) when applied to eMAS observations of wildfire events during the FIREX-AQ field campaign.

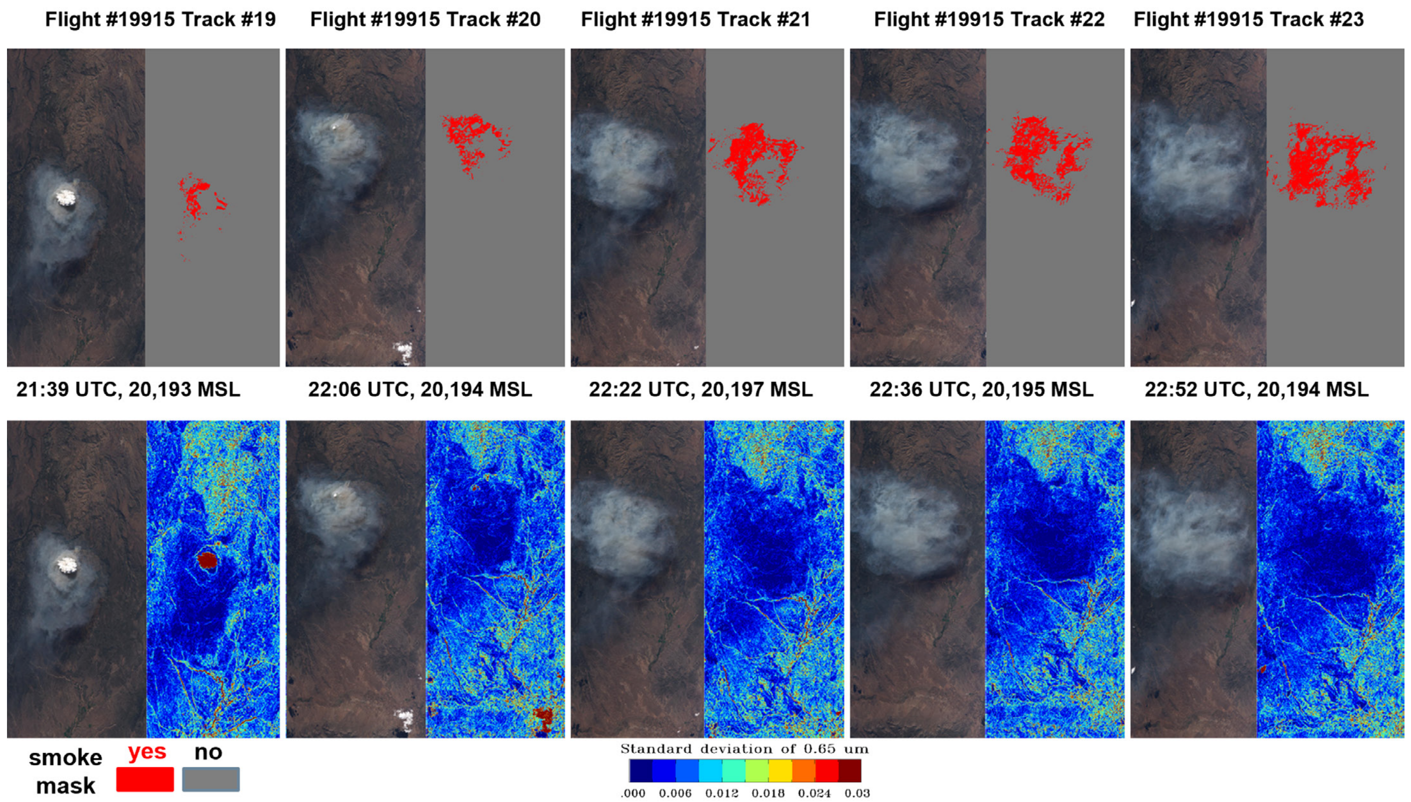
"The advantage of using eMAS measurements is that we can visit the same smoke plume in a short time period," explains Dr. Ciren. Looking at back-to-back observations of the 2019 Williams Flats Fire, IR-Visible algorithm performance varies even though the observations are taken 30-60 minutes apart. The best performance is along Track #9 (below right), where the view angle is different than other tracks as shown by the sun glint over the river. These results suggest that satellite viewing geometry, or view angle, affects aerosol detection. View angle is the angle a remote sensing instrument looks at the surface, which changes as it moves and impacts the measured reflectance.



Performance of the Aerosol Detection Product (IR-Visible algorithm path) when applied to eMAS observations of the Williams Flats Fire that were taken minutes apart on August 7, 2019.

The team performed a similar test on eMAS observations of the 2019 Sheridan Fire where the growth of a smoke plume was compared over about an hour (below). The plume appears mostly uniform over time in RGB images (top row), confirmed by the small standard deviation values (bottom row). But when the ADP IR-Visible algorithm was run, smoke coverage was smaller than smoke seen in RGB imagery. Again, only thick parts of the plume were detected.

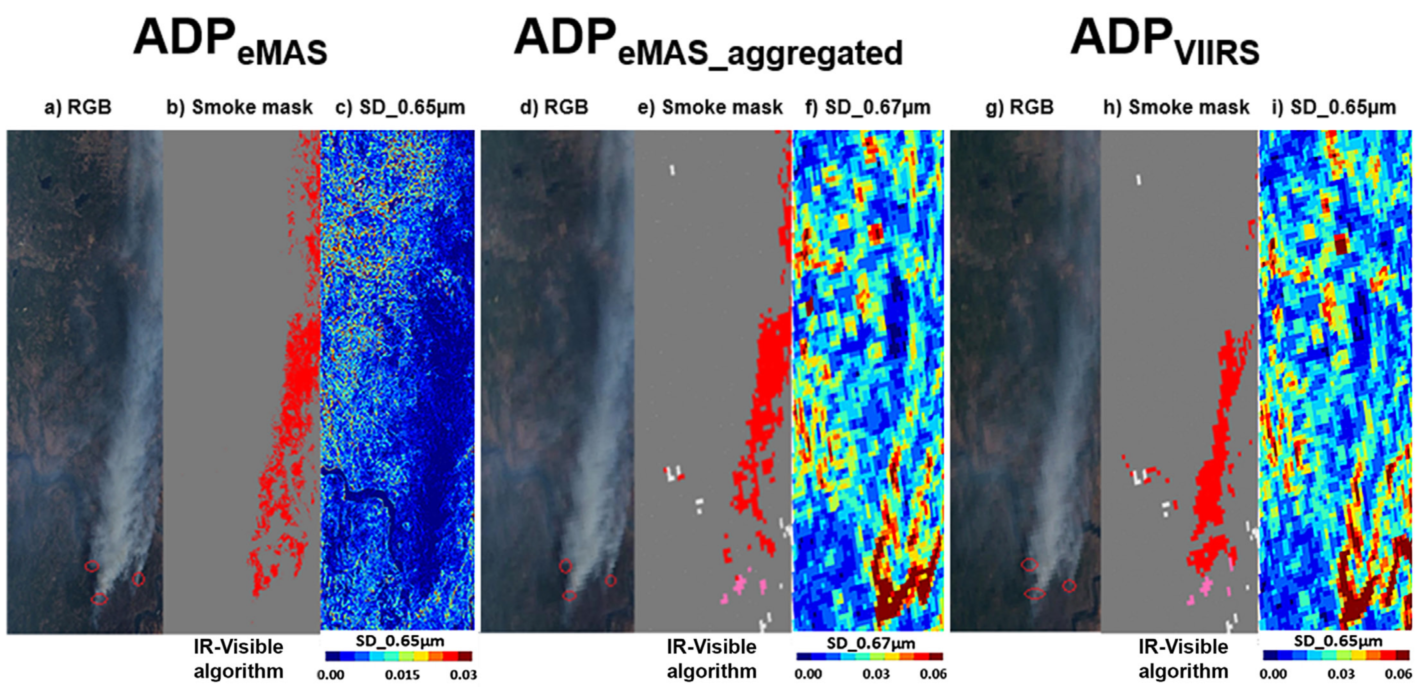
Based on these findings, Dr. Ciren questioned why the IR-Visible path does not "see" thin smoke as well as thick smoke. To answer this, Dr. Ciren compared the ADP derived from both eMAS and VIIRS observations.



Top row: Performance of the Aerosol Detection Product (IR-Visible algorithm path) when applied to eMAS observations of the Sheridan Fire that were taken minutes apart on August 15, 2019. Bottom row: Standard deviation showing that smoke plumes are mostly uniform.

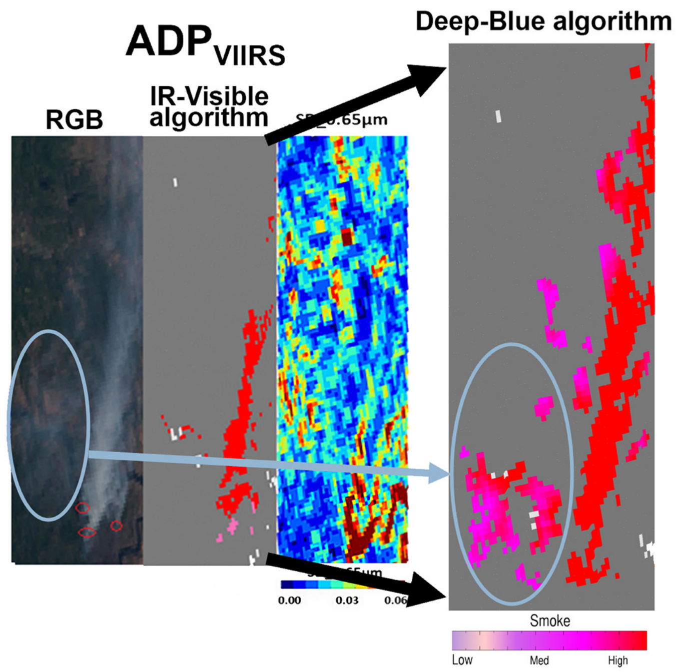
Using Collocation to Compare Smoke Detection Across Two Sensors

Running the ADP IR-Visible algorithm path on three sets of collocated data (eMAS at 50m original resolution, eMAS aggregated to 750m resolution, and VIIRS at 750m original resolution), the researchers found that the algorithm detects a smaller, more compact smoke plume at the coarser resolution (750m). It also appears to miss detection of thin smoke at the edge of the plume, confirmed by the higher standard deviation values seen in the "eMAS aggregated" and "VIIRS" runs, below.

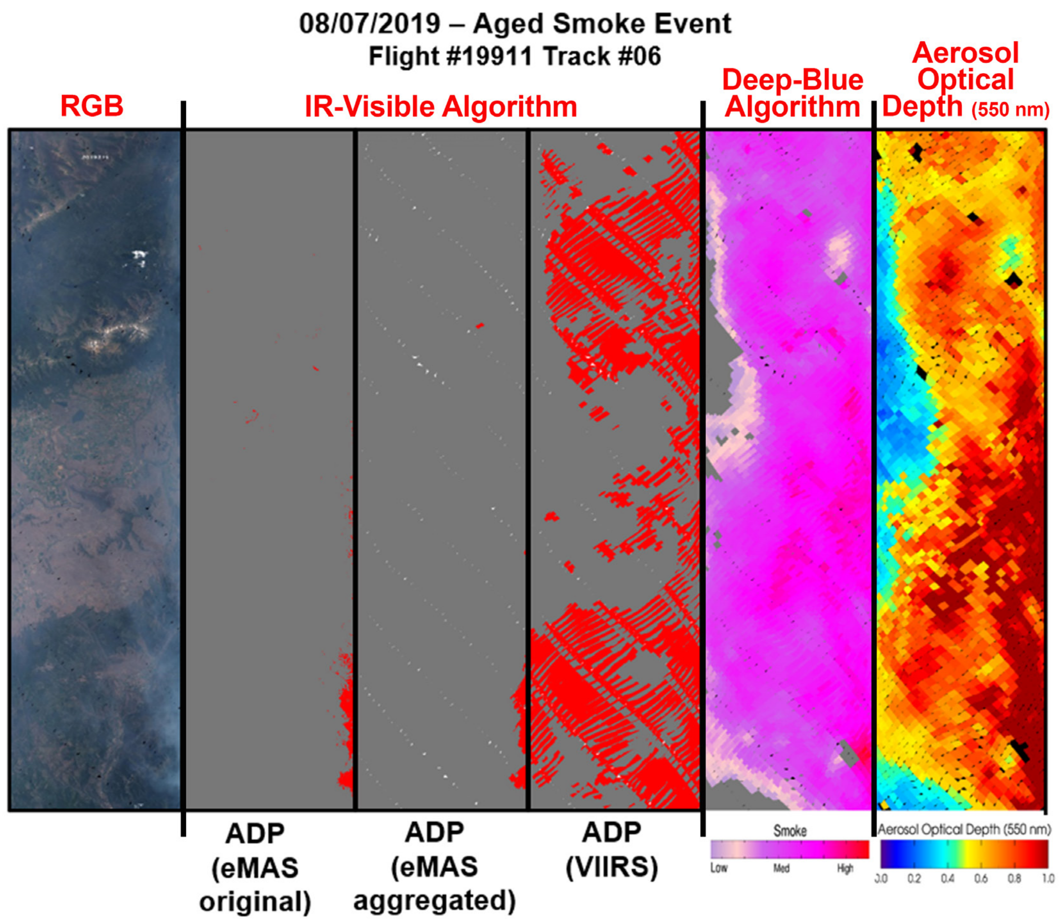


CLICK IMAGE TO ENLARGE. Evaluation of Aerosol Detection Product (IR-Visible algorithm path) using the collocated datasets between eMAS and VIIRS sensors. The images include a reference RGB image (left), Aerosol Detection Product smoke mask (middle), and standard deviation values (right).

While the Deep-Blue path was not run on eMAS observations because of a mismatch in bands, it was available for the VIIRS observations. Comparing the results from the IR-Visible path and Deep-Blue path run on collocated VIIRS data and using reflectance at 0.47µm >0.2 as a proxy for smoke pixels, Dr. Ciren found that the Deep-Blue path detects thin smoke better (shown on the right in pink) than the IR-Visible path.



Digging deeper, Dr. Ciren applied both algorithm paths to small, aged smoke plumes. Again, results (below) indicate the Deep-Blue path is superior to the IR-Visible path in detecting thin smoke and is more consistent with higher Aerosol Optical Depth, a quantitative measure of aerosol concentration that is included for reference. A large difference is also seen in how well the IR-Visible path performs when run on eMAS versus VIIRS observations, which Dr. Ciren notes "is caused by the difference in viewing geometry between eMAS and VIIRS observations."



WHAT DOES VERIFICATION TELL US?

Lessons Learned

A few reasons support why the IR-Visible path does not "see" thin smoke as well as thick smoke. Dr. Ciren suggests that the IR-Visible path may have a dependence on the view angle of the sensor. The view angle varies depending on where the smoke lies along the sensor's scan path. This means that the VIIRS and eMAS sensors "see" smoke differently depending on the time of day and where they are located with respect to the surface when observations are made.

Adding to the challenges, analysis also revealed that the surface reflectance parameterization is not adequate for all conditions. The surface reflectance relationship in the ADP algorithm is derived from VIIRS observations and may not be optimal for eMAS observations. This difference impacts IR-Visible path performance when applied to eMAS observations in thin smoke conditions.

More Challenges, Many Opportunities

FIREX-AQ data provided valuable information about the VIIRS ADP performance. Comparison of the VIIRS smoke mask to the eMAS smoke mask shows that the probability of correct detection is >80% for thick smoke plumes with either the Deep-Blue path or the IR-Visible path. For thin smoke plumes, the Deep-Blue path (75%) is more accurate than the IR-Visible path (33%). These findings are consistent with previous tests that compared the product to the CALIPSO/CALIOP Vertical Feature Mask that uses lidar to look at the distribution of aerosol and cloud particles.

Right now, when smoke is heterogeneous—made up of thick and thin smoke—only parts of the plume are detected with ADP. Dr. Ciren explains that "sub-pixel variability affects smoke detection" particularly for thin smoke, and improvements are underway to address these challenges. One opportunity is to use the VIIRS Day/Night Band or other night observations to make nighttime smoke detection possible. Another is revising the IR-Visible algorithm path to include view angle dependence for some spectral contrast thresholds.

PERSPECTIVE

Observations from field campaigns, like FIREX-AQ, provide a unique opportunity for in-depth analyses of algorithms like those for the VIIRS Aerosol Detection Product. Despite challenges, the VIIRS ADP already has the needed accuracy and measurement range to reliably observe smoke events to help air quality forecasters provide timely warnings and alerts to the public.

For interested readers, the VIIRS Aerosol Detection Product is available on the NOAA AerosolWatch website at https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/, which updates VIIRS observations daily. These data play an essential role in tracking smoke plumes as they move and grow, which is critical as wildfires become more extreme and frequent. ✦

STORY SOURCE

The information in this article is based, in part, on the February 23, 2022, JPSS Science Seminar titled "Heterogeneity of Smoke from Fires: Evaluation of VIIRS Smoke Detection Using FIREX-AQ Field Campaign Data" presented by Dr. Pubu Ciren, I.M. Systems Group, with contributions from Dr. Shobha Kondragunta, NOAA/NESDIS Center for Satellite Applications and Research (STAR), Co-lead for the NPP/JPSS Aerosol Calibration and Validation Team.

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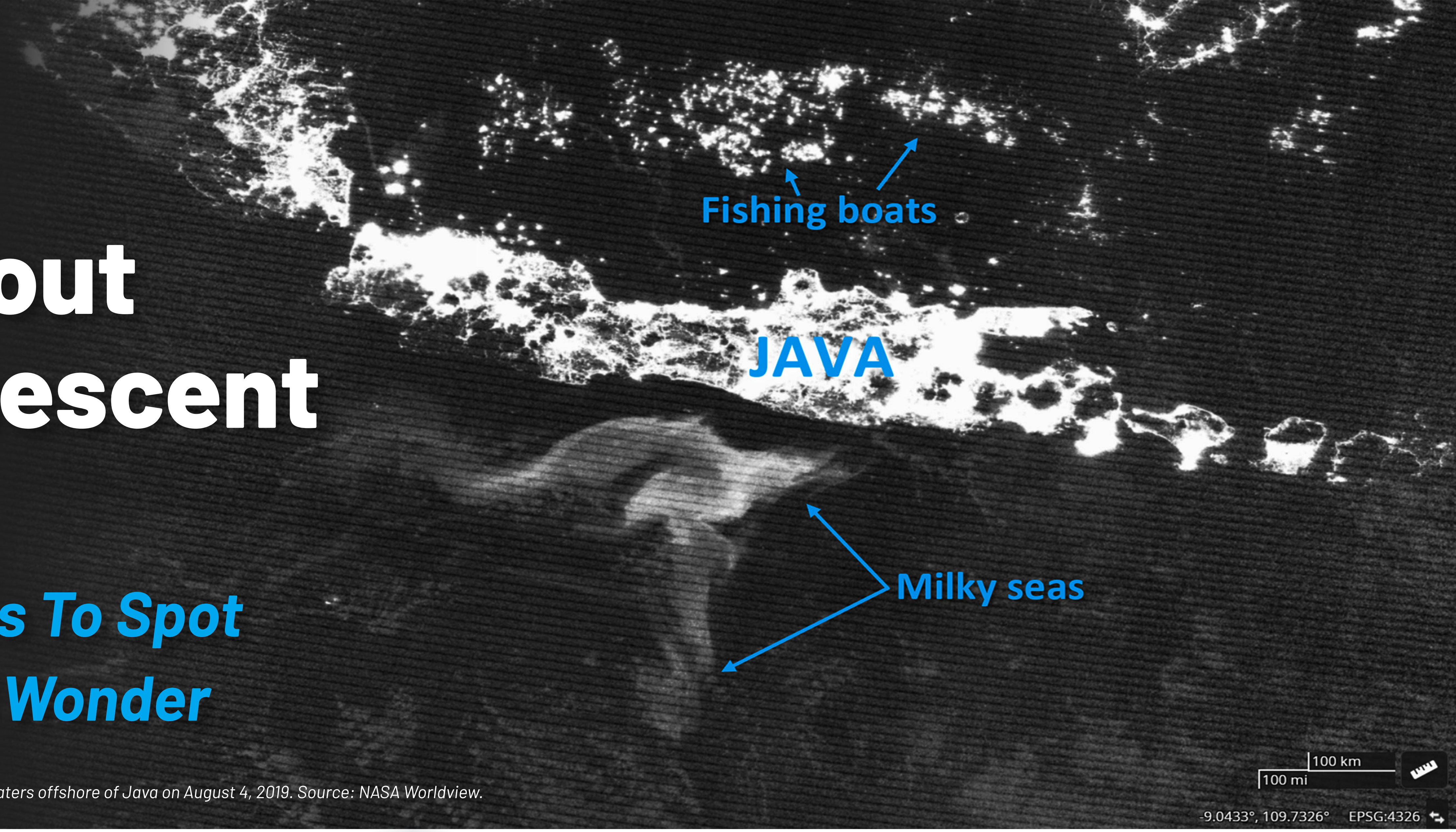
FEATURE 3

On the Lookout for Bioluminescent Milky Seas:

Using NOAA Satellites To Spot a Mysterious Natural Wonder



A 100,000 km^2 milky sea as seen with the VIIRS Day/Night Band drifts in the waters offshore of Java on August 4, 2019. Source: NASA Worldview.

For hundreds of years, mariners have told and retold a tale of ghostly seas, glowing as if covered by a stark white sheet, that stretch on as far as the eye can see while sailing on the high seas under the dark, moonless night skies. Maritime reports from as far back as the 1600s give detailed accounts of this seemingly impossible sight—a phenomenon called "milky seas." A uniform white light, milky seas are surreal and disorienting and can make swells disappear to the eye creating the illusion of a ship hovering above the ocean's surface. The character of a milky sea's glow is steady, widespread, and unbroken, occurring as often in calm and rough seas. This natural wonder, which can last for hours, days, or weeks on end, has puzzled mariners and scientists alike for centuries.

Mariner tales of milky seas eventually made their way back to shore, inspiring the content of many maritime novels—both *Moby Dick* and *20,000 Leagues Under the Seas* mention the remarkable sight in their adventures. But milky seas have largely remained a mystery to science because of their remoteness and passing nature. Dr. Steven Miller, a Professor at Colorado State University's Department of Atmospheric Science and Director of NOAA's Cooperative Institute for Research in the Atmosphere (CIRA), explains, "The maritime folklore is full

> "The whole appearance of the ocean was like a plain covered with snow. There was scarce a cloud in the heavens, yet the sky appeared as black as if a storm was raging."
>
> Captain Kingman of the American clipper ship Shooting Star, Java, 1854

This sample of bacterial bioluminescence in a flask demonstrates the effect as currently understood. Source: S. H. D. Haddock, Monterey Bay Aquarium Research Institute.

of wild and crazy stories—some of them turn out to be hoaxes, others are honest misperceptions, and a few, like the 'Kraken' sea monster—a giant squid that attacked the *Nautilus* in *20,000 Leagues Under the Seas*—are rooted in reality. Milky seas sort of fall in that category of '*we know they're out there, but we're not entirely sure what they are or what causes them*.' Until we can objectively study them, they remain outside of our scientific knowledge."

That claim does not stop the fun of hypothesizing. Milky seas are thought to be caused by certain strains of bacteria that emit light through a process called bioluminescence. More familiar light-emitting organisms, like dinoflagellates, produce sporadic flashes of light to startle and chase away predators when water is disturbed, like at shore break or in ship wakes. But milky sea bioluminescence is different—it is steady and constant and seems to have a different purpose.

Very little is known about why milky seas are so uncommon in nature despite the abundance of oceanic bacteria. Knowledge as to how or why they form, where and when they do, their composition and space/time structure, or their role within the marine ecosystem continues to evade researchers. Prof. Miller hypothesizes that the light of milky seas could attract fish, which might have meaning for the fishing industry, but he is quick to note that the sporadic and remote nature of milky seas could make such a use impractical. Miller suggests, "The *'so what?'* of milky seas could in fact run much deeper. They could hold important clues to understanding broader questions about extreme responses of the marine ecosystem and primary production—at the very base of the food chain—in the face of a changing earth system."

With such looming questions, understanding the milky sea phenomenon seemed important enough to warrant more than a brief investigation of what has historically been a "golly gee whiz!" topic of fascination. So far, there are many clues. Key to the pursuit of answers is a means to detect them, getting out to them, and measuring them on-site. At the March 2022 JPSS Science Seminar, Miller shared his team's early success in beginning to unravel the secrets of bioluminescent milky seas, the subject of two recently published science articles (https://www.nature.com/articles/s41598-021-94823-z and https://www.pnas.org/doi/10.1073/pnas.2207612119).

CHANCE ENCOUNTERS ON THE HIGH SEAS

There exist few known scientific encounters with bioluminescent milky seas in recent history. The first occurred in July 1985 when the US Naval research vessel (R/V) Wilkes stumbled upon a milky sea located east of Socotra in the Arabian Sea. The research crew aboard the vessel

British merchant vessel S.S. Lima.

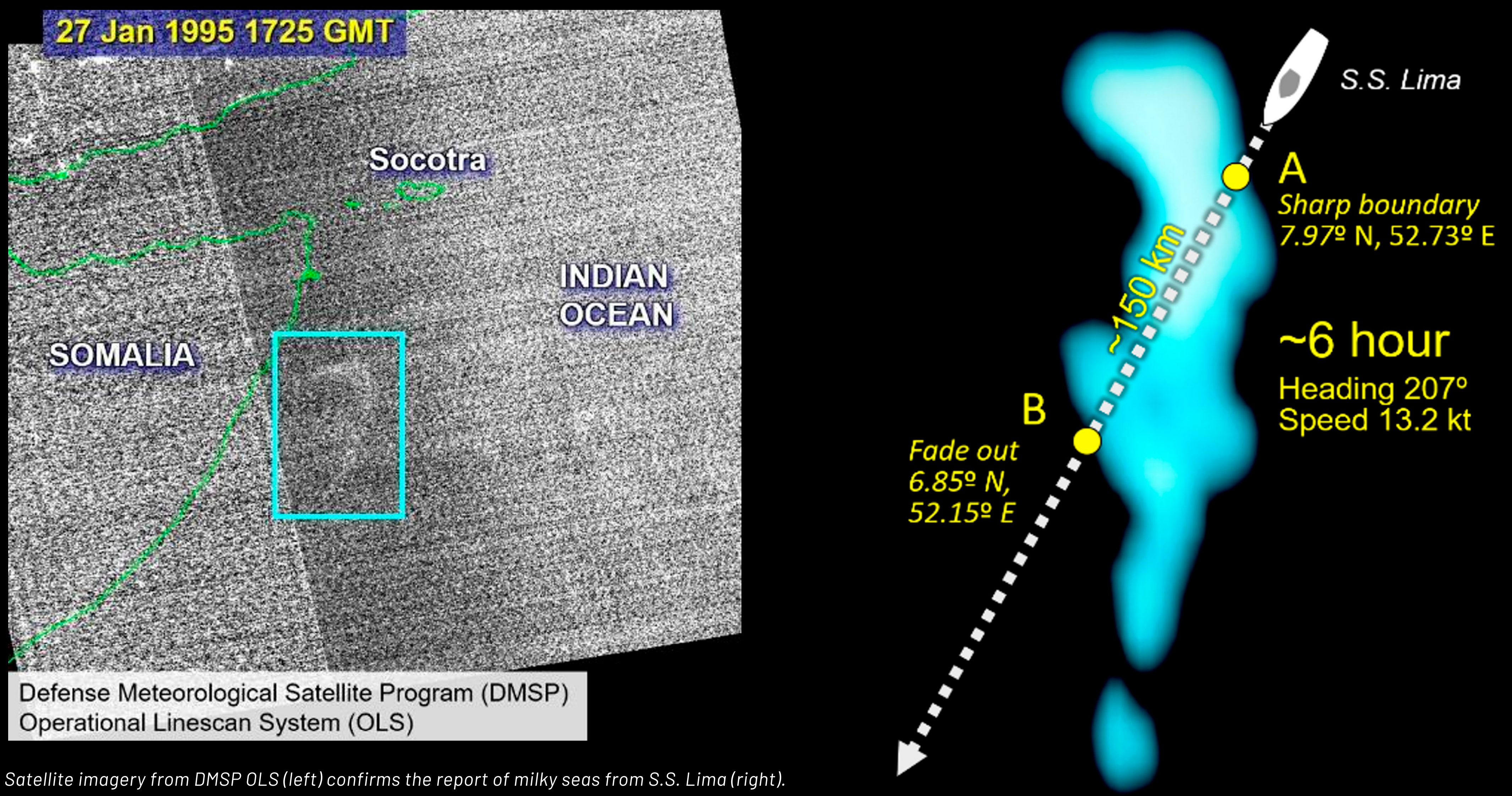
had been studying more common forms of bioluminescence when they unexpectedly found a remarkably different bioluminescent "sheet" that is specific to a milky sea. A filtered sample of the near-surface waters showed the presence of the luminous bacteria *Vibrio harveyi* together with a strain of algae called *Phaeocystis*. Much like previous accounts, they described brightly glowing water extending "horizon to horizon in all directions," contrasting sharply with the night sky. The dark wake produced by R/V Wilkes suggested a possible organic surface slick being colonized by the luminous bacteria. They also thought the glow hovered above the surface, almost like a "milky fog," but a milky sea's brightness can impact depth perception. Other accounts of milky seas describe a glow from below the surface, leaving open this important question of structure.

A decade later, on a moonless night in 1995, the British merchant vessel steam ship (S.S.) Lima was sailing offshore of the Horn of Africa (150 nautical miles east of the coast of Somalia) and suddenly crossed into bright milky white waters. Captain J. Briand described the event "as though the ship was sailing over a field of snow or gliding over the clouds." During their travels, the crew noticed black patches in the water that they confused for slicks of oil. Closer inspection with on-board lamps revealed that these patches were kelp that looked black against the bright white water.

Relying on chance encounters to learn more about milky seas is not practical. Finding a way to remotely locate them on a global scale would give scientists a better chance to thoroughly sample them on-site using the right equipment and across their full life cycle. Miller found a promising pathway toward achieving this goal in Earth observation satellites. NOAA's new generation of polar-orbiting satellites, the Joint Polar Satellite System (JPSS), carry a sensor specially tuned to see very low levels of light at night. While the intended purpose of this sensor was for detecting clouds at night from reflected moonlight, its measurements have benefited many other pursuits ranging from auroras, to fires, to human-produced lights, and in this case, bioluminescence.

HUNTING FOR MILKY SEAS FROM SPACE: A EUREKA MOMENT

The question initially arose in 2003 during a lunchtime science conference chat between Miller and his colleagues: could bioluminescence be seen from space? The understood answer in the community was that "no, the light is too weak, too transient, and occurs over too small of an area compared to the spatial scales resolved by satellites." But this was a "pie in the sky" type question, as the friends considered the future of low-light sensing technologies. Intrigued, Miller (who at that time was a satellite meteorologist stationed at the Naval Research Laboratory in Monterey, CA) searched the internet for any nuggets related to "bioluminescence, ocean, widespread." What he found was an obscure website curated by William Corliss, called *Science Frontiers*[1]—a sort of online depot for "fact, or fiction?" scientific curiosities. On that site was a feature on the S.S. Lima report, extracted from a publication in the journal Marine Observer.



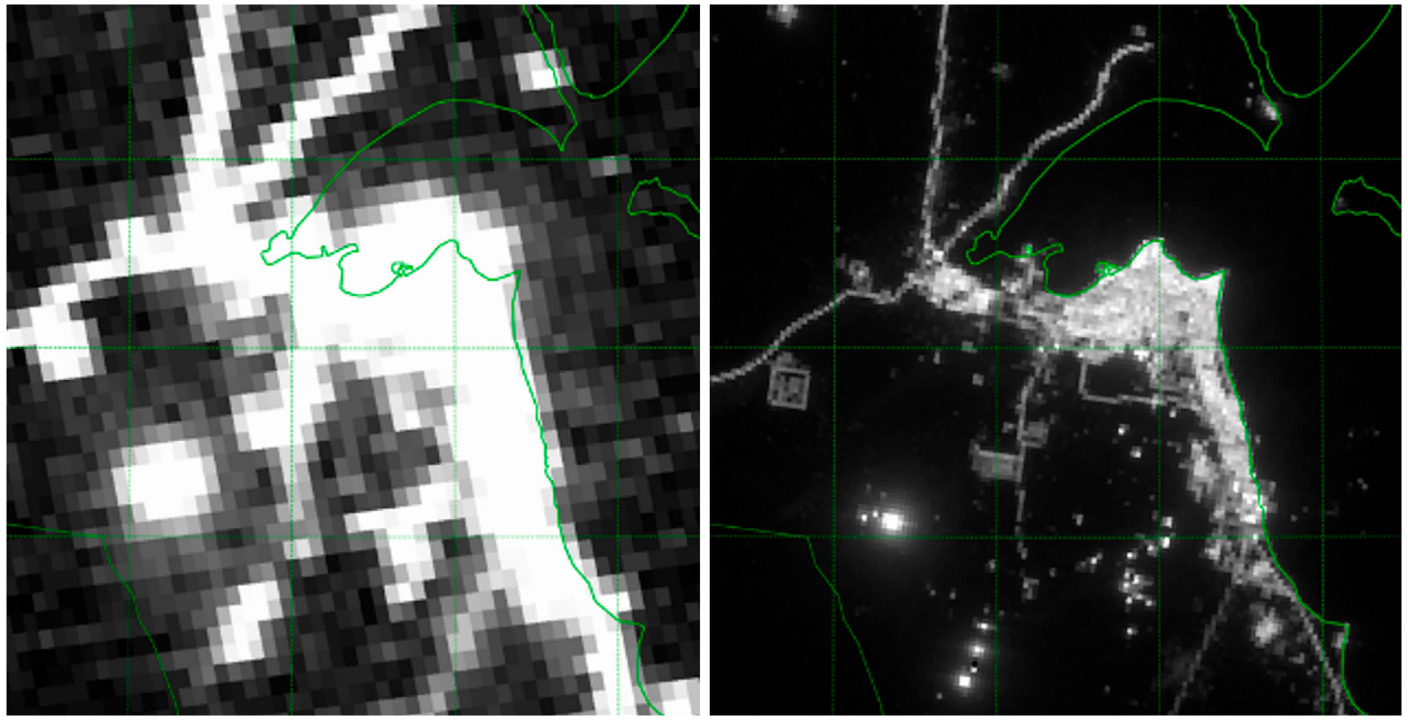
Satellite imagery from DMSP OLS (left) confirms the report of milky seas from S.S. Lima (right).

The S.S. Lima report had details about the milky sea encounter, including date, location, temperature, and wind. Using Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) nighttime lights imagery, Miller and a specialist in marine bioluminescence from the Monterey Bay Aquarium Research Institute, Dr. Steven Haddock, studied images from the date and location in the ship report. Both researchers noticed a faint smudge just like the S.S. Lima account. The feature persisted over several nights, swirling in a counterclockwise motion that matched the analyzed sea surface currents of an eddy, a circular current of water opposite to the main current. It was the first confirmation of a bioluminescent milky sea from space and the first view of a milky sea in its entirety—this one spanning 15,400 km^2, about the size of Connecticut. *Eureka!*

Building on this discovery, Miller's team dove into other historical maritime reports matched to the DMSP OLS imager, but without success. While the satellite imagery of the S.S. Lima sighting offered researchers hope, the quality of DMSP OLS imagery was too poor to reliably find milky seas. With a spatial resolution of 3-5 kilometers (km), very noisy ("salt-and-pepper") data, and very limited sections of usable imagery swath, using OLS imagery to locate milky seas was nearly impossible without prior knowledge about their occurrence and exact location. The S.S. Lima and OLS pairing teased what might be possible from space, but Miller and his team needed new remote sensing technology to know for sure. More detailed, better resolution imagery was needed to find unknown events. Enter the NOAA JPSS and its Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band.

The Revolutionary Capabilities of the VIIRS Day/Night Band

The VIIRS Day/Night Band, a next generation nighttime low-light sensor, debuted in 2011 on the NOAA Suomi National Polar-orbiting Partnership (Suomi NPP) satellite. It is about 100 times more sensitive than the DMSP OLS and can spot faint nighttime lights over land and sea and in the atmosphere. "The spectral bandpass of VIIRS is very similar to DMSP but the spatial resolution is significantly better, offering sub-kilometer spatial resolution," notes Miller. This significant improvement can be seen in the comparison below.



Nighttime city lights over Kuwait City captured by the DMSP OLS sensor at 3-5 km resolution (left) and the VIIRS Day/Night Band at 742 meter resolution (right).

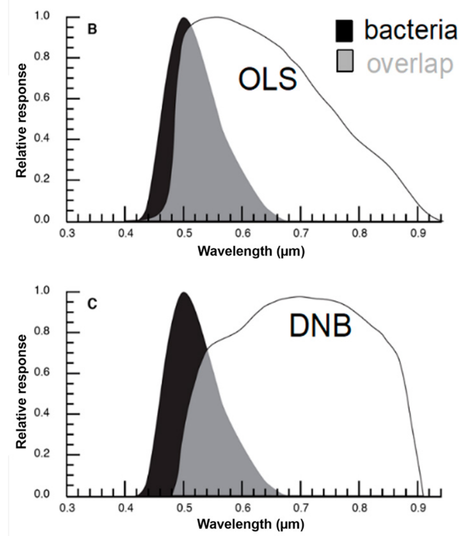
> Day/Night Band capabilities are revolutionary!

"Day/Night Band capabilities are revolutionary!" exclaims Miller. "The sensor resolves the light across a large dynamic range of brightness, allowing satellites to distinguish sources ranging from the faintest light of reflected moonlight to the brightest lights of cities, fires, and lightning flashes," he continues. "It can penetrate thin cirrus clouds to see low level circulations of developing tropical storms. It can even see the faint glow produced by Earth's atmosphere, and the ripples of light produced by the propagation of gravity waves carrying energy from one place to another!"

These qualities are useful to weather forecasters, disaster responders, weather and climate modelers, physical scientists, and now, researchers hunting for bioluminescence. The Day/Night Band currently flies on two NOAA satellites, Suomi NPP and NOAA-20, whose orbital formats provide two to three nighttime passes over low- to mid-latitudes occurring about 50 minutes apart around 1:30 AM local time. These latitudes are where milky seas have historically been reported, especially in the Indian Ocean, and the dual-angle views of the two Day/Night Band sensors make for a powerful one-two punch in deciding if a spot on an image is a cloud, airglow, or something else entirely, like a bioluminescent milky sea.

The Challenges of Using the VIIRS Day/Night Band to Evaluate the Milky Seas

Seeing milky seas from space requires the darkest of nights. The VIIRS Day/Night Band performs so well in low-light conditions that it picks up faint moonlight, airglow, and light reflected off clouds from those sources. While this sensitivity might seem ideal for locating bioluminescence, the problem is that these other light sources confuse the scene, making the weak glow of a milky sea hard to spot. Since in most cases moonlight is about 100 to 1,000 times brighter than the bioluminescent signals, milky seas are only visible on imagery when the moon is below the horizon when VIIRS passes overhead—about 15 days during each ~29-day lunar cycle. Compounding the problem, the spectral response of the Day/Night Band overlaps only partly with bioluminescent light, as shown in the figure, meaning that the sensor does not sense the strongest light from the likely source of milky seas (luminous bacteria). Despite these limitations, Miller believed that milky seas—if large enough—might still be detectable by the VIIRS Day/Night Band on moonless nights because of their steady, constant, and persistent glow combined with the sensor's superior sensitivity (roughly 10x) to the legacy OLS. To find out, his team carefully studied Day/Night Band observations in regions where milky seas were commonly reported. It took years of looking, learning, and languishing, but with a perseverance fueled by hope, in the end what they found was remarkable.

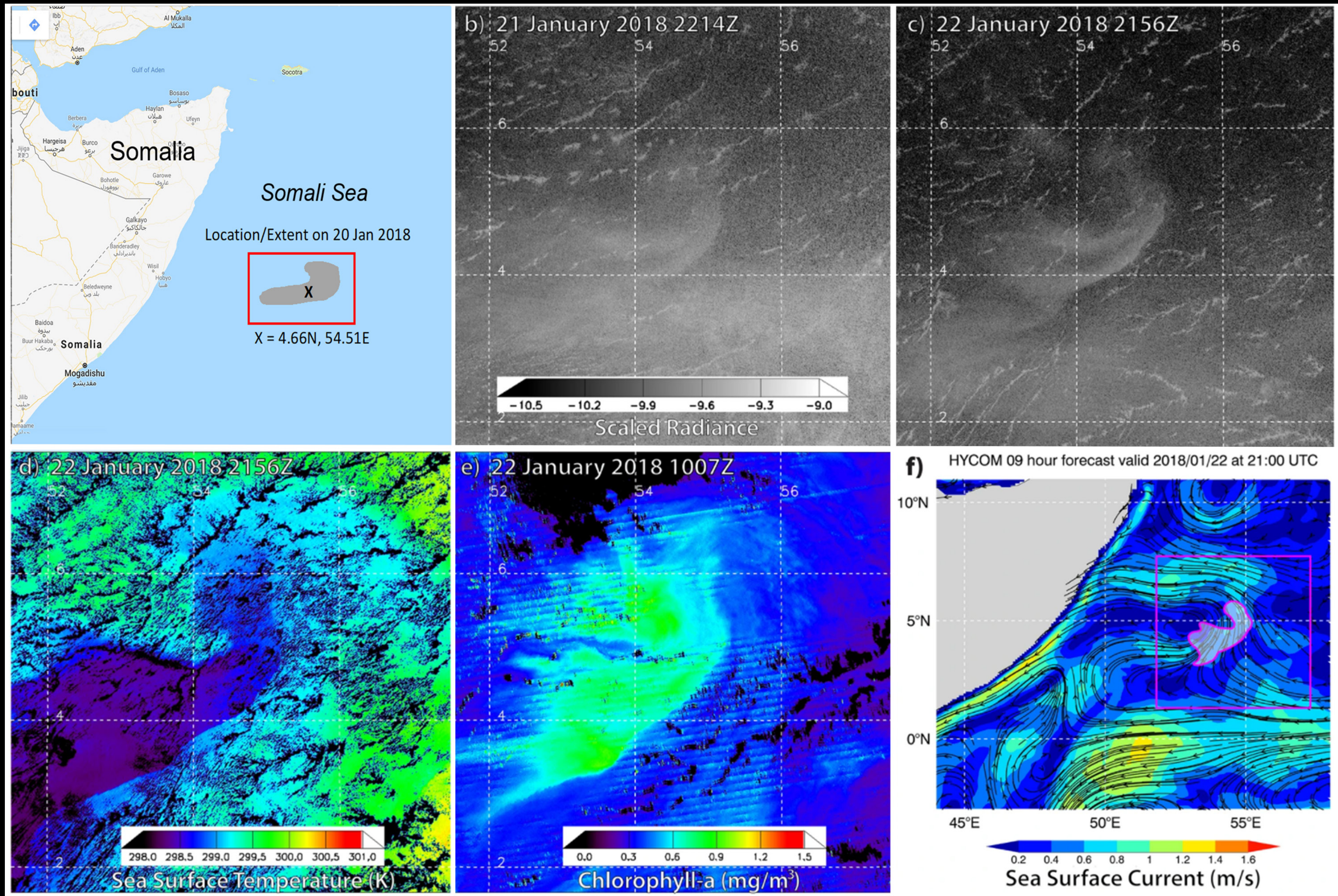


CLICK IMAGE TO ENLARGE. Spectral response functions of the DMSP OLS sensor (top) and VIIRS Day/Night Band (bottom) showing the spectral overlap for bioluminescent bacteria (in gray).

THE TIDES TURN: A RETURN TO SOMALIA AND JAVA

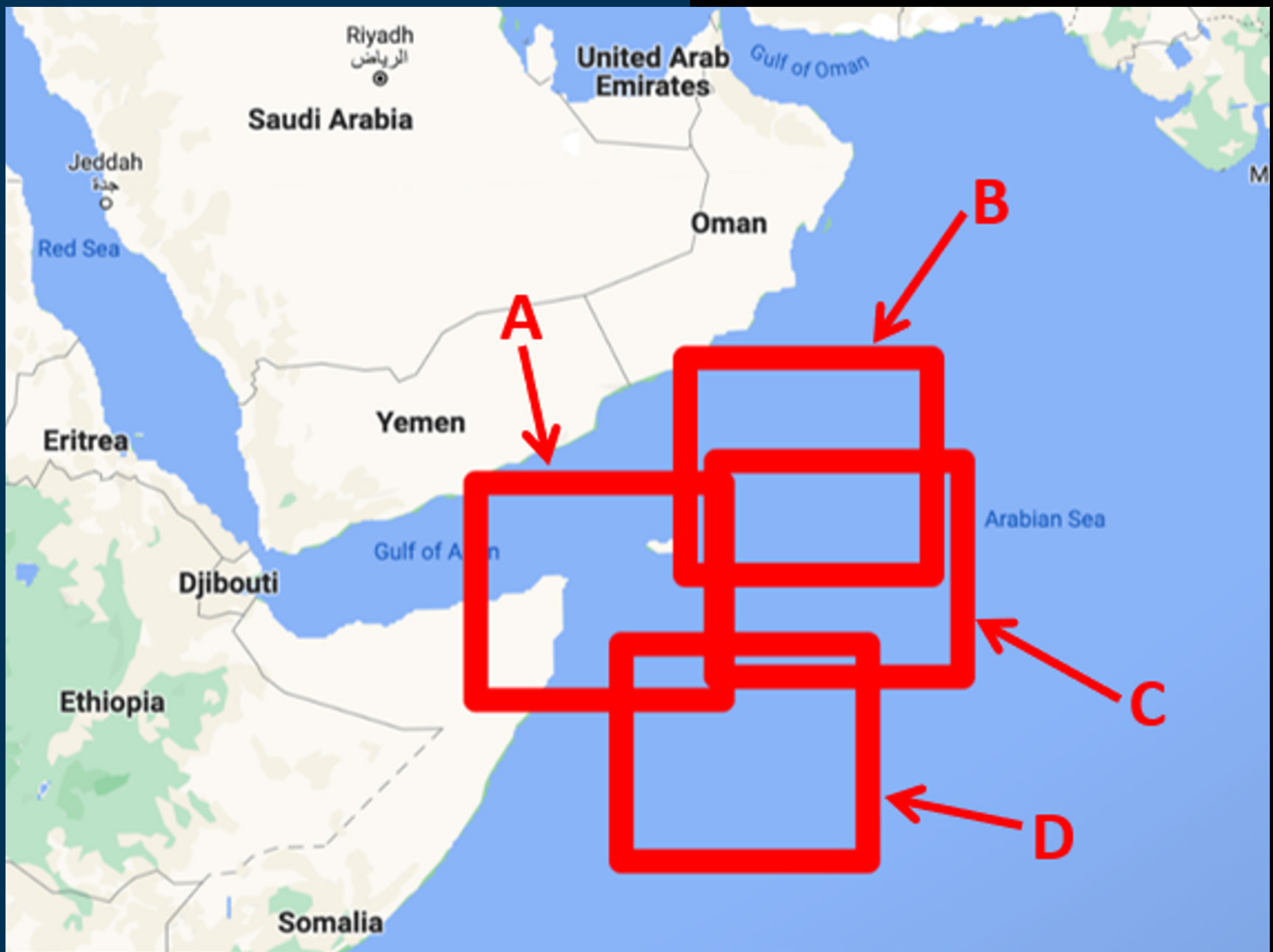
Everything changed when the team looked at Day/Night Band imagery of the Somali Sea from 2018 and saw something curious—a shadowy swoosh that persisted in the same place for night after night. Miller recalls, "...climatologically speaking, it's the right spot to see something. Best thing might be to look at adjacent nights, the night before last and tonight. I just did this...holy cow...I think we have something here!!! Look—a stable feature over multiple nights!!!"

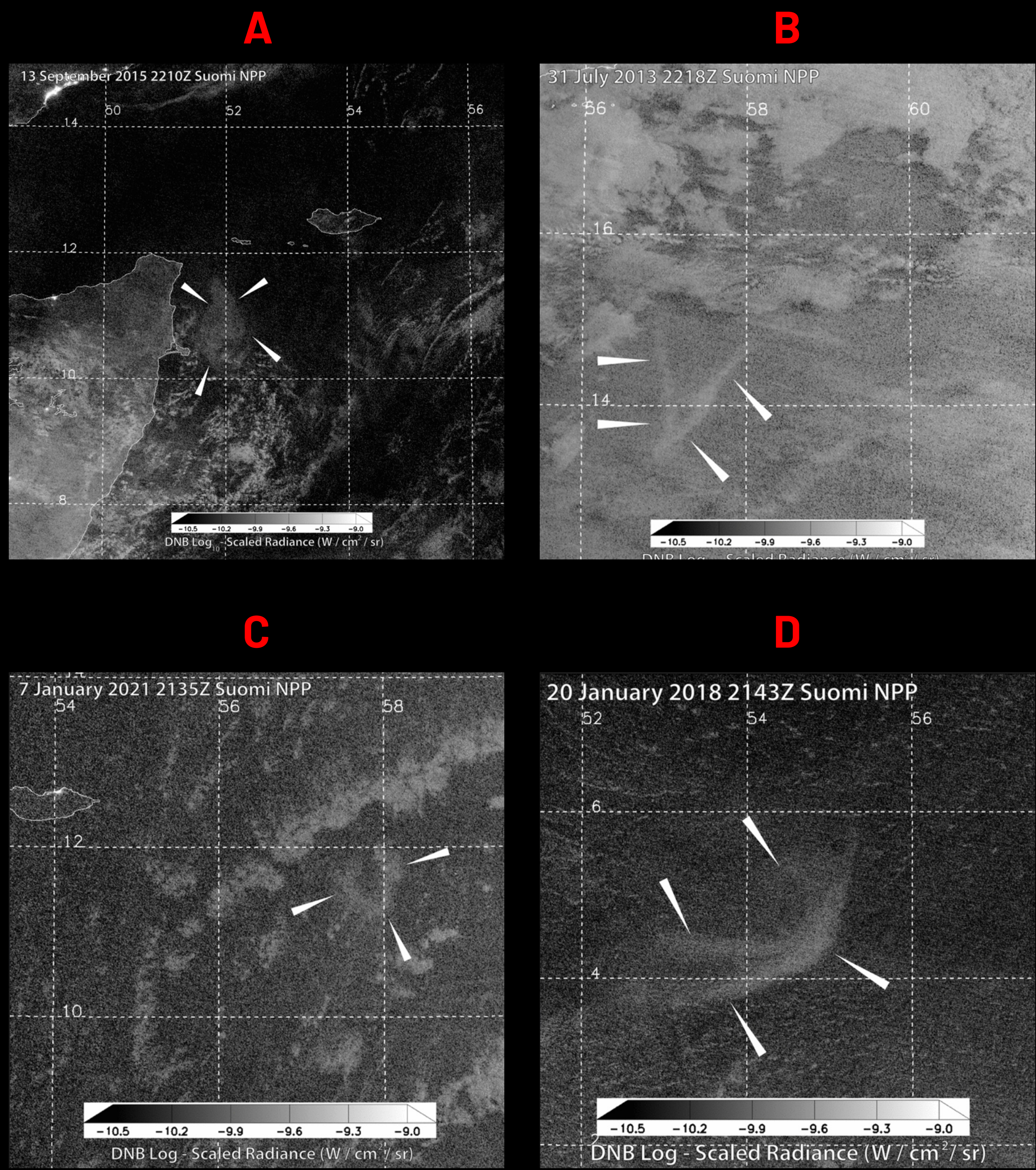
Further tests checked all the boxes for a bioluminescent milky sea, and incredibly, it was in the same general area and time of year as the S.S. Lima sighting 23 years earlier. When the team looked at ocean conditions from other satellite and model data for the date and location, they saw changes in sea surface temperature, elevated biomass (in terms of chlorophyll-a concentration), and sea surface currents that lined up with milky sea boundaries and explained its drift over several consecutive nights. Could this provide a clue for an ideal habitat?



A milky sea in the Somali Sea corresponds with changes in sea surface temperature, chlorophyll-a concentration, and sea surface currents.

Most maritime accounts from the past two centuries have been logged in the Indian Ocean, especially the northwest region that includes the Somali and Arabian Seas, indicating a potential hot spot for activity. When Miller and his team focused on this region, they found several more potential milky seas in Day/Night Band imagery archives. But the best was yet to come on the opposite side of the Indian Ocean and in a spot with its own unique milky sea history.



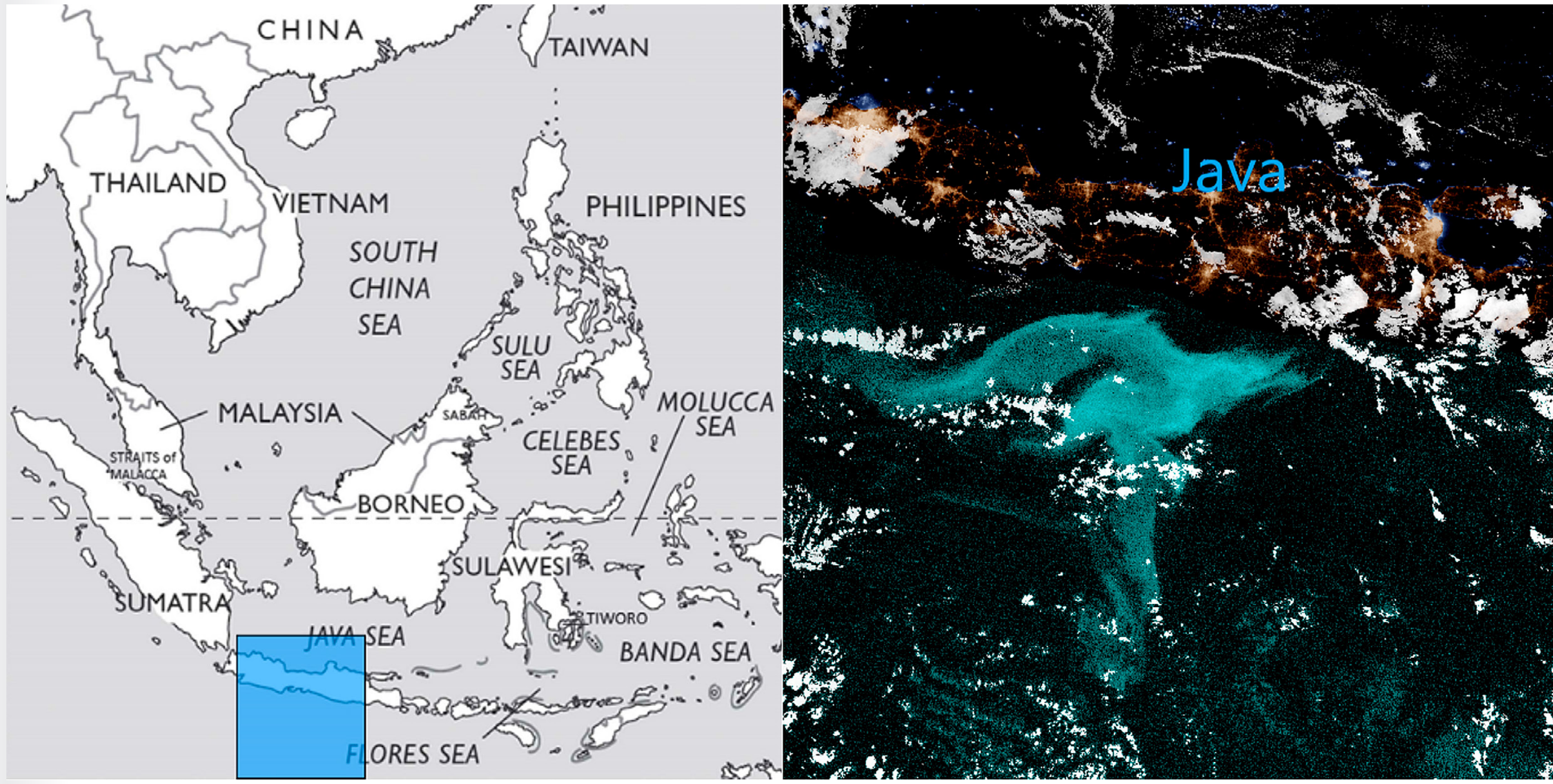


Several milky seas identified in the northwest Indian Ocean near the Horn of Africa during July, September, and January. Each structure (highlighted by pointers) was observed to persist and drift with the analyzed sea surface currents over multiple nights and was not correlated with the ever-changing meteorological cloud field.

In late June of 1854, a lone American Clipper ship, the Shooting Star, sailed silently over the midnight black waters of the tropical eastern Indian Ocean south of Java. Suddenly, to the amazement and horror of the crew, they find themselves confronted with something otherworldly. According to the ship's Captain:

> The whole appearance of the ocean was like a plain covered with snow. There was scarce a cloud in the heavens, yet the sky appeared as black as if a storm was raging. The scene was one of awful grandeur, the sea having turned to phosphorus, and the heavens being hung in blackness, and the stars going out, seemed to indicate that all nature was preparing for that last grand conflagration which we are taught to believe is to annihilate this material world!
>
> Captain Kingman, *Shooting Star*

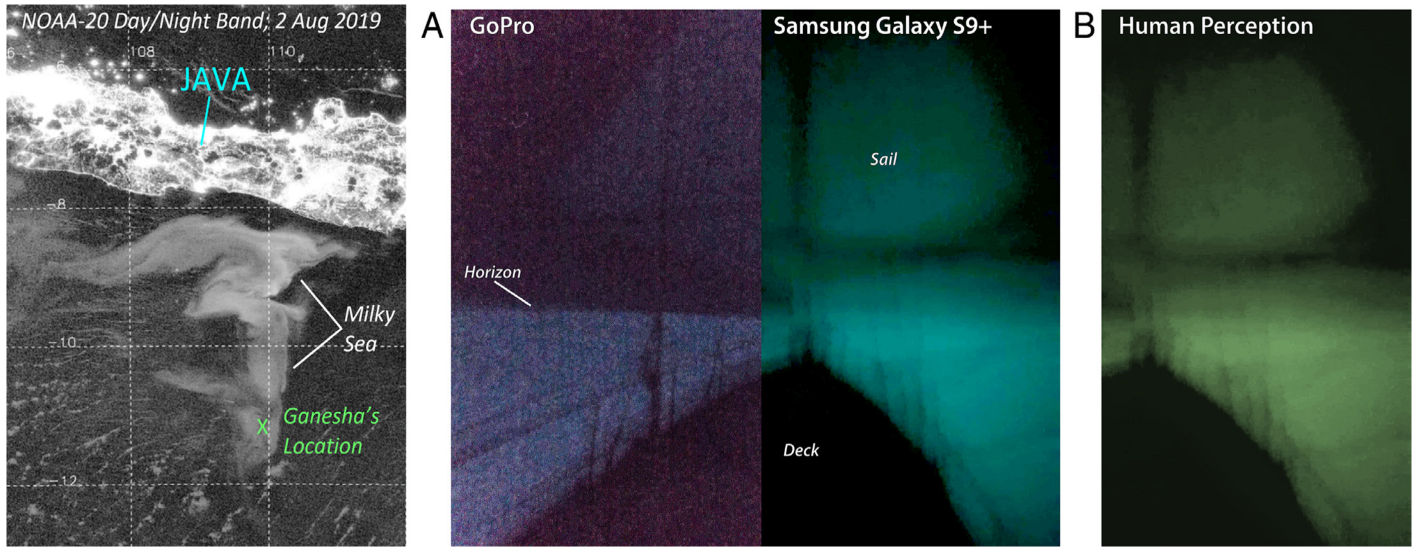
Fast-forward to the same location 175 years later (July 2019) and from 824 km (512 miles) above the Earth's surface, the orbital altitude of JPSS satellites. Miller was looking at VIIRS Day/Night Band imagery around the Maritime Continent—the region between the Indian and Pacific Oceans that includes Java in Indonesia. In this case, he was searching for examples of "false alarms" for milky seas, sometimes caused when similar cloud structures form in the same place from night to night because of repeating patterns known as the diurnal cycle. Instead, and to a level of surprise rivaling that of Captain Kingman, Miller noticed a massive swirling feature south of Java with all the tell-tale signs of a milky sea. A thermal emission was immediately ruled out because, per Planck's law, the sea surface temperature would have to have been an unrealistic 620°F (327°C/600°K) to produce a thermal signal measurable by the Day/Night Band. Miller had accidentally stumbled upon the largest milky sea detected from space to date, and one that would change the game in terms of offering key clues on composition and structure.



The largest milky sea detected to-date off the southern coast of Java lasted July-September 2019. On the right is VIIRS Day/Night Band False Color imagery showing the enormous extent of the milky sea.

This glowing swath of ocean south of Java spanned over 100,000 km^2, about the size of Iceland. At that scale, it would take about six hours at 50 miles per hour (80 km per hour) to "drive" across it from end to end. Other satellite data showed cooler water temperatures, higher concentrations of chlorophyll-a, and two eddies that matched up with milky sea edges and explained its changing shape over time. These conditions were consistent with previously identified events but with detail never seen before. In one portion of the waters, the glow was so bright that small cumulus clouds appeared as dark objects in the imagery because they obstructed some of the light coming up from the water. What a sight this must have been at the surface!

Remarkably, on the night of August 2, 2019, a private yacht called *Ganesha*, crossed through a portion of the glowing waters. After later learning about Miller's research from media coverage, the *Ganesha* crew reached out to Miller to share their recollections and the first photographs of a milky sea in nature (below). Like previous mariner reports, they described the experience as if they were "sailing on snow"—an unchanging and steady glow brighter than the night sky. But, they also remarked that the light appeared to emerge from deep within the ocean, maybe even as deep as 30 feet, throwing into question the idea of a milky sea "surface slick" previously hypothesized. Even with surface observations, questions remain!



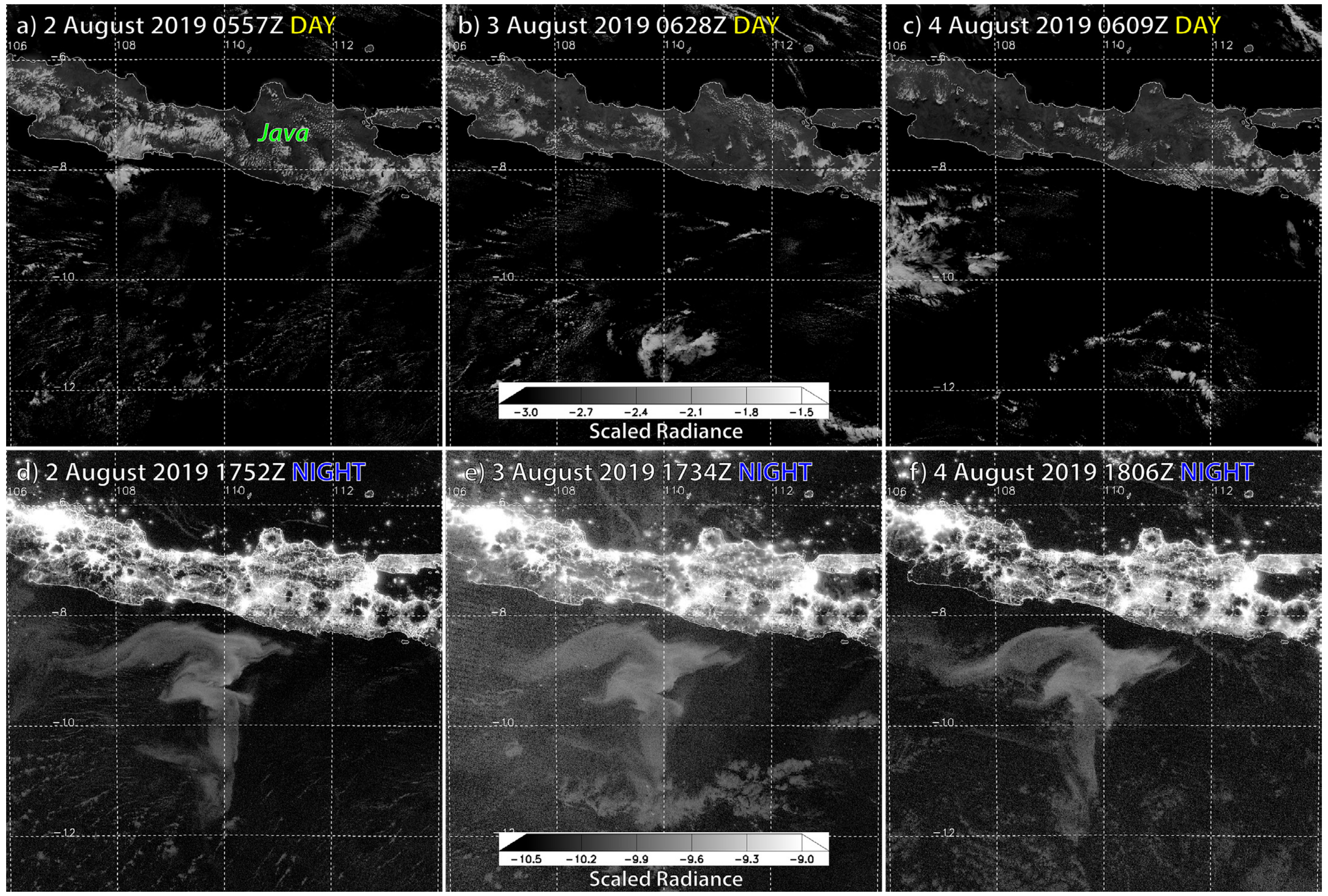
Left: VIIRS Day/Night Band imagery from August 2, 2019 showing the milky sea and the approximate location of the yacht Ganesha on that date. Middle (A): GoPro and smartphone photographs of the milky sea glow captured by Ganesha's crew. Right (B): A color-adjusted version of the smartphone photo approximating the visual perception of the glow from the Ganesha. Source: Miller 2022.

The Java milky sea endured for more than 40 nights in 2019, tracked with satellites by Miller, including a two week pause in observations when the moon was too bright for the glow to be visible on Day/Night Band imagery. The surprise of seeing the milky sea reappear after this interruption gave Miller new hope that a future large event could stick around long enough for researchers to reach it in a realistic time frame and sample its waters, potentially laying to rest some of the mystery.

A 100,000 KM² VANISHING ACT

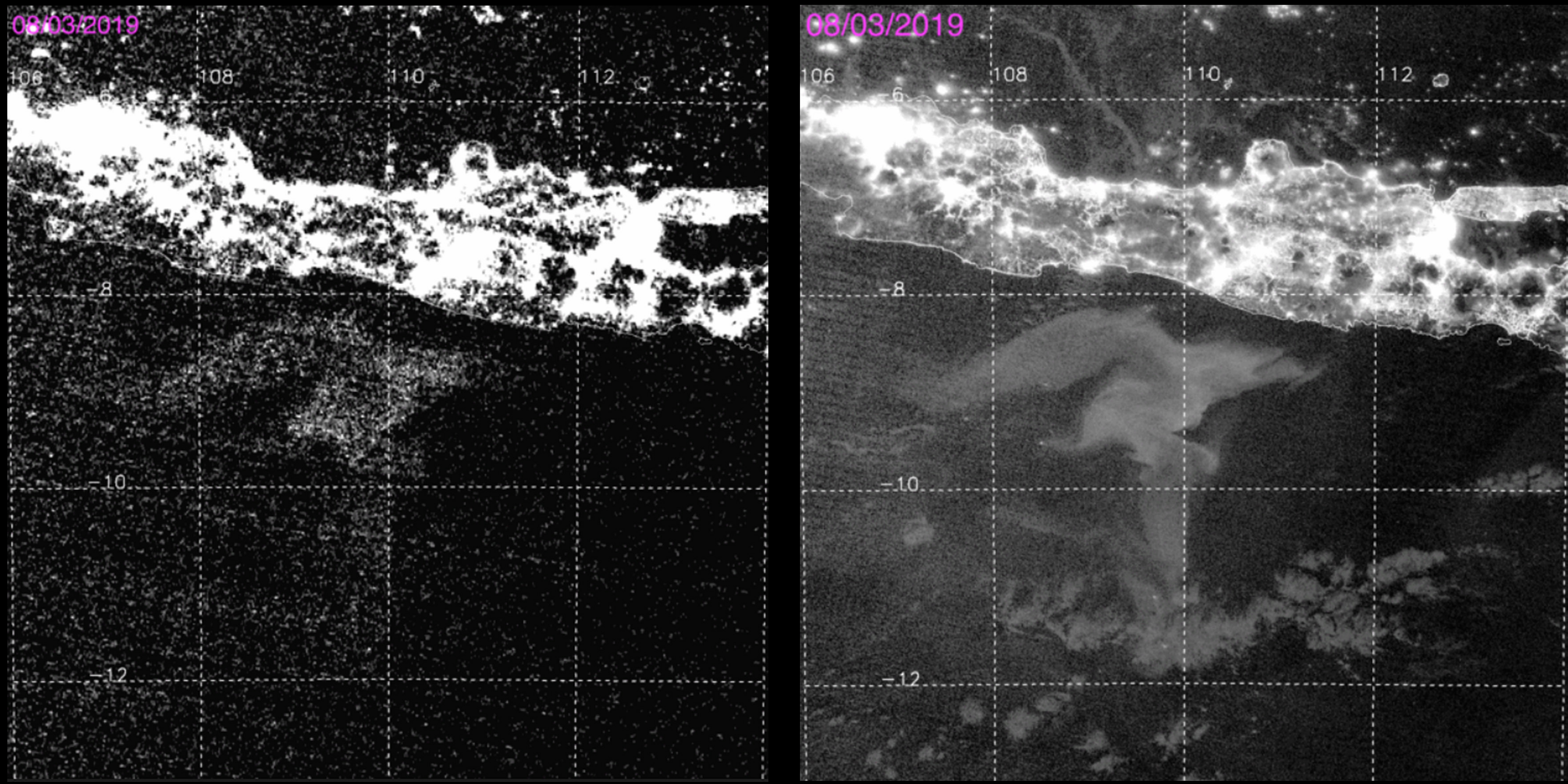
Complicating the hunt for milky seas is the unique way they emit light. Milky seas do not produce infrared or reflective signatures and their light emissions are about 10-100 million times fainter than daylight scenes, which means they are completely invisible in daytime satellite imagery (despite the likelihood that the bacteria are also glowing during the day). As mentioned before, moonlight makes it hard to continuously hunt for milky seas, as moonlight is about 100 to 1,000 times stronger than these bioluminescence signals. Because of this, milky seas are only detectable on moonless nights—about half of the 29.5-day lunar cycle. Looking at Day/Night Band imagery of the Java event during a moon-free period (below), the 100,000 km² milky sea off the coast of Java is undetectable in the daytime imagery but is unmistakable as a persistent bright anvil shape at night.

Milky seas are hard to spot and fleeting—smaller events only appear to last a few days or a couple of weeks



Day/Night Band images from day (top row) and night (bottom row) for three consecutive moon-free dates during a milky sea event off the southern coast of Java.

at most. So how are researchers sure that a smudge on a satellite image is a milky sea and not one of the many other possibilities, like clouds reflecting airglow? Several clues and techniques help piece this together. Milky seas move and change slower than clouds over consecutive nights, making them easy to tell apart in most cases, and most clouds tend to be colder than what lies beneath them, which helps them stand out in nighttime infrared imagery. Reflective suspensions in water are sometimes viewable at night, but if that were the case it would also imply that the reflected suspension would easily be seen in daytime by reflected sunlight. The off and on nature of milky seas between day and night helps to single out the bioluminescence.



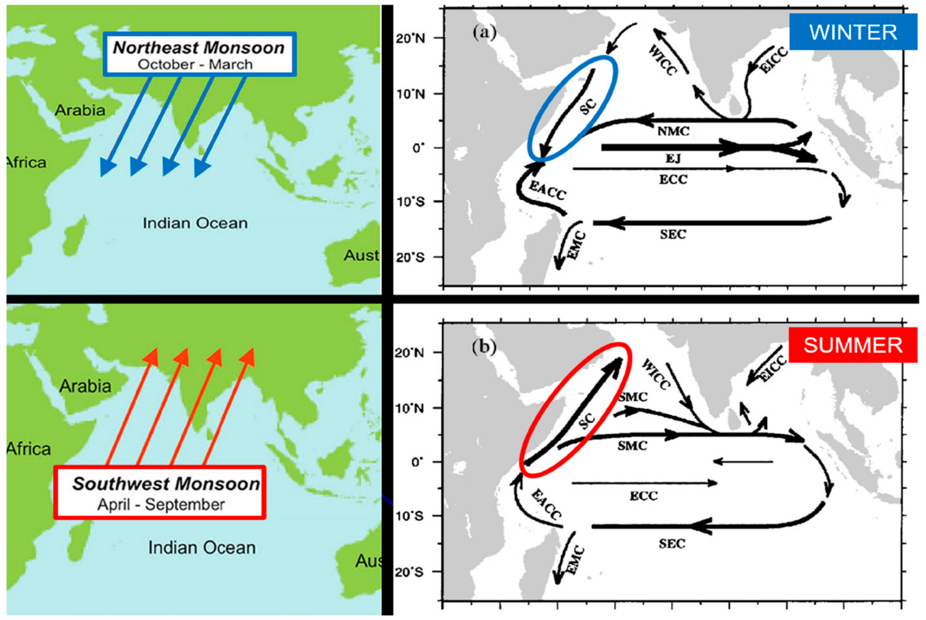
The Java milky sea event in August 2019 as detected by OLS (left) and VIIRS Day/Night Band (right).

Also, because there are two Day/Night Band sensors on two JPSS satellites collecting measurements about 50 minutes apart, a milky sea can be looked at from two different angles and checked for parallax shifts. Parallax shifts occur when a satellite views something that is above the surface (like a cloud) from two different angles. The higher the altitude of the object—its vertical elevation above the surface—and the more tilted and opposite the two viewing angles are from each other, the larger the shift will be. A milky sea, which is part of the surface (not on top of it), produces no parallax shifts and so it appears stationary. This makes it easier to tell apart from clouds and airglow features in the atmosphere. Clouds and airglow can also evolve and move rapidly, unlike milky seas, which are subject to much slower ocean currents.

Through all this high-tech multi-spectral sleuthing, 'Sherlock' Miller and his team of 'Watsons' showed that not only can the VIIRS Day/Night Band detect milky seas, but at a reliability that presents a dramatic improvement over the OLS sensor. Importantly, the improved image quality of VIIRS may be sufficient to locate milky seas remotely and without the help of a surface observer. But detection is one thing—understanding the cause and making accurate predictions of future events is another. The reasons for milky sea formation and their preference for the Indian Ocean are not well understood. Coordinating a milky sea response team will require a better sense for what makes milky seas "tick," and this defines the current direction of scientific inquiry.

HOT SPOTS: WHAT'S SO SPECIAL ABOUT THE INDIAN OCEAN?

Indian Ocean Monsoon Seasons



CLICK IMAGE TO ENLARGE The winds (left) and sea surface currents (right) during the Northeast Monsoon season (top) and Southwest Monsoon season (bottom). Source of surface current schematic: Shenoi et al., 1999.

After searching through thousands of Day/Night Band images, going over hundreds of historical ship reports, and reading the sparse but useful scientific literature on the topic, it became clear to Miller's team that there was something very special about the Indian Ocean. They noticed that milky sea activity peaks in the northwest Indian Ocean during winter and summer months, coinciding with the northeast (winter) and southwest (summer) monsoon seasons. During winter months, cool air streaming down from the Tibetan Plateau and continental interior causes a strong northeasterly flow that defines the Northeast Monsoon. The opposite phenomenon occurs during the hot summer months of the Southwest Monsoon season, when the Tibet Plateau heats up and draws in warm, moist air over the Indian subcontinent.

These summer and winter season monsoonal winds blowing across the northwest Indian Ocean transfer some of their momentum into the water, driving surface currents that cause mixing and upwelling along the northeast African coast. Upwelling draws nutrients up from deeper water to the ocean surface. Algae (or plankton) feed on these nutrients, which explode into huge 'blooms' and set the biological process of milky sea formation into motion. The more nutrients, the more algae, the more bacteria can colonize. But if it were that simple, why do milky seas seem to be so uncommon?

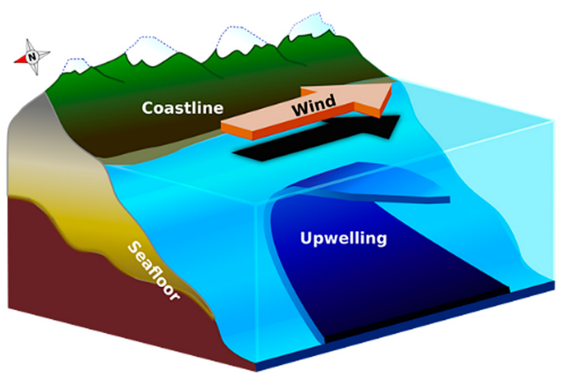
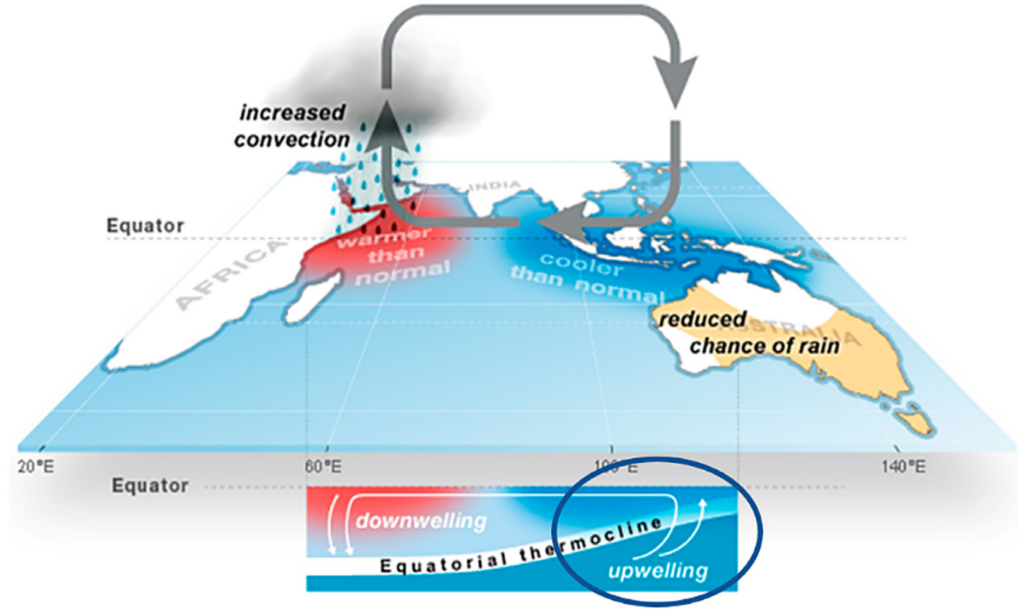


Illustration of the upwelling process. Source: Wikipedia Creative Commons.

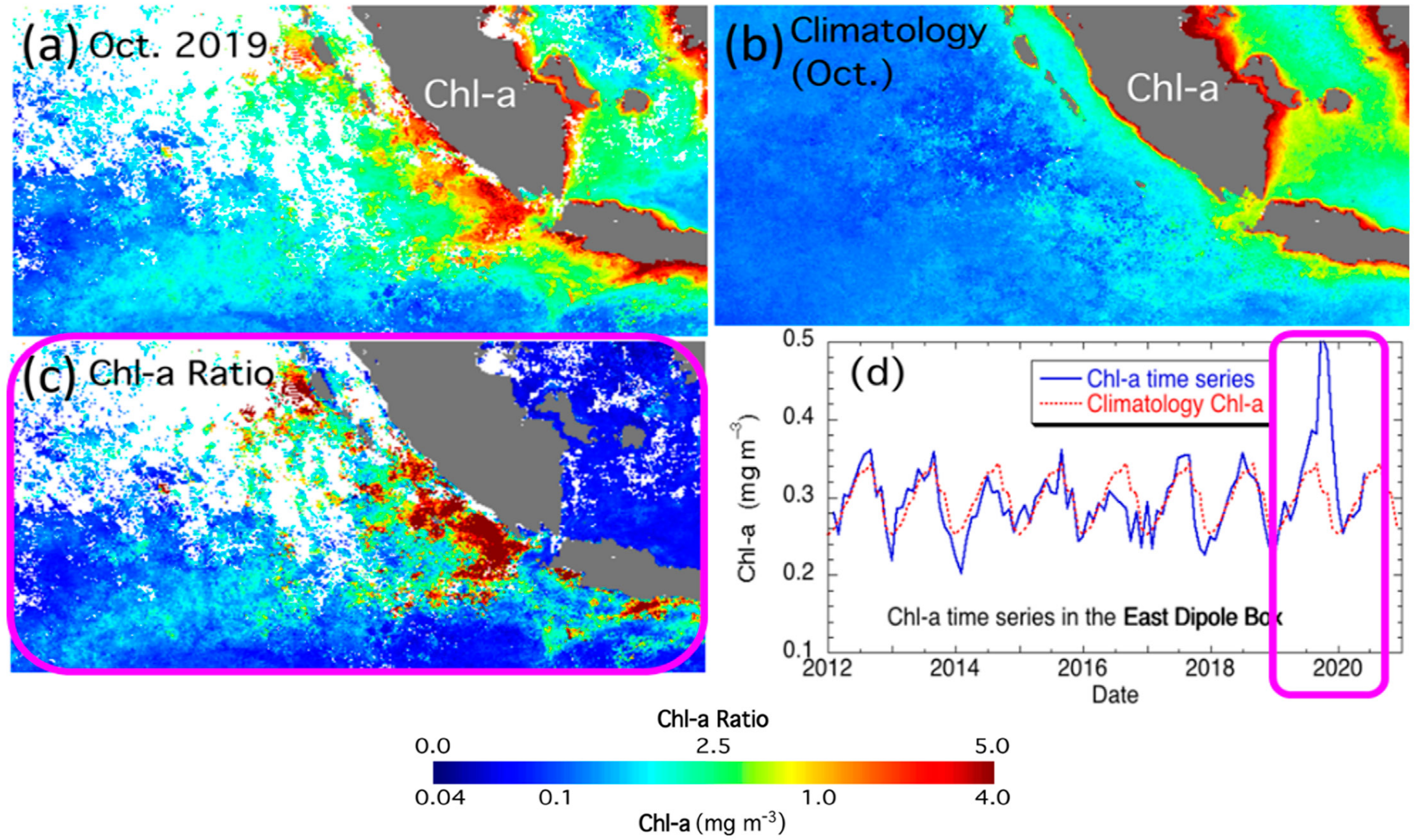
The Indian Ocean Dipole of the Maritime Continent

For milky seas in the Maritime Continent region (eastern equatorial Indian Ocean), the process is less obvious as there is no apparent link to seasonal weather. But there is a coupled atmosphere-ocean circulation known as the Indian Ocean Dipole (IOD). This circulation is like the El Niño Southern Oscillation that affects U.S. wintertime weather but occurs in the Indian Ocean instead of the Pacific Ocean. It involves a flip-flop in sea surface temperatures and rainfall across the equatorial Indian Ocean basin, with the positive phase producing a warmer, wetter west and a cooler, drier east, and the opposite during the negative phase. For the Maritime Continent, it is this positive IOD phase—when stronger than normal easterly winds blow across the region—that promotes mixing and upwelling, potentially leading to more productive algal blooming and favorable conditions for milky sea formation.



Indian Ocean Dipole (IOD): **Positive phase**

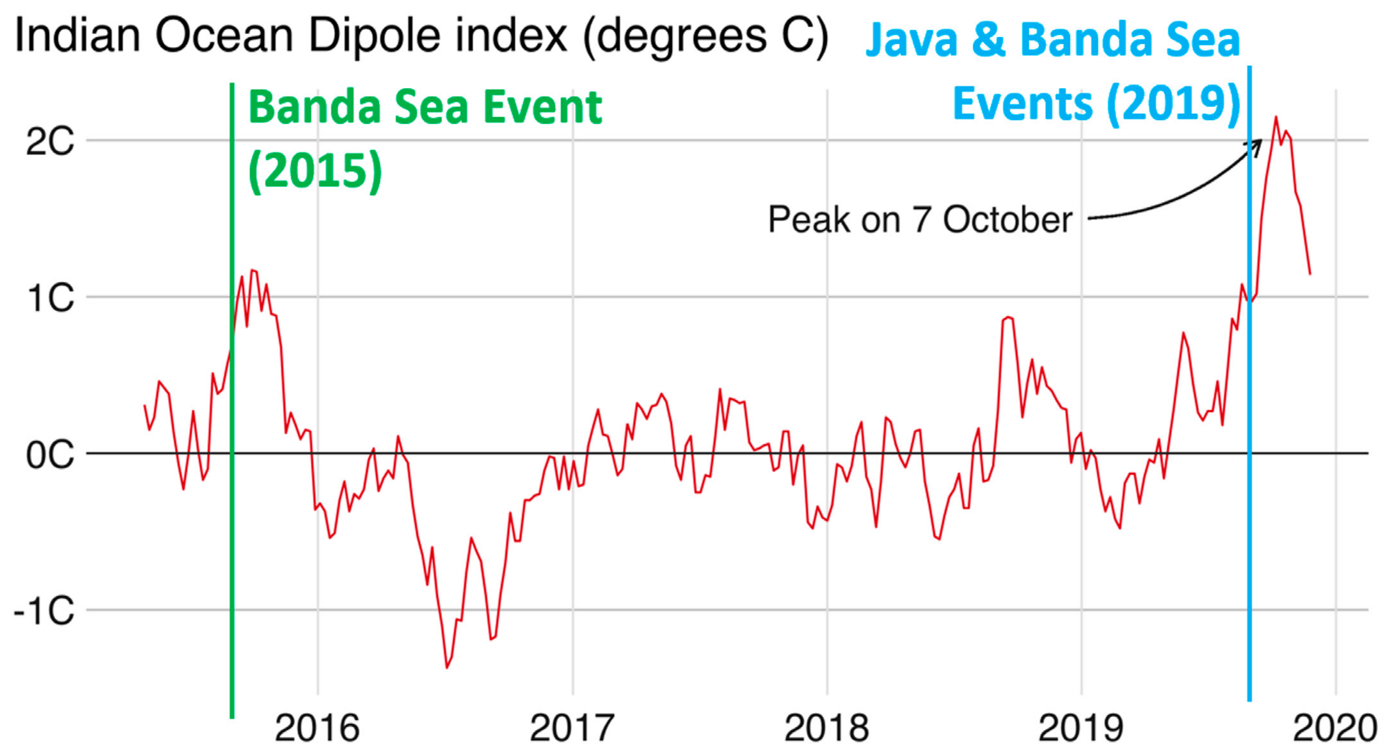
Although the data are sparse, there is anecdotal evidence that the IOD may be an important player in this process. During the massive Java milky sea event in 2019, a major positive IOD phase was occurring. Sea surface temperatures were unusually cool with high concentrations of chlorophyll-a—a measure of algae extent in water—seen in areas of upwelling (along with increased sightings of filter-feeding whale sharks by divers near Christmas Island!). Four years prior, in 2015, another Banda Sea event was linked to a positive-phase IOD. Miller and his team continue to explore this plausible hypothesis for the erratic but sometimes enormous milky seas of the Maritime Continent.



Analysis of primary production off the southern coast of Java in late 2019 showing (a) anomalously high chlorophyll-a (Chl-a) compared to (b) climatology, producing (c) a high climatological ratio. The event occurred during a particularly strong positive mode of the IOD (d).

Map showing the relative proximity of the simultaneous milky sea events off the coast of Java (left) and in the Banda Sea (right) in July and August of 2019. The date break for the Java event pertains to limitations in the Day/Night Band to observe milky seas under moonlight conditions; the event was likely continuous over this period. Map source: Britannica.

At the same time as the Java event, a smaller milky sea was occurring in the Banda Sea—also within the Maritime Continent but off to the northwest by 2,000 km. The coexistence of these events and their geographic closeness suggest a regional response to the IOD. The irregularity of the IOD, whose strength is thought to depend on its phasing with the El Nino Southern Oscillation further to the east, may also help explain why fewer milky seas are reported in the Maritime Continent compared to the northwest Indian Ocean. Basically, more "stars need to align" compared to the regular seasonal heating and cooling of the Tibetan Plateau, which is thought to regulate the northwest Indian Ocean milky seas.

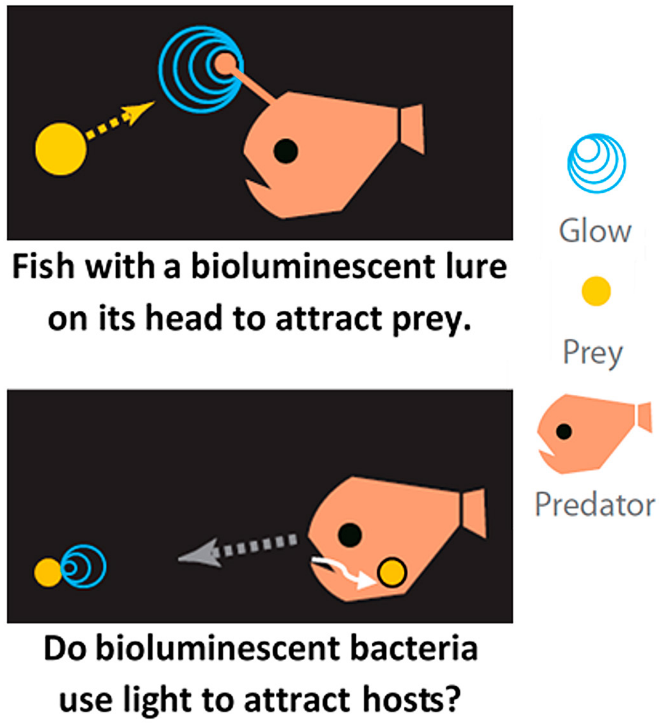


Maritime Continent milky seas correlate with the positive phase of the Indian Ocean Dipole. The index shown here refers to the temperature difference between two points in the Indian Ocean. Source: Australia's Bureau of Meteorology.

TRILLIONS OF BACTERIA GLOWING IN UNISON, BUT FOR WHAT PURPOSE?

Nutrient-rich upwelling waters offer ideal habitats for large algal blooms (for example, Phaeocystis), which are targets for luminous bacteria (like *Vibrio harveyi*) thought to cause milky seas because of the steadiness of their glow—a unique characteristic of bacterial bioluminescence that separates it from the dinoflagellate "flashing" light. Once the number of bacteria has exceeded a critical threshold—about 100 million cells per milliliter of water—collective glowing is triggered. Bacteria "turn on" their light (bioluminescence) almost in unison through quorum sensing, a communication technique that allows bacteria to coordinate group behavior according to population density. When trillions of bacteria light up across thousands of ocean miles, the visual effect is a constant and uniformly glowing sea. It takes a lot of energy for bacteria to emit light, so why do they do it?

One popular idea is that glowing bacteria want to attract a predator, like a fish, and be swallowed by it. Bacteria love to live close to fish, typically in their gut. Once swallowed and inside the fish, bacteria can thrive in the gut and no longer need an algal bloom to feed on. So, the would-be predator is in fact a host. The relationship between the algae, bacteria, and fish is still murky but scientists think it could be mutually beneficial for all organisms involved.



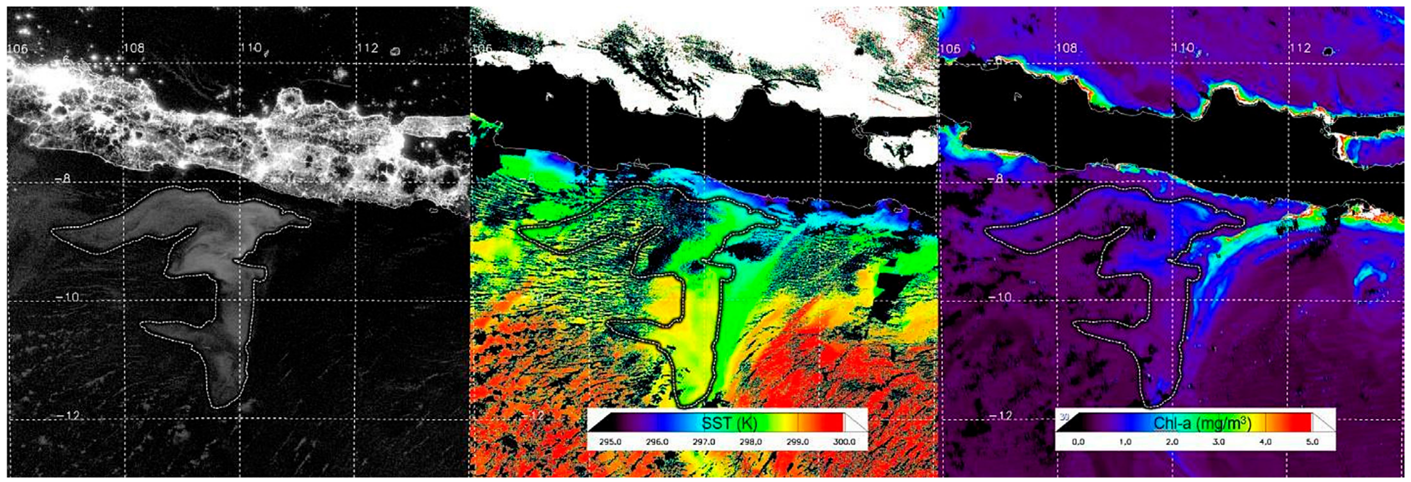
The role of bacteria in luring is not new. The ocean is full of animals that support luminous bacteria inside their bodies to take advantage of bioluminescence for hunting, camouflage, and in the most basic sense, survival. For example, the bizarre anglerfish has a glowing orb protruding from its head to attract prey and some jellyfish do the same with their tentacles. Some fish can even light up their underbellies to blend in with light shining down from the ocean surface so that predators swimming below cannot pick them out.

In this line of thinking, Miller suggests milky seas may be yet another expression of survival with a remarkable bulk visual effect—a typically microscale phenomenon exploding to the macroscale:

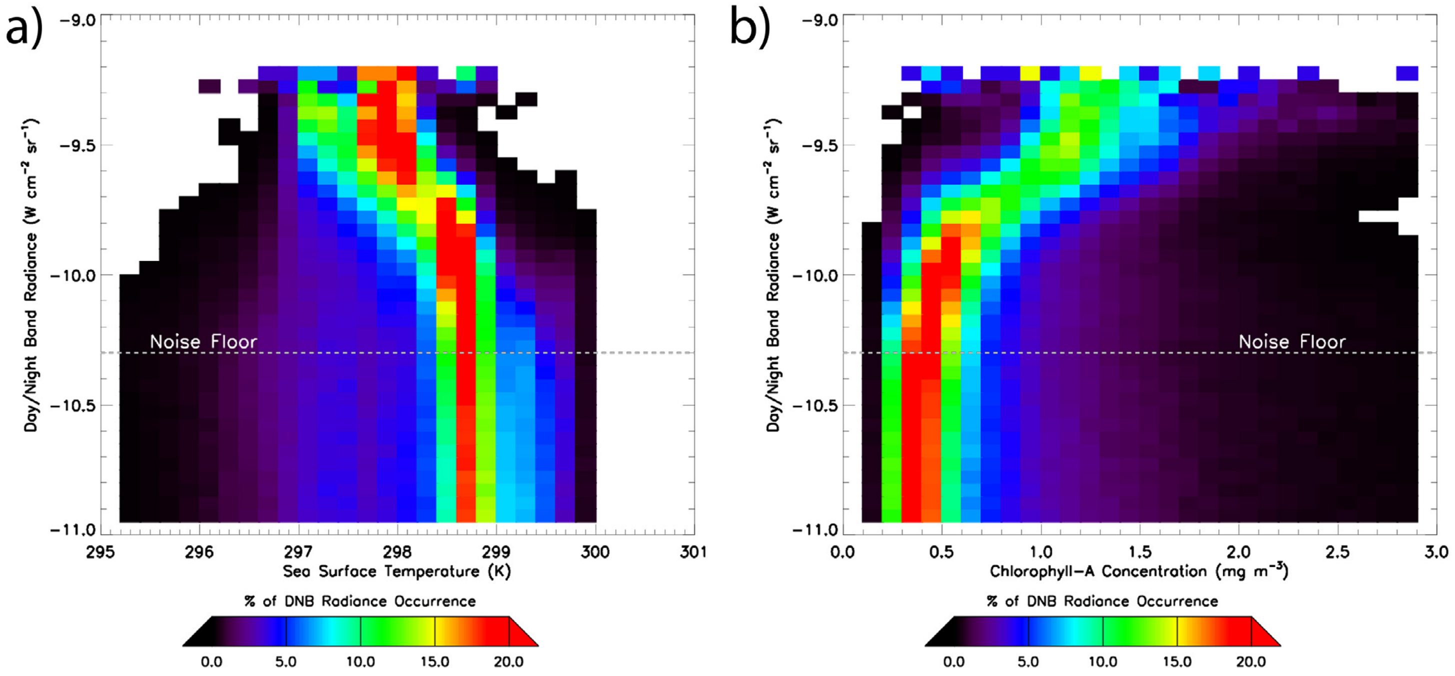
> ***"The glow of a milky sea may in fact be the result of trillions of little individual glowing specks of colonized algae or other organic matter in the water. It's like [the Dr. Seuss book] Horton Hears a Who, but in this case the Who's are hundreds of millions of bacteria living on each speck, all calling out in unison a luminous chorus of 'We Are Here!!' In the more common case of an isolated glowing particle, 'Horton the Haddock' finds the lure, eats it, and they all live happily ever after! But the extreme case of a milky sea, who knows how the story ends?"***

Clues Point to a 'Goldilocks Zone' for Milky Seas

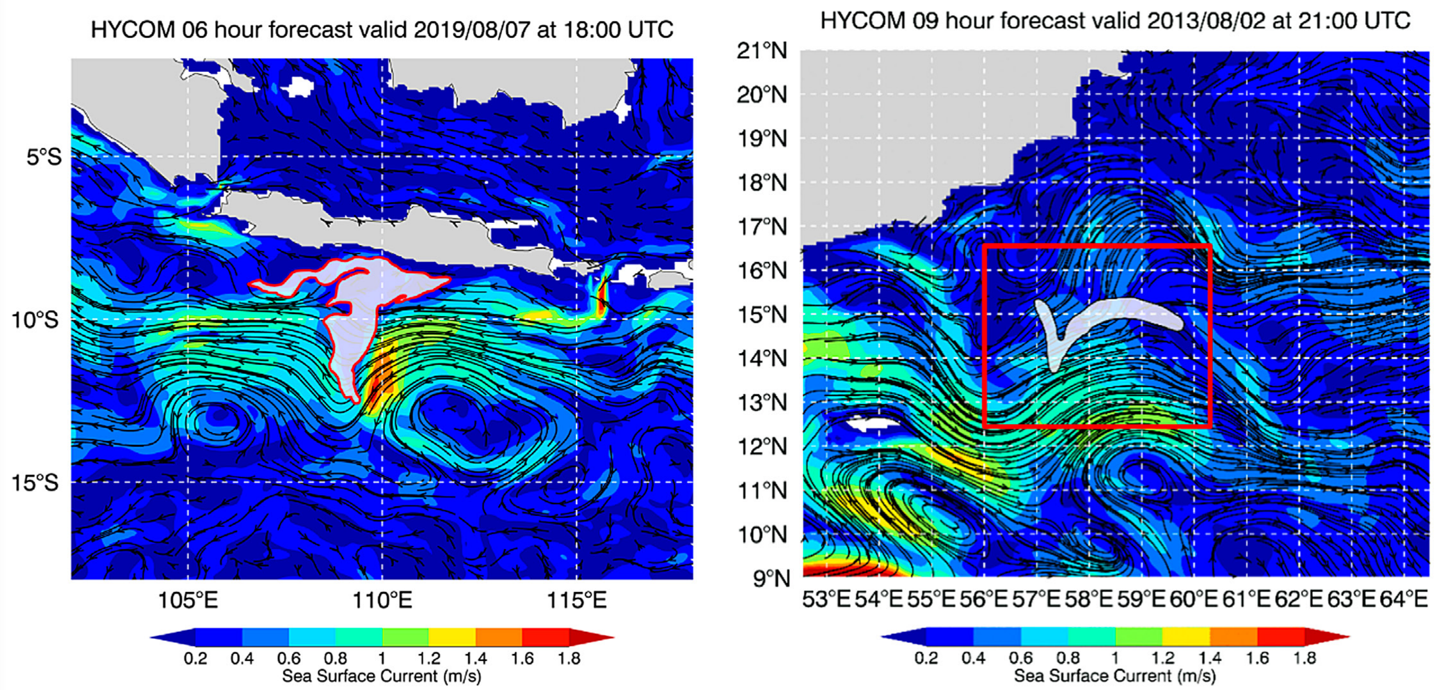
With such an extremely high concentration of bacteria needed to produce a glow, what conditions could possibly support such a large population? Miller explains that evidence gathered from satellites points to a possible preferred habitat for milky seas bacteria: "What we are seeing in the data are characteristics of these glowing water—their temperature, their organic content, and their positioning amidst the currents—that point to some patterns. For one thing, these milky seas tend to occur on the peripheries of, not atop, the coolest waters with high biomass."



CLICK IMAGE TO ENLARGE. VIIRS Day/Night Band imagery (left), sea surface temperature (middle), and chlorophyll-a concentration (right) for the 2019 Java milky sea event.



CLICK IMAGE TO ENLARGE. Sea surface temperature (left) and biomass (chlorophyll-a) concentration (right) truncation suggests preferred milky sea environment.



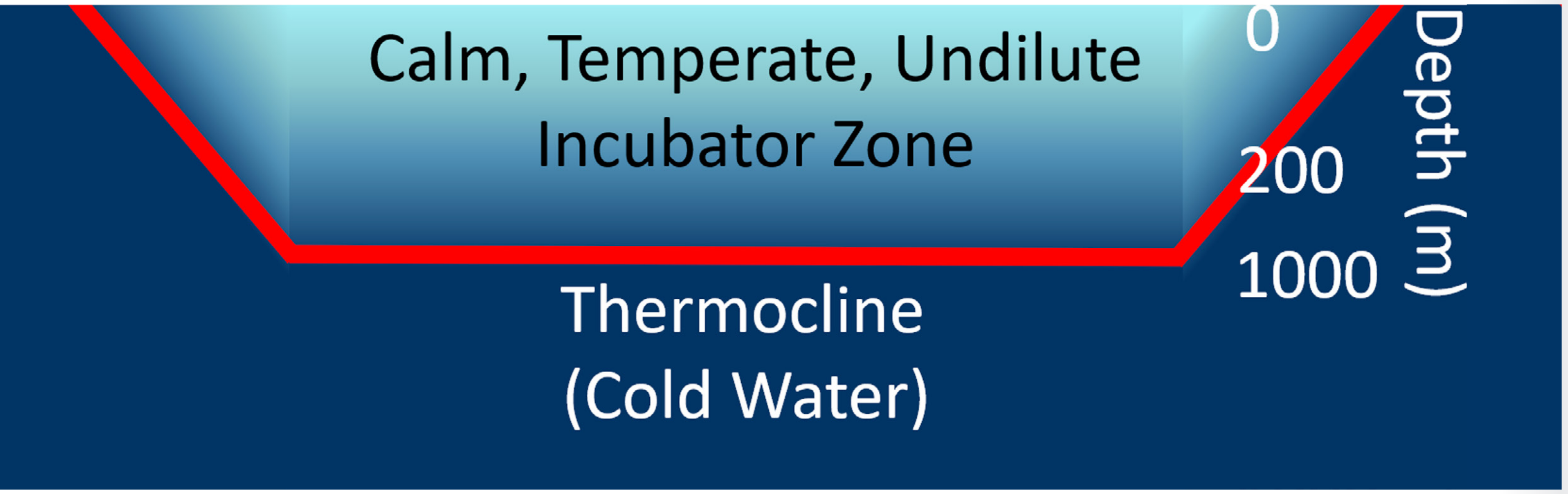
CLICK IMAGE TO ENLARGE. Sea surface current data showing a milky sea between doldrums (left) and drifting out of the doldrums between eddies (right).

Statistics show that the glow of milky seas intensifies with decreasing sea surface temperature and increasing chlorophyll-a concentration, but this relationship levels off in the brightest waters. Miller explains, "We reach a point where the water conditions are not-too-cold, not-too-hot, just the right amount of biomass, and perhaps other ingredients we are not detecting, where milky seas thrive." In fact, he notes, "it's almost like a 'Goldilocks Zone' is at play, which could explain why they are not so common in nature when all the ingredients need to line up." The ideal conditions in this zone seem to be about 77°F (25°C/298°K) for water temperature and 1.2 mg/m3 of chlorophyll-a concentration.

Combining satellite observations of swirling waters aglow and model analyses of ocean currents provides yet another clue to milky sea formation. Often, milky seas sit within the doldrums—calm regions of weak ocean surface currents—traveling along with them between stronger currents. The 2019 Java milky sea was sandwiched between two eddies, and nightly imagery from the Day/Night Band shows it moving along with them, at times breaking off some of its glowing waters to the faster currents. Other milky seas seen by the Day/Night Band drifted from their doldrum zones of formation and were carried up into faster flow. Still others appeared to align right on the edge of strong currents along the African coast, or up on the edge of oceanic fronts where there is a sudden change in the water's properties, much like the warm and cold air masses in the atmosphere that move along and form our changing weather patterns. A key to milky sea habitat seems to be having the right kinds of waters that do not mix much with the surrounding environment, retaining their special properties for an extended period.

The *Natural Flask* Hypothesis

All these clues about milky sea activity and habitat led Miller to ask a natural next question: what physical properties could produce such a habitat in the open ocean? The open ocean contains no artificial barriers to wall-off and nurture an isolated habitat for milky seas, but some naturally occurring processes could serve that function. This idea guided Miller toward a Natural Flask hypothesis. The idea is that the thermocline (cold water) from below and ocean current shear layers or water density gradients (oceanic fronts) from the sides can create a natural enclosure (like a laboratory flask) to support a habitat for milky seas—a calm, temperate, unmixed zone. With all the right ingredients in place—sea surface temperature, organic content, water chemistry, strain(s) of luminous bacteria, and perhaps other factors—could such a "natural flask" serve as an incubator for milky seas? Testing Miller's hypothesis will require directing research ships out to collect samples for further study, the logistics of which point to the central role of satellite remote sensing.



The Natural Flask hypothesis is based on the idea that calm, temperate, and undilute waters could form an incubator zone for luminous bacteria growth and ensuing milky sea formation.

THE QUEST FOR ANSWERS CONTINUES

While Prof. Miller and his team are starting to understand milky sea structure and preferred environments from afar, many questions remain that only on-site sampling can answer. The newly demonstrated ability to remotely observe milky seas with a new generation of low-light sensors in space paves the way toward possible research vessel deployments. Detailed and targeted measurements from such an excursion could help answer several key science questions surrounding this long-standing mystery of the high seas and fascinating symbol of maritime lore. Namely, what are the exact sources of bioluminescence involved in milky seas? Where in the water does the glow come from? How do milky seas relate to the marine ecosystem? What can their formation tell us about an air-sea-biosphere connection? The relationship between fish behaviors in and around milky seas is unknown.

Miller and his team continue the satellite-based hunt for milky seas with VIIRS Day/Night Band observations lighting the way. They are exploring ways of applying machine learning to help with the overwhelming task of sifting through massive amounts of satellite imagery in search of new cases. Miller's hope is to use an automated technique to at least filter out obvious noise, like clouds that can be easily separated based on their thermal signatures, and to improve the speed at which events are identified.

Miller is working with the maritime community and bringing awareness about the research to NOAA, NASA, and international scientists who run field programs in regions where milky seas are commonly seen. He is also in touch with several nature production film crews who are keen to capture milky seas on film for the first time. The hope is that satellites can help guide them there. "To me, milky seas are like the 8th Natural Wonder of the World—if I ever had the great fortune to find myself on-deck, gazing down upon a milky sea, I would throw caution to the wind and dive right in," Miller muses. "To finally be surrounded by that glow that keeps calling out to me, beckoning from the recesses of my mind and over the course of my career...*We Are Here!! Come Find Us!*"

The quest continues! ✦

STORY SOURCE

The information in this article is based, in part, on the March 21, 2022, JPSS Science Seminar presented by Prof. Steven D. Miller, Department of Atmospheric Science and Director, Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, with contributions from many, including Steven H. D. Haddock, Monterey Bay Aquarium Research Institute; William C. Straka, III, University of Wisconsin-Madison; Curtis J. Seaman, Cynthia L. Combs, and Wei Shi, Colorado State University; Menghua Wang, National Oceanic and Atmospheric Administration; and SungHyun Nam, Seoul National University.

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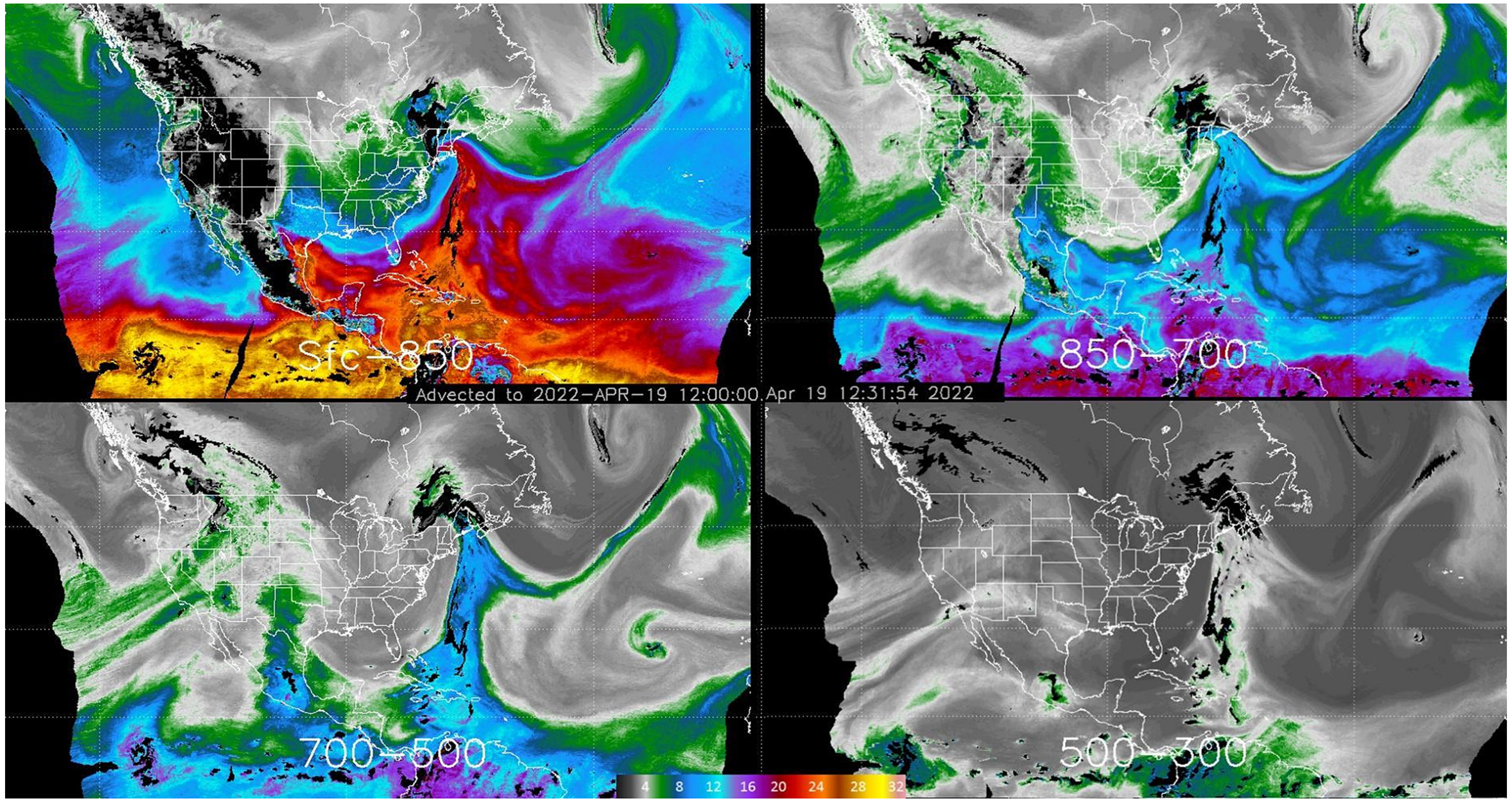
FEATURE 4

Inspecting the Atmosphere's "Plumbing" With Multi-satellite Water Vapor Products

Flooding is destructive to humans and the natural environment. Flood waters can destroy wildlife habitats, devastate crops and livestock, and spread debris and pollutants far and wide. Every year, flooding damages critical infrastructure, like roads and hospitals, and causes property damage. It impacts public health by disrupting water supplies and sewage systems, spreading infectious disease, and displacing people from their communities. Flood events can cause psychological trauma, injury, and even death. In fact, flooding is the second highest cause of weather-related fatalities in the U.S. (based on a 10-year average from 2011 to 2020).

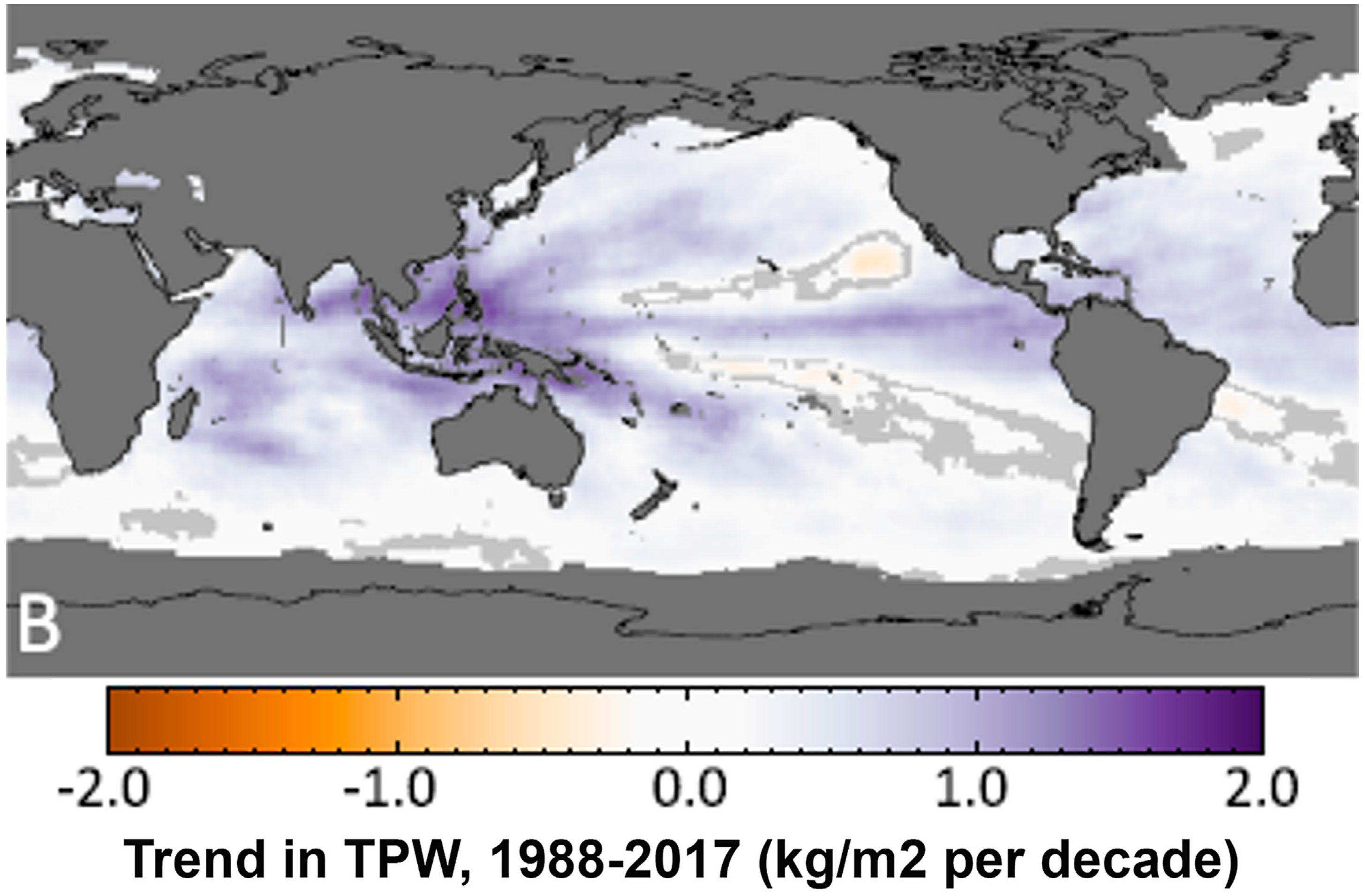


The Advected Layered Precipitable Water (ALPW) product, derived from Microwave Integrated Retrieval System (MiRS) retrievals of moisture and temperature from six polar orbiting satellites, offers a 4-dimensional look at water vapor. Shown here is the ALPW (mm) hourly loop for April 19, 2022 at 12:31:54. Source: Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University.

These impacts add up. From 1980 to 2020 flooding in the U.S. caused more than 3,750 fatalities and $165.8 billion in losses, and annual damages are on the rise—a recent analysis estimates that losses will increase to $40.6 billion per year by 2050. In 2019, a historic flooding event across the Missouri, Arkansas, and Mississippi River basins cost $20 billion alone.

These events are not going away. Satellite data shows that the amount of water vapor in the atmosphere fueling heavy rain is increasing globally at a rate of about 1.5% per decade as the climate warms (based on the 30-year passive microwave record of Total Precipitable Water over the ocean). Supporting this are decades of research that suggest an increase in extreme rainfall events from rising global surface temperatures and worsening storm surge from sea level rise. Case in point: 2021 was the fifth consecutive year

Source: NOAA National Severe Storms Laboratory, https://www.nssl.noaa.gov/education/svrwx101/floods/.

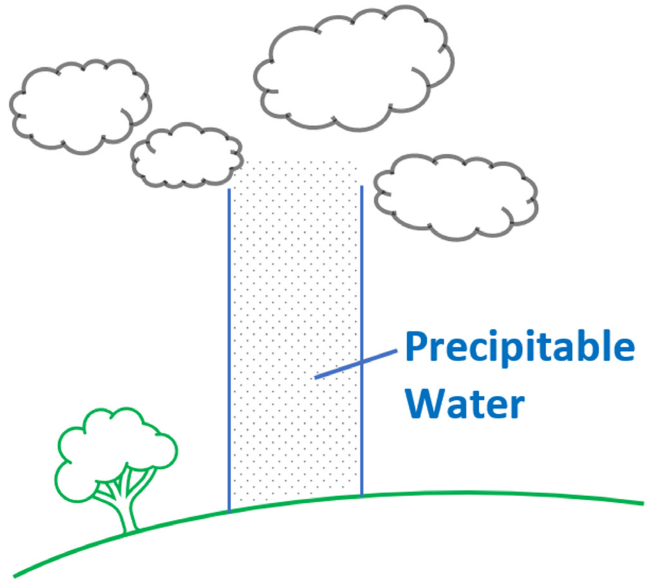


Trend in Total Precipitable Water from 1988 to 2017 showing an ocean-only increase of 1.49% per decade. Source: Mears et al. 2018.

that the U.S. experienced extreme rainfall and devastating floods from tropical cyclones. As flooding intensifies and becomes more frequent, early recognition of weather patterns is critical for providing timely alerts to the community and relevant authorities.

Weather forecasters use a variety of tools to detect conditions that could lead to flooding to warn and protect the public. Knowing the amount of moisture in a vertical column of air, called precipitable water, gives forecasters an idea about how much rainfall is possible.

Water vapor in the atmosphere is an essential ingredient for forming clouds and precipitation. "To protect life and property and predict destructive floods, weather forecasters need to see how much water vapor is in the atmosphere and how it is flowing," explains John Forsythe, a Senior Research Associate at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. He notes that "often this moisture is far away over distant oceans where satellites provide the only way to see what's happening."



Precipitable water is the amount of atmospheric water vapor contained in a vertical column above a fixed point between any two specified levels. It does not indicate how much it will rain, but rather, how much moisture is in the air within a vertical column. Diagram adapted from Goenka 2017.

USING MICROWAVES FOR WEATHER FORECASTING

Forecasters use water vapor data from satellite-based microwave instruments, like the Advanced Technology Microwave Sounder (ATMS) onboard NOAA Joint Polar Satellite System (JPSS) satellites, to monitor the movement of atmospheric moisture. Microwaves penetrate clouds allowing forecasters to "see" the moisture beneath them, and microwave sensors have water profiling capability important for weather forecast modeling. Knowing what is happening under the clouds is critical for early emergency planning in areas at risk for flooding.

Microwave data are used, in part, to create water vapor products that help forecasters identify areas of high moisture that can lead to heavy precipitation. Historically, these products have been hard to use because they combine data from many satellites that have different retrieval times—data is stitched together and can appear disjointed or be missing when a forecaster needs to make a decision during a busy shift. To tackle this and other challenges, Forsythe and his colleagues at CIRA and Tony Wimmers of the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison have applied new scientific approaches to improve two existing multi-satellite water vapor products that give forecasters a unique view of water vapor in the sky.

Atmospheric Rivers: The "Plumbing" of the Sky

Atmospheric rivers are streams of water vapor moving through the sky. They typically come from tropical areas of warm, moist air, flowing long distances and over mountains where they drop water in cooler areas as rain or snow. Atmospheric rivers can be thought of as a set of pipes with different diameters and flows, some coming together and some not. Meteorologists use satellite-based water vapor products to monitor this "plumbing" of the sky and plan for heavy rainfall events that could cause flooding.

Two of these products are the newly enhanced Blended Total Precipitable Water (Blended TPW) product developed collaboratively by CIRA and CIMSS with support from the NOAA JPSS Proving Ground, and the Advected Layered Precipitable Water (ALPW) developed by CIRA. Both products are largely independent of numerical models for the water vapor distribution, which is useful for model comparison, and give forecasters an understanding of how different factors relate. As Forsythe explains, "Forecasters look at these products to see where moisture is coming from that day, how do 'pipes' of water vapor align—this provides situational awareness of atmospheric conditions." The blended TPW upgrade and the new ALPW product will be fully operational in 2023 and allow forecasters to see the flow of atmospheric moisture globally. In the interim, CIRA distributes the ALPW to National Weather Service (NWS) National Centers and partner Weather Forecast Offices (WFOs).

Key Concepts

Total Precipitable Water (TPW) *is the condensed depth of water from the ground surface up to space, in other words, the entire column of water vapor if it were condensed.*

Layer Precipitable Water (LPW) *is the amount of water in a layer of the atmosphere between two specified pressures—a pressure layer.*

Advected Layer Precipitable Water (ALPW) *is LPW but with model wind data added to move (or "advect") the LPW retrievals forward to a common time. It is used to separate moisture into layers.*

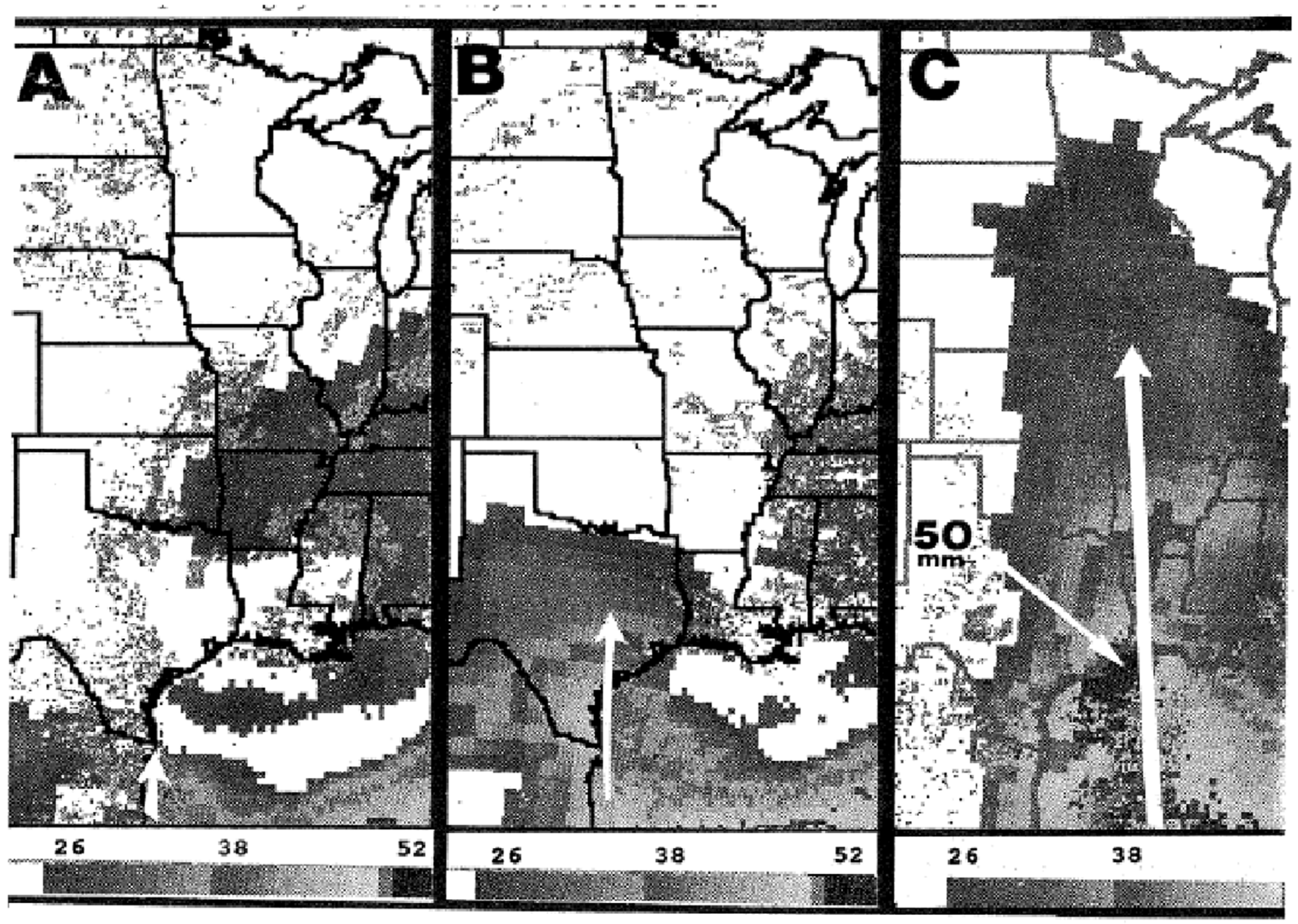
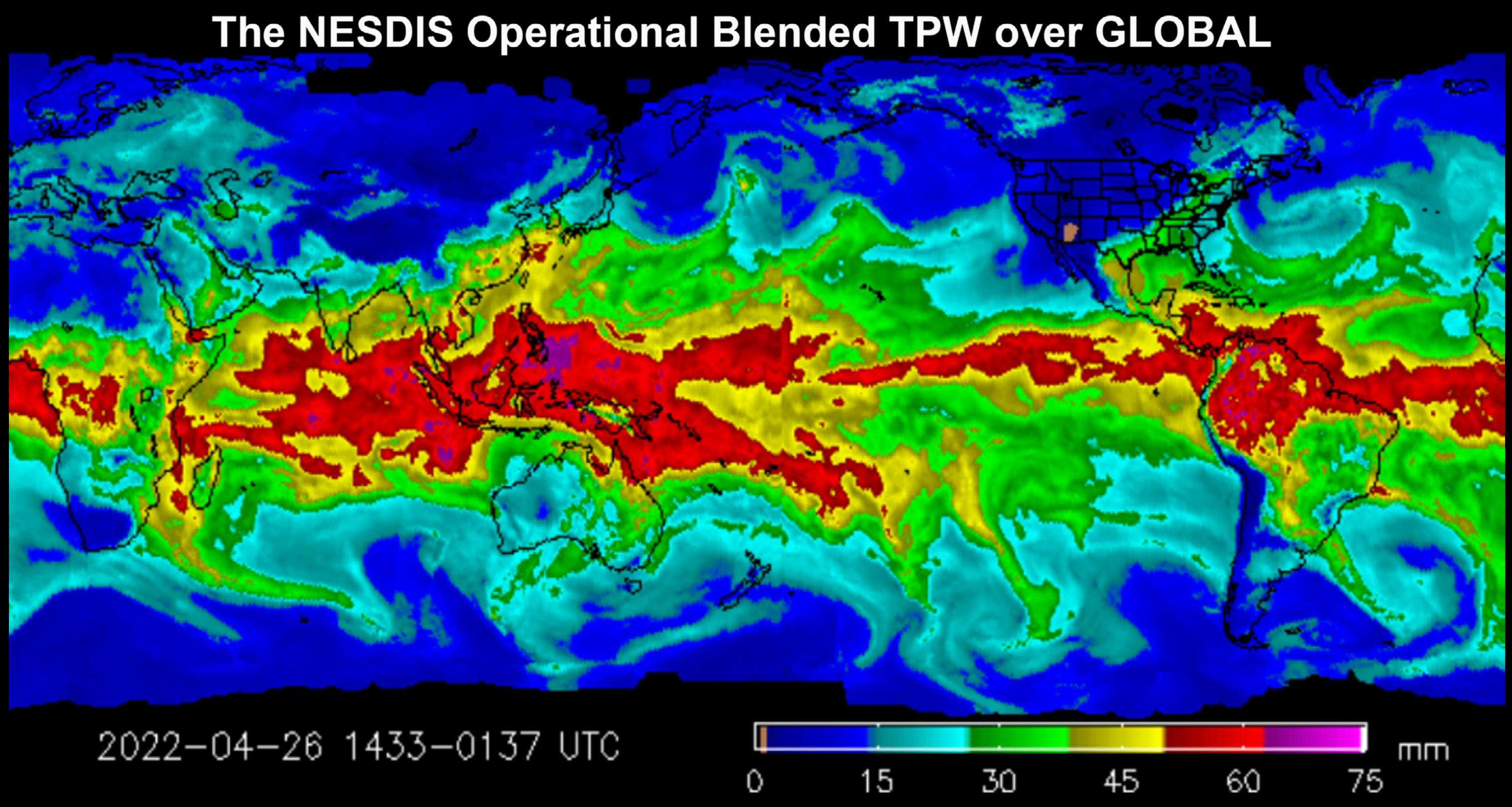


Figure 2a. Blended Precipitable Water (mm) Product for October 14, 1994, 0000 UTC
Figure 2b. Blended Precipitable Water (mm) Product for October 15, 1994, 0000 UTC.
Figure 2c. Blended Precipitable Water (mm) Product for October 15, 1994, 1200 UTC.

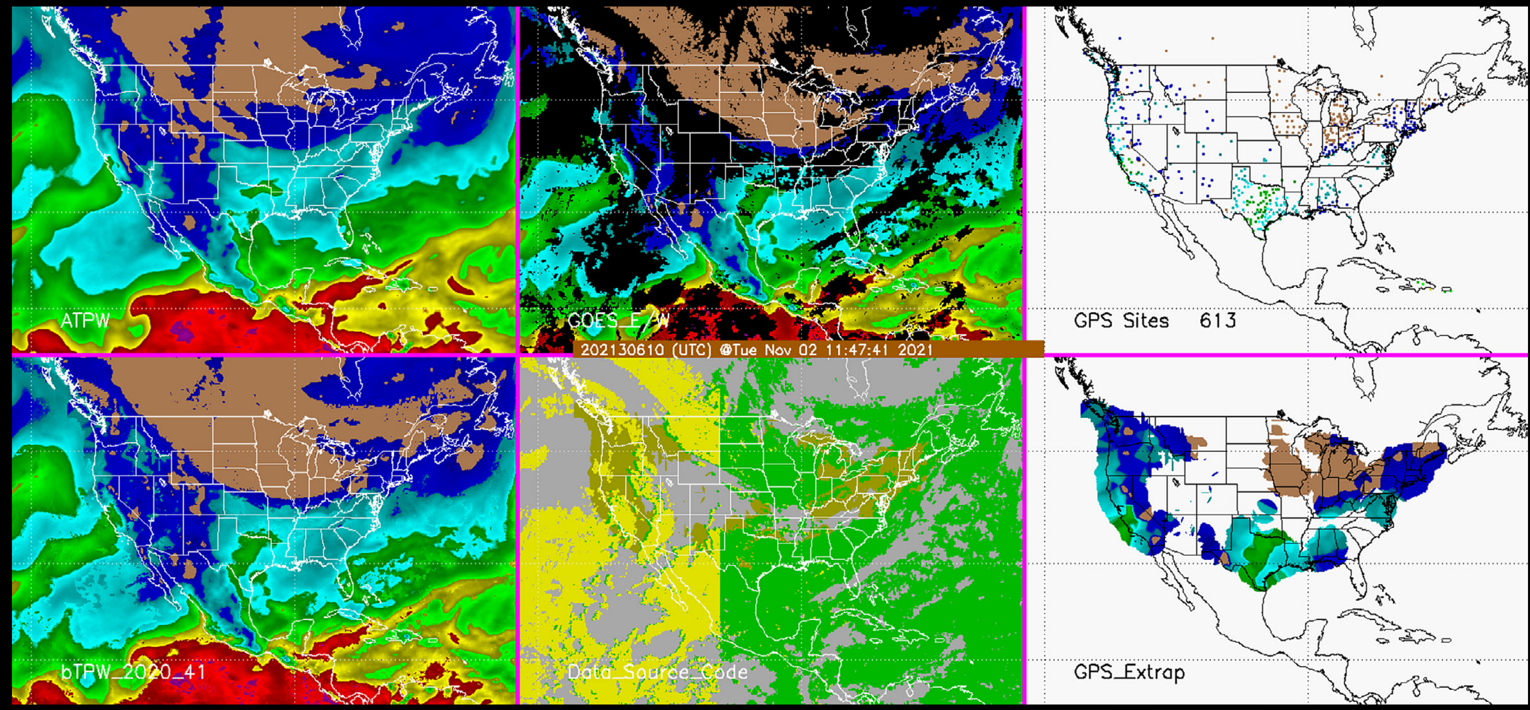
The first Blended TPW product developed by NOAA in 1996 captured a large rainfall event near Houston.

Blended Total Precipitable Water (TPW) Product Enhancements

The first attempt at a Blended TPW product was in 1996 by Sheldon Kusselson, Forsythe's colleague at CIRA. Working at NOAA at the time, Kusselson and colleagues created the product for internal use with two Special Sensor Microwave/Imager (SSM/I) instruments, the Geostationary Operational Environmental Satellite (GOES) sounder, and the Eta model—an atmospheric model used for short-term weather prediction in the U.S.—to capture an event that dropped 29 inches of rain near Houston in 1994. Since then, the product has evolved and improved based on available satellites and satellite instruments.



Example of the NOAA operational Blended TPW global product.



Example of the enhancements to the Blended TPW product (CIRA experimental product) that is set to go operational in 2023. Clockwise from top left: MIMIC, GOES E/W, GPS Sites via MADIS, GPS extrapolated, Data Source, and Merged.

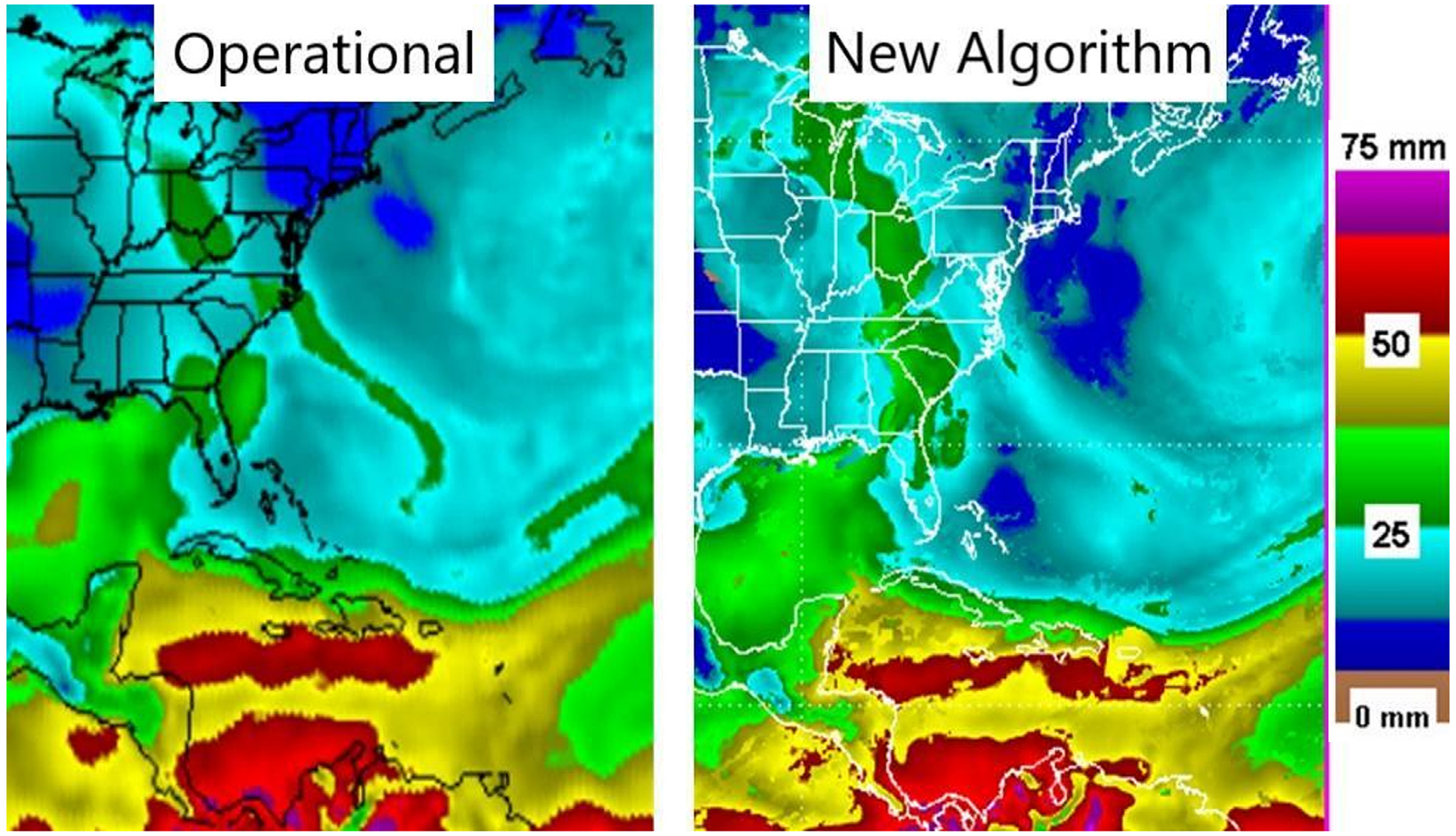
Today's NOAA Blended TPW product became operational in 2009 and is shared with forecasters through the Advanced Weather Interactive Processing System (AWIPS) meteorological display and analysis platform. It merges water vapor data from the surface-based Global Positioning System (GPS) with data from several microwave sensors onboard different satellites, retrieved through the NOAA operational Microwave Integrated Retrieval System (MiRS). The result is a unified global map showing areas of high moisture, like those linked to atmospheric rivers.

Product enhancements made by CIRA go a step further by adding GOES-East/West Total Precipitable Water (GOES TPW) for clear skies and localizing GPS coverage down to 100 km over the mainland U.S. Beginning with the launch of GOES-16 in 2016, the GOES-R generation of satellites offers significantly improved temporal and spatial coverage compared to previous GOES spacecraft. The team also applied Morphed Integrated Microwave Imagery at CIMSS (MIMIC) to Total Precipitable Water microwave retrievals to blend the different types of imagery—a needed upgrade since retrieval times vary

between satellites. The result is a more forecaster-friendly product.

To see if they were on the right track, CIRA surveyed different sets of forecasters about the enhancements. They gained access to end users through the 2019 NOAA Hazardous Weather Testbed Severe Weather Experiment that ran over several weeks and gave participants a real-time environment to test products, and the 7th Annual Flash Flood and Intense Rainfall Experiment held from June 17–July 19, 2019, by the Hydrometeorology Testbed at the Weather Prediction Center that brought together the meteorological community to explore products and increase forecast skill for heavy rainfall and flash flooding. Most surveyed participants (about 70%) thought the Blended TPW enhancements (tested without GPS) performed "better" or "much better" than the current operational product.

The addition of GOES and GPS data fills "holes" when no MiRS (microwave) Total Precipitable Water retrievals are available. GOES TPW retrievals, while only available in clear skies, are of high quality and add capacity to the updated



Comparison of then current operational Blended TPW product (left) and the new, enhanced Blended TPW product (right). With the new algorithm small scale changes in precipitation fields are better represented.

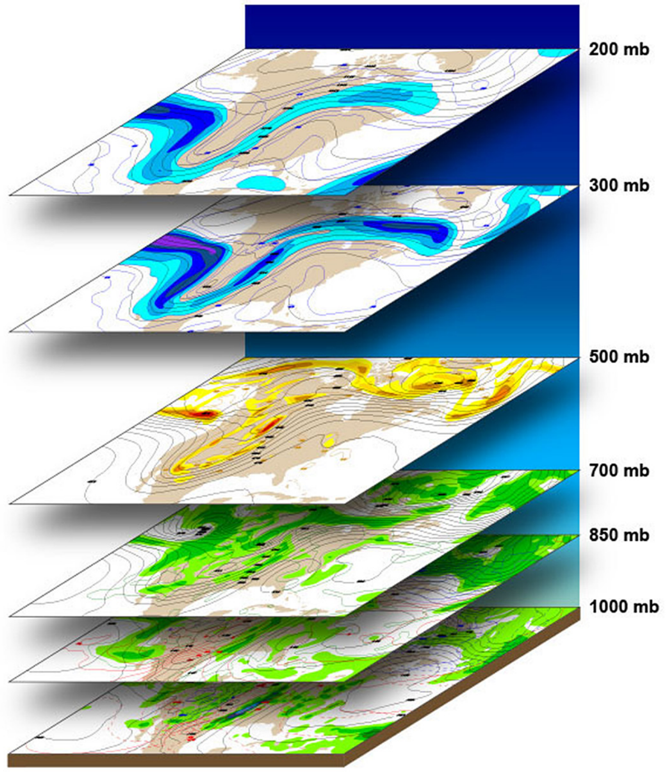
Blended TPW product. Merging these data sources draws on their strengths and provides seamless global coverage for a more unified and complete analysis of atmospheric moisture over land and ocean in both cloudy and clear conditions. More data means more timely forecasting.

The newly enhanced Blended TPW product, the first blending algorithm update in a decade, is expected to go operational in 2023. Data animations on an hourly loop from the updated (experimental) product are available at http://cat.cira.colostate.edu/btpw_2020/.

A Layered Precipitable Water Product

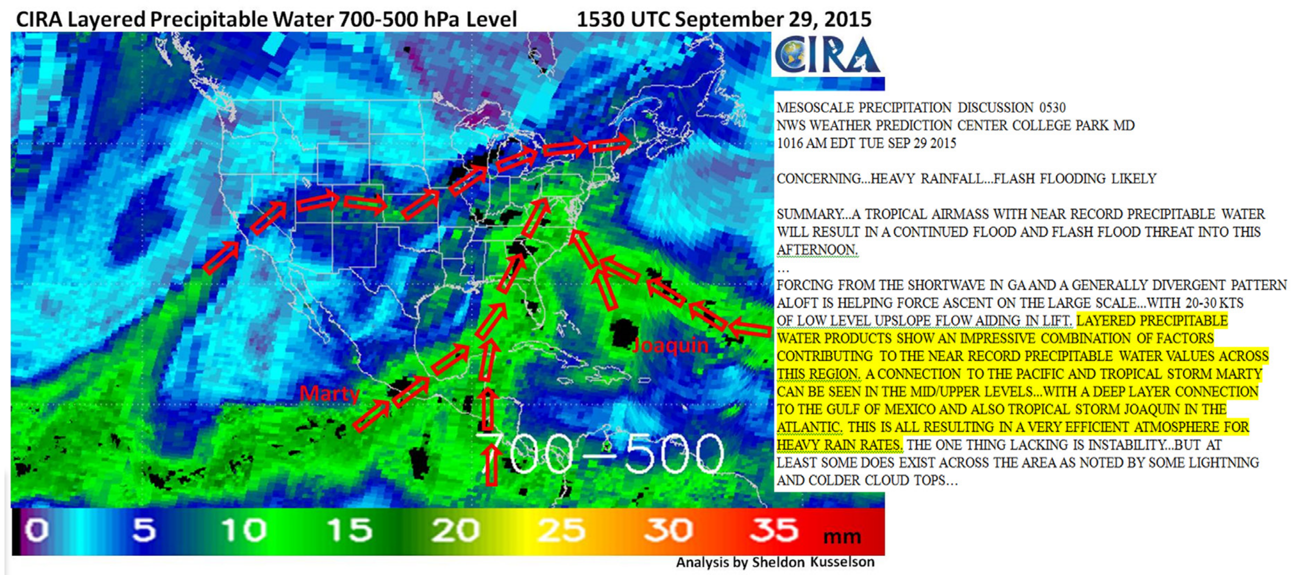
One limit of the Blended TPW product, even with its enhancements, is that it cannot reveal how much water vapor is between atmospheric layers. This information is needed to evaluate moisture depth, which can be a sign of possible heavy rainfall. To fill this gap, about a decade ago CIRA, NOAA, and NASA developed the Layered Precipitable Water (LPW) product. It uses microwave data to separate precipitable water values into four different atmospheric layers (pressure levels as they relate to sea level): surface-850 millibars (mb), 850-700 mb, 700-500 mb, and 500-300 mb. This is valuable because precipitable water changes from layer to layer. Understanding the vertical structure of precipitable water improves a forecaster's situational awareness.

MiRS is the backbone of the LPW product, providing microwave retrievals from JPSS satellites and other spacecrafts. LPW offers a near-global look at middle- and upper-level moisture that is not well covered by other products. While not an official NOAA operational product, LPW has been available at the Weather Prediction Center (WPC) since early 2015. It is used by operational forecasters at WPC's Meteorological Watch (Metwatch) desk to find areas of enhanced rainfall efficiency—warm rain and "seeder-feeder" events—and to look at the depth of atmospheric rivers.



CLICK IMAGE TO ENLARGE. Example pressure chart with typical levels, each showing different aspects of the atmosphere. Source: NOAA National Weather Service.

Blended, layered water vapor products fill a gap in vertical observations. But LPW measurements are stitched together from observations made at different times by different

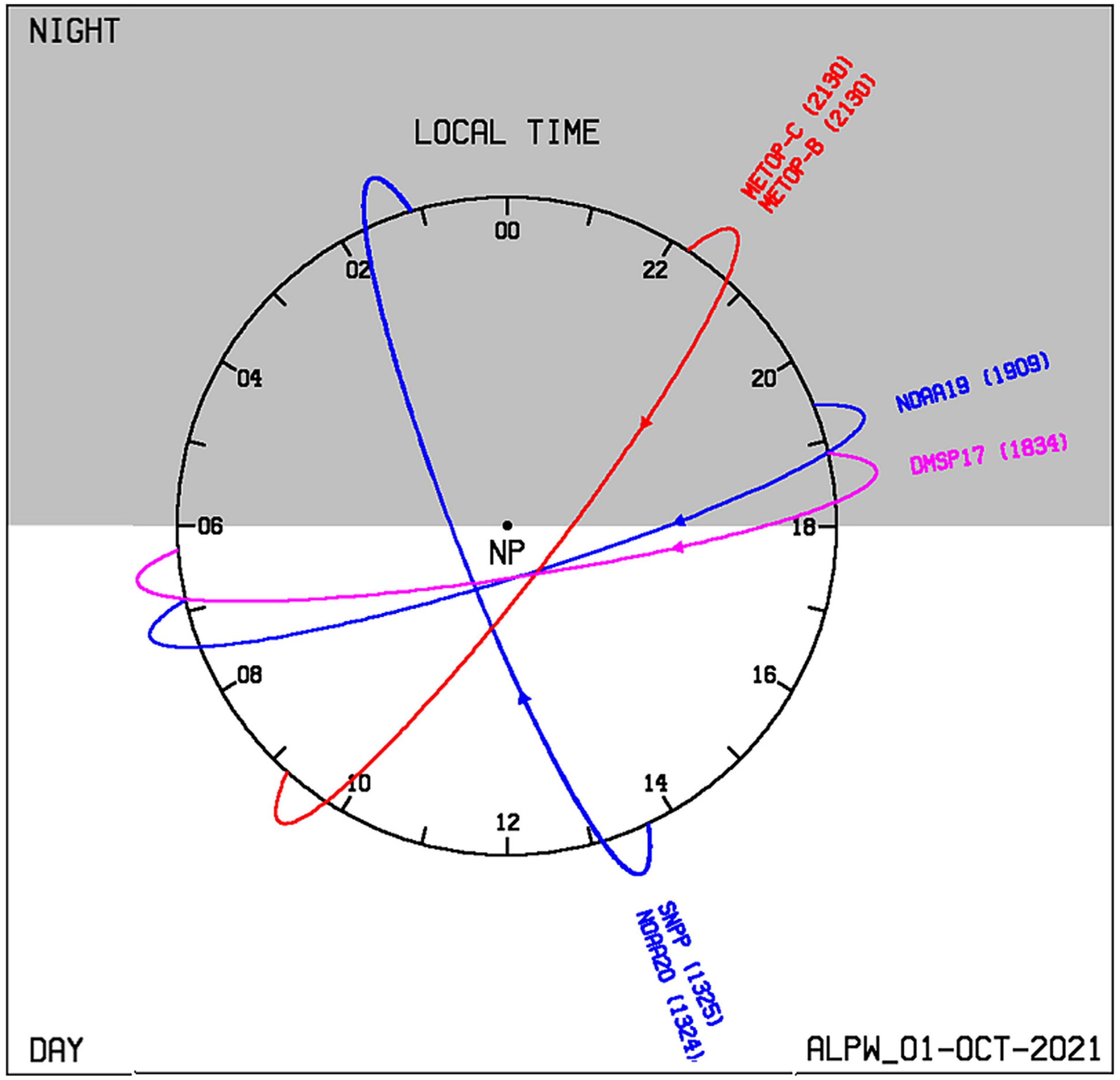


CLICK IMAGE TO ENLARGE. The CIRA LPW product showing five streams of moisture fuel that triggered historic flooding in South Carolina in September 2015, along with the NWS Weather Prediction Center's mesoscale precipitation discussion.

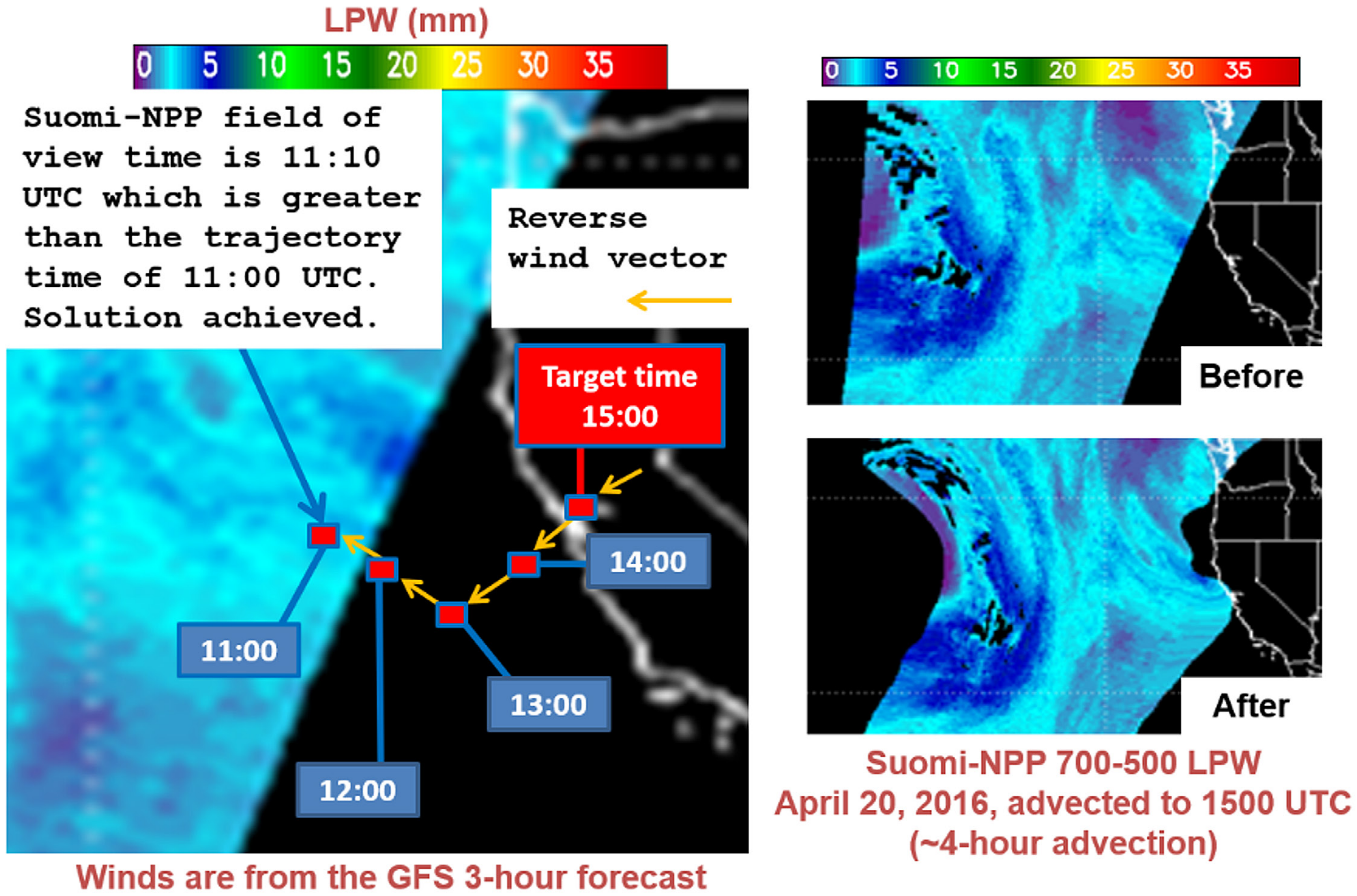
satellites. The result is non-uniform data coverage with periods of high sampling but at irregular times. “Optimally, we would want to have the time interval equally spaced between spacecraft, which would require more satellites,” says Forsythe. The more realistic option is to smooth out the time spacing after data retrieval. This is where CIRA’s experimental advected product comes in.

Smoothing Out Time: The Advected Layered Precipitable Water (ALPW) Product

Like LPW, the experimental ALPW product shows atmospheric moisture in four layers based on passive microwave observations from multiple satellites retrieved by MiRS. But unlike its predecessor, the experimental product relocates (“advects”) the time spacing of the satellites to make it appear as



This “clock diagram” shows the local time of polar orbiting satellites used to produce the ALPW product. Note the different orbits that contribute to irregular observation times.



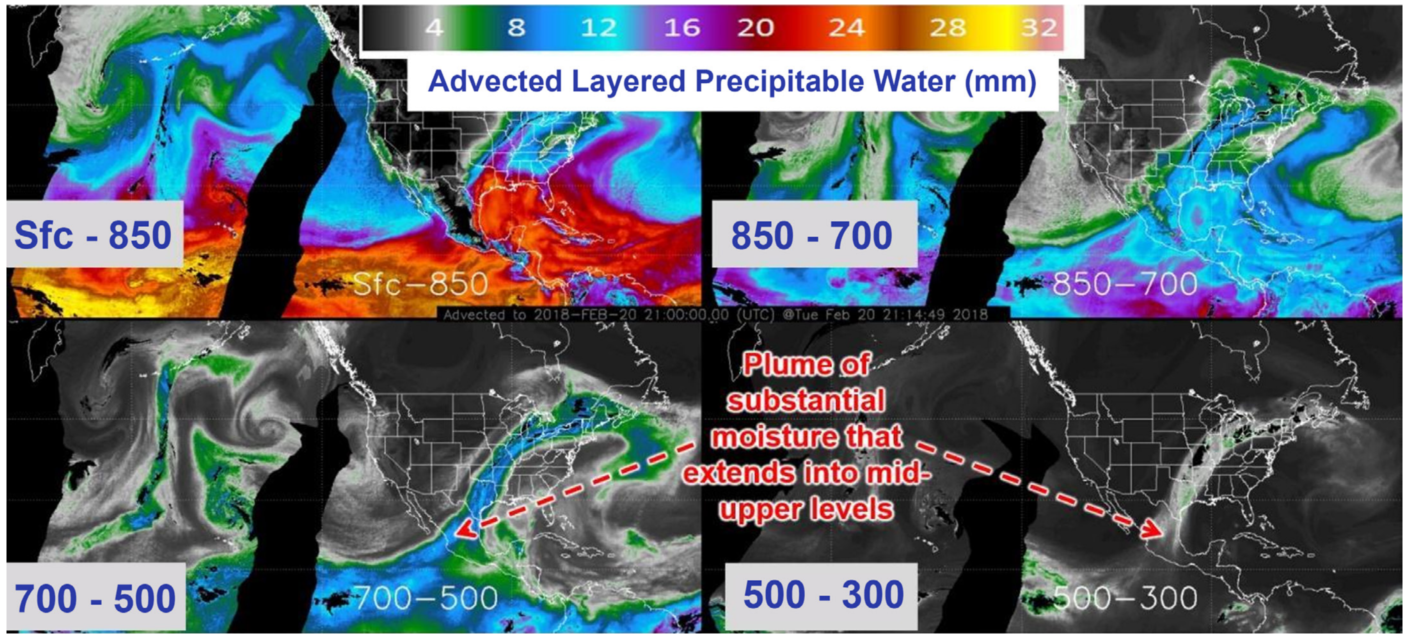
Schematic showing how the back-trajectory method works for advection.

if they pass over one point every hour instead of at different times, largely removing satellite swath lines and data breaks. The result is a more continuous and forecaster-friendly product.

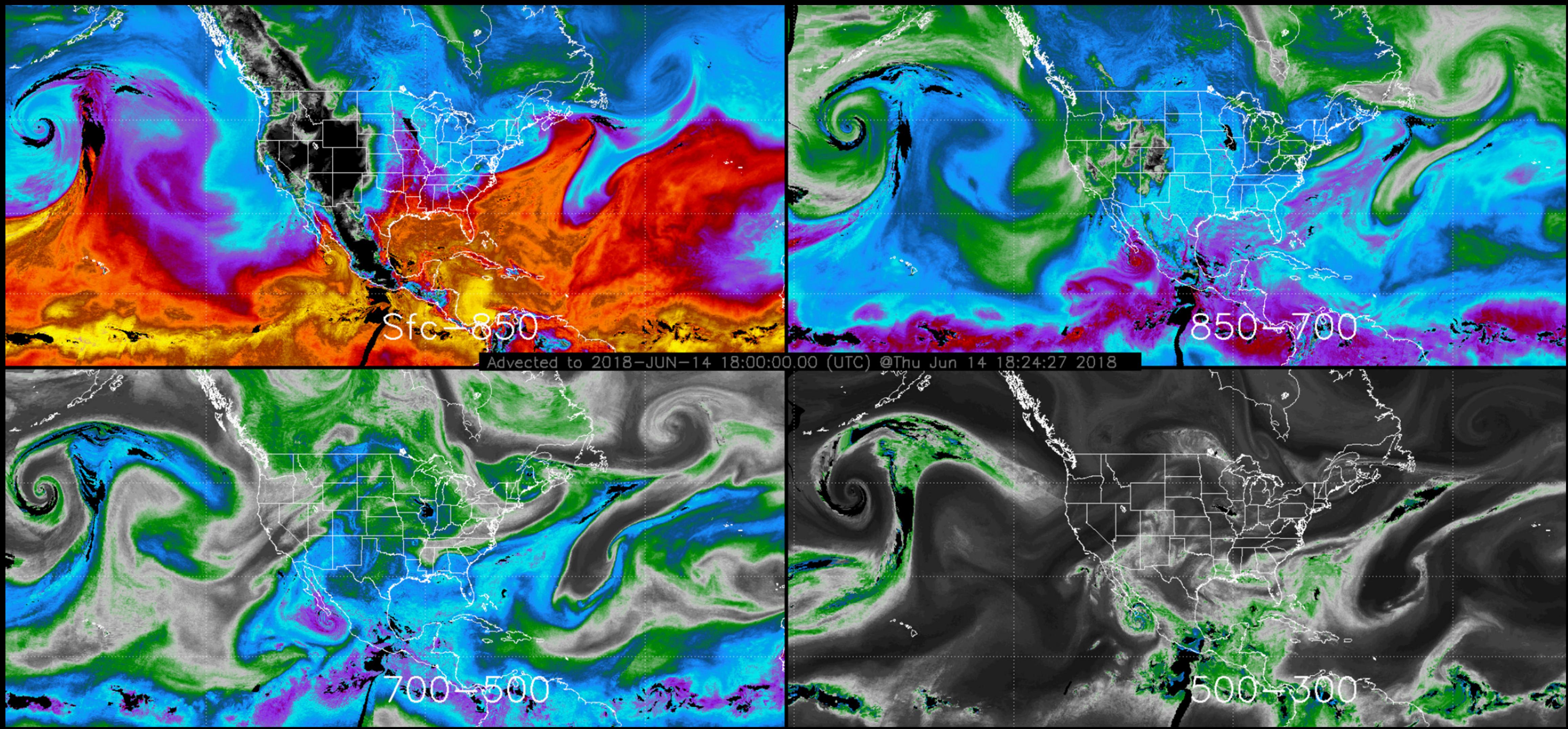
ALPW uses Global Forecast System model wind data to map individual observations from differently timed satellites to a common time by looking at where trajectories started. The figure above shows how this works. On the right (“before”) is a swath of water vapor data from the JPSS Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite. Wind data is added, and prior trajectories are looked at in time (left), allowing for data to be merged to a desired target time. The advected result is shown in the “after” image on the right.

Operational forecasters at NWS, Weather Prediction Center, National Hurricane Center, and select WFOs have been using ALPW experimentally since 2015. It is expected to go operational in early 2023 along with the Blended TPW enhancements and be widely available through AWIPS. So far, the product has been mostly used for precipitation forecasting and to look at the environment around tropical waves. Says Forsythe, “High amounts of water vapor fuel excessive precipitation and may drive convective or monsoonal flooding, but sometimes it is the transport of moisture which is key.” Having a good look at this moisture is important so forecasters can react quickly.

A key feature of ALPW is that it is independent of forecast model water vapor fields and uses all available data from sensor measurements in the satellite swath, in contrast to model data assimilation methods that may exclude or “thin” data (strip it of its contextual meaning). Because the water vapor solution is not linked to dynamical model output, forecasters can use ALPW to see how well forecast models handle water vapor. ALPW also helps forecasters understand moisture transport and connect it to heavy precipitation. Forsythe explains, “Plumes of moisture can travel long distances and be at different layers—they can have an upper layer source.” This is seen in the images to the right where the 700-500 mb and 500-300 mb layers show a moisture plume from the Pacific Ocean flowing into the Central U.S. and increasing flash flood risk. ALPW gives forecasters something they had been missing—a picture of the vertical structure of water vapor. And thanks to the use of microwave sensors, the picture can be viewed in both clear and cloudy skies.



CLICK IMAGE TO ENLARGE. Example of the ALPW product output showing a plume of substantial moisture that extends into the mid-upper levels of the atmosphere. Note that the dark black areas indicate no data.

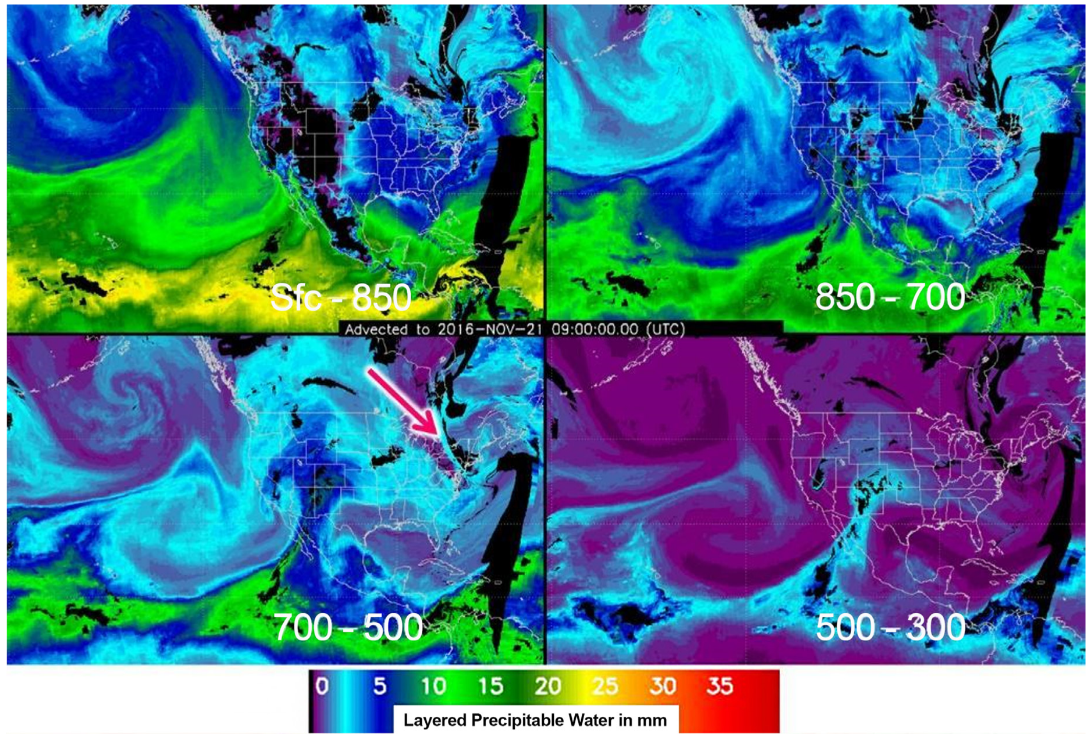


Example screenshot of ALPW product as it is seen in the product interface.

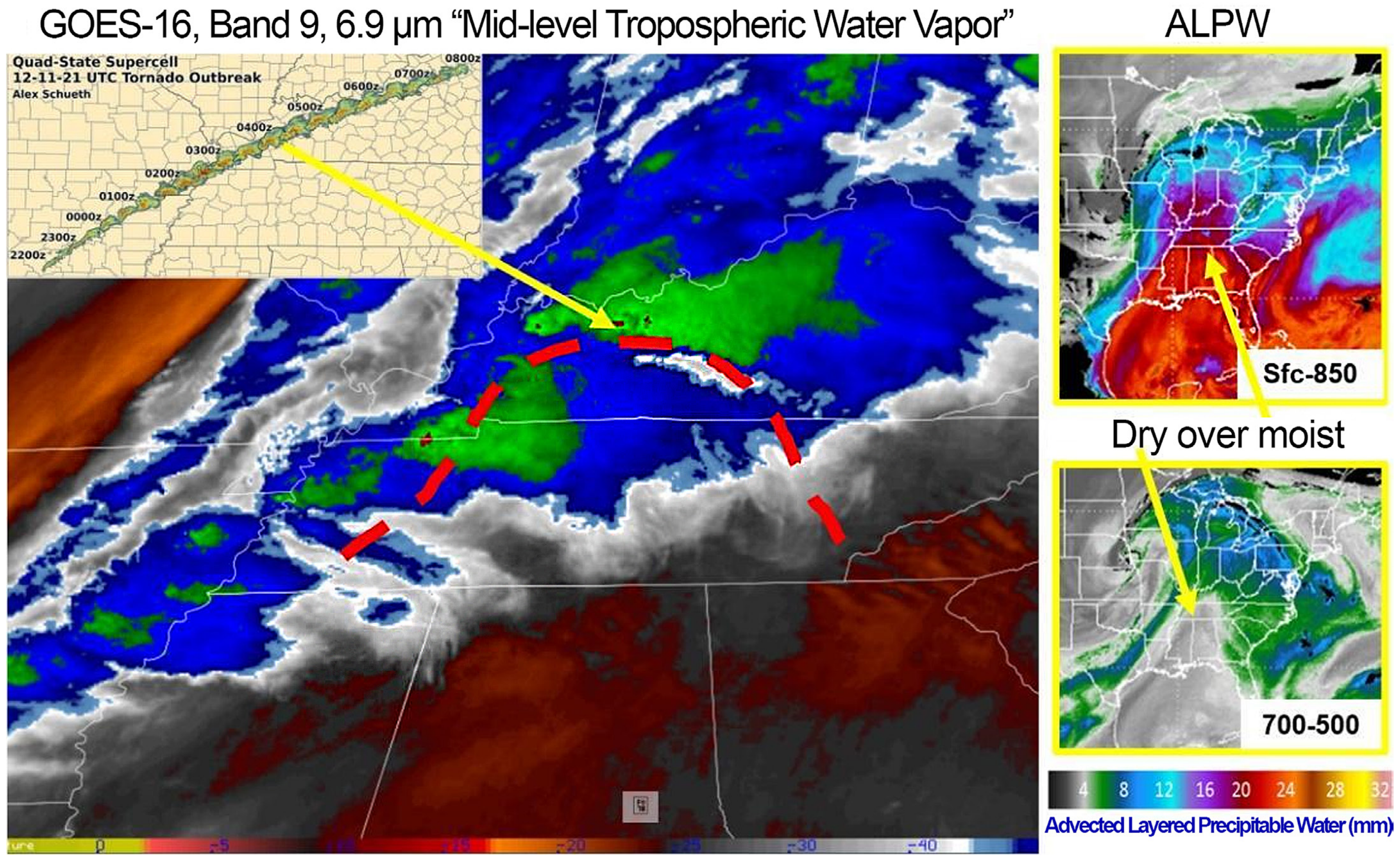
OTHER FORECASTING BENEFITS OF MULTI-SATELLITE WATER VAPOR PRODUCTS

Aside from their main use in flood forecasting, TPW and LPW can help forecast other types of events, like heavy snow. Looking at the example below, the Binghamton NWS WFO found Layered Precipitable Water useful in monitoring water vapor as it wrapped around the Atlantic region, fueling several feet of snow.

> "A pretty amazing lake-effect/lake-enhanced event is unfolding for western/central NY tonight. Layered Precipitable Water data shines again, as the 700-500 mb panels show a lengthening moisture inflow, from the southeast coastal waters, all the way around the comma-head of the storm over northern New England/southern Ontario. Mid-level moisture is normally the Achilles heel of many otherwise good lake-effect events, but not so this time."
>
> Michael Jurewicz, NWS WFO, Binghamton, NY, November 20, 2016



CLICK IMAGE TO ENLARGE. Example of heavy snow forecasting with Layered Precipitable Water from the Binghamton, NY NWS Weather Forecast Office for a November 2016 snow event in the Atlantic region. The 700-500 mb layer shows a lengthening moisture flow not seen in other layers, which resulted in several feet of snow.



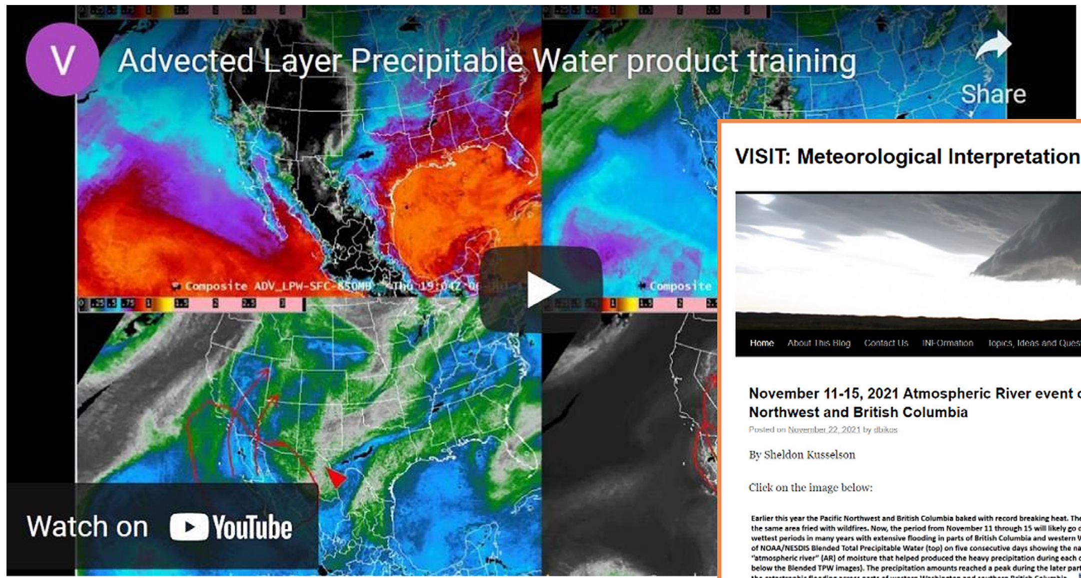
A line of tornadoes passed through the Midwest and Southern U.S. in December 2021. On the left, GOES-16 imagery fails to detect the dry over moist air because of cloud interference. On the right, ALPW detects dry air at the 700-500 layer over the moist layer at surface to 850 mb.

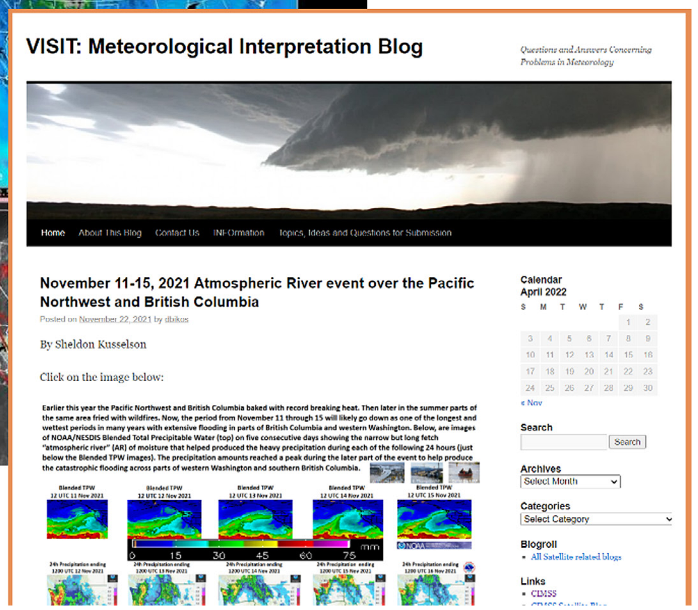
Researchers and forecasters are still learning to use ALPW for severe weather, like tornado outbreaks, but this potential use has promise. In the GOES-16 image above (left), mid-level water vapor (band 9, channel 6.9 µm) is hidden by cirrus clouds over Tennessee and Kentucky. Because band 9 "sees" in infrared, it cannot "see" through clouds. On the right, ALPW for the same date shows moist low-level air and dry air over the moist at the 700-500 layer. This is one of the benefits of ALPW and its microwave data—it penetrates clouds—which has proven to be highly useful for operational forecasters in dealing with diverse challenges in evolving situations.

MAKING THE JUMP FROM RESEARCH TO OPERATIONS

Forsythe learned early on that getting experimental products into the hands of operational forecasters is important for gathering feedback and buy-in. Luckily, NOAA uses a cooperative institute model so there are long-standing processes to pass data to NWS systems. Because CIRA has an AWIPS-2 system—the display system that forecasters use—products can be developed at CIRA and provided directly to forecasters in their operational environment. In fact, CIRA runs and distributes ALPW every hour in AWIPS-2 format to 27 NWS WFOs, the National Hurricane Center, and the Weather Prediction Center. This kind of access to operational forecasters during product development is vital to bridge the gap between research and operations.

Letting forecasters play with new products goes a long way toward proving their capabilities. So does education and training. These products have been a big part of the JPSS Proving Ground Risk Reduction (PGRR) River Ice & Flooding and Hydrology Initiatives, which allow NWS collaboration with developers to improve the operational use of JPSS data and products. The precipitable water products were also included in the World Meteorological Organization Caribbean, Central and South American Training Workshops. CIRA's own Virtual Institute for Satellite Integration Training (VISIT) program offers numerous training sessions to instruct forecasters on how to use and apply new products to their process.





Their Meteorological Interpretation Blog digs deeper into how water vapor products benefit forecasters, including real world examples. VISIT even has a help desk where NWS forecasters can ask satellite-related questions. The VISIT program website is at https://rammb2.cira.colostate.edu/training/visit/. Dan Bikos, Jorel Torres, and Sheldon Kusselson of CIRA continue to play a key role in engaging and educating forecasters.

The biggest challenge in getting forecasters to use precipitable water products is their geographic location, finds Forsythe. He explains, "The West Coast of the U.S. with atmospheric rivers coming in from the ocean where there are no surface observations—here there is high interest in these products because they are surrounded by ocean and other data is limited." The same goes for Alaska and Hawaii, but the opposite seems true for landlocked regions. Forsythe continues, "For forecasters in the Midwest and Southern states, multi-satellite water vapor products are not as high a priority because they have radiosondes [weather balloons] and other things they can look at." Interestingly, he notes that television meteorologists will often use CIRA's data to enhance their forecasts—perhaps an unexpected but welcome outcome of widely sharing these products.

PERSPECTIVE AND WORK IN PROGRESS

Extreme precipitation events are here to stay and understanding what drives them is critical to protect lives and property. The success of making the new Blended TPW enhancements and ALPW available to NWS forecasters and others has helped instill greater confidence in evaluating heavy rainfall threats. Still, work remains.

Through the JPSS Proving Ground, CIRA is making progress on the historical context of extreme rainfall events by adding a climatology component to rank big atmospheric rivers. In the future, forecasters will be able to get weekly or monthly water vapor transport data from the ALPW product and rank events as they happen. Being able to compare an evolving situation with previous events will help forecasters and the public better understand the threat and proper response.

Forsythe and his colleagues are also looking at minimum and maximum ALPW values and how they relate to weather conditions from a historical perspective, which may shed light on the cause of past flood events. Was an event linked to a big atmospheric river or something else entirely? "This is the value of doing climatology that you don't see comparing day-to-day retrievals," says Forsythe. Climatology and day-to-day observations go together and strengthen each other and will serve as a foundation for future work. ✦

STORY SOURCE

The information in this article is based, in part, on the December 13, 2021, JPSS science seminar presented by John Forsythe, Senior Research Associate, Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, with contributions from Dr. Stanley Kidder (CIRA/Colorado State University), Dr. Andrew Jones (CIRA), Sheldon Kusselson (CIRA), Dan Bikos (CIRA), NOAA forecasters, and many others.

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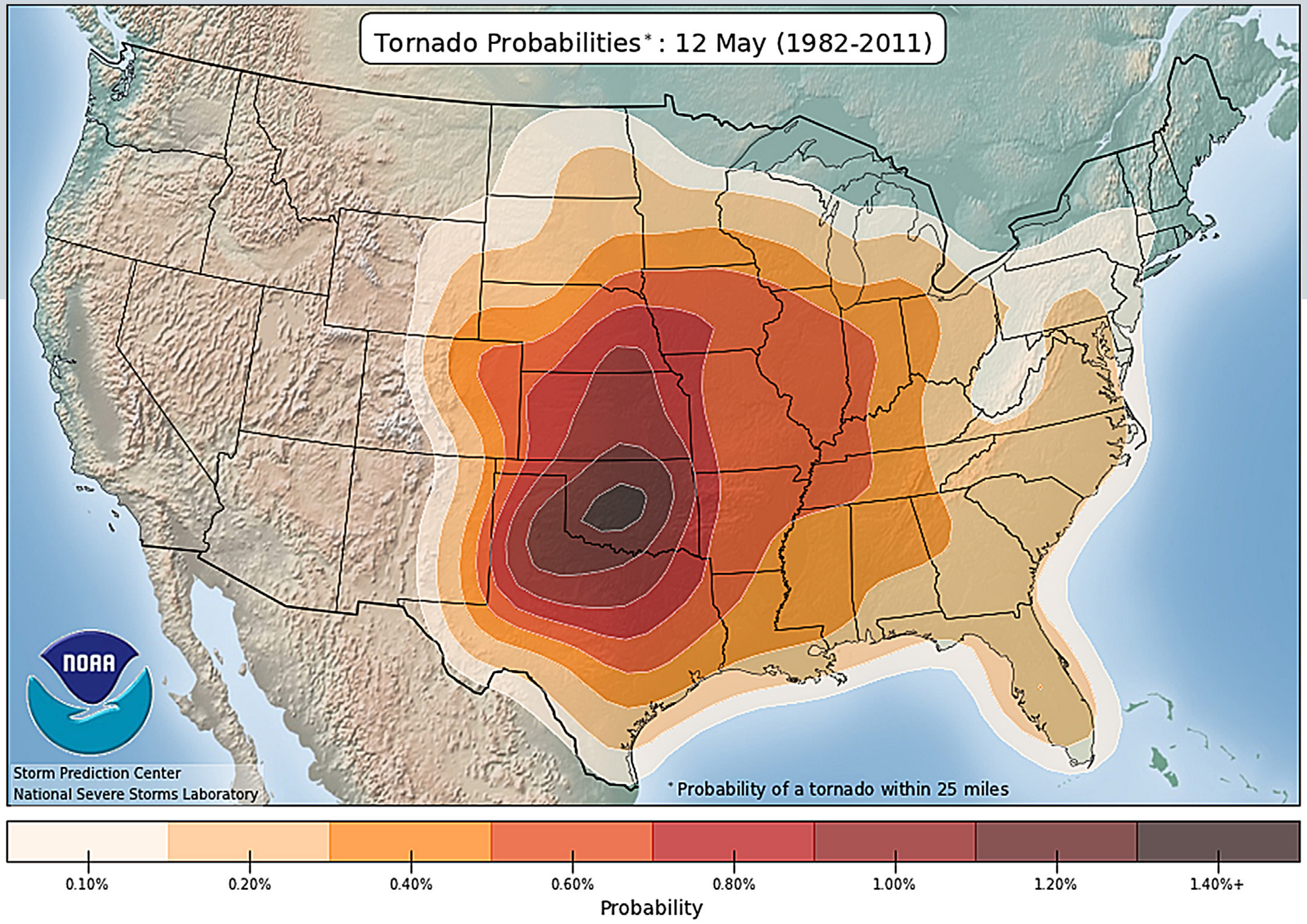
FEATURE 5

The NOAA Unique Combined Atmospheric Processing System (NUCAPS):

A Supplementary Tool for Forecasting Severe Storms

In 2021, the U.S. witnessed 11 severe storms causing 114 deaths and $20.8 billion in losses. On top of that, at least another 7 lives and $2.6 billion were lost from flooding caused by heavy rainfall or thunderstorms. Thunderstorms can produce softball-sized hail that damage cars and windows; strong winds that knock down trees, power lines, and mobile homes; and tornadoes that destroy nearly everything in their path. The greatest severe weather threat in the U.S. is in “tornado alley,” an unofficial and shifting region where tornadoes occur more frequently than anywhere else in the world. This area generally extends from Minnesota down to Texas where Kaitlin Rutt works as a forecaster in the National Weather Service (NWS) Amarillo, TX Field Office.

A supercell thunderstorm in Kansas. Source: Michael Coniglio, NOAA National Severe Storms Laboratory (NSSL).



Probability of a tornado occurring within 25 miles on May 12, 2022, estimated from a 30-year period of severe weather reports from 1982-2011. Source: NOAA NWS Storm Prediction Center.

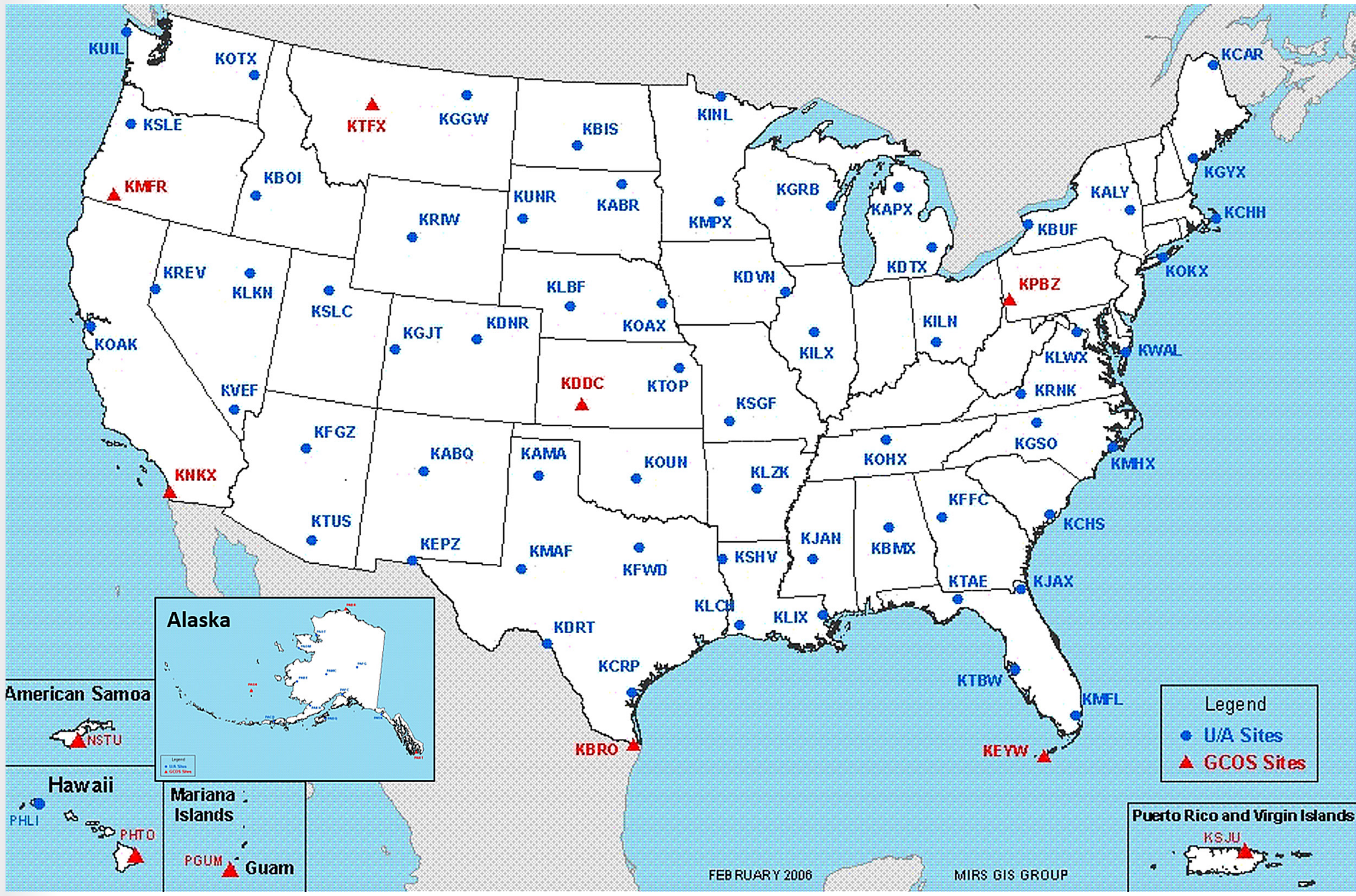
As a meteorologist in Texas, Rutt is faced with severe convective weather that can form quickly and put small communities in imminent danger. During the summer, Texas forecasters need to watch for atmospheric conditions that can lead to severe weather. Timely warnings about damaging wind or hail, or the possibility of a tornado or flash flood, is critical to keep the public safe. Meteorologists use computer forecast models to help decide if conditions will be right for the development of thunderstorms. One of these models is the Rapid Refresh (RAP) model, a short-range operational weather prediction system run at the NOAA National Centers for Environmental Protection (NCEP). Since it updates hourly, RAP is particularly useful for the U.S. severe weather forecasting community in predicting what might happen that same day. The model collects data from weather balloons, radar, surface observations, aircraft, and satellites to produce forecasts going out 21 hours. It is up to meteorologists like Rutt to compare model output with current atmospheric conditions and identify areas of potential severe weather.

Convective Weather

Convective weather is the vertical transport of heat and moisture in an unstable environment that produces severe local storms associated with thunder, lightning, heavy rain, strong winds, and hail.

ATMOSPHERIC SOUNDINGS FROM SPACE

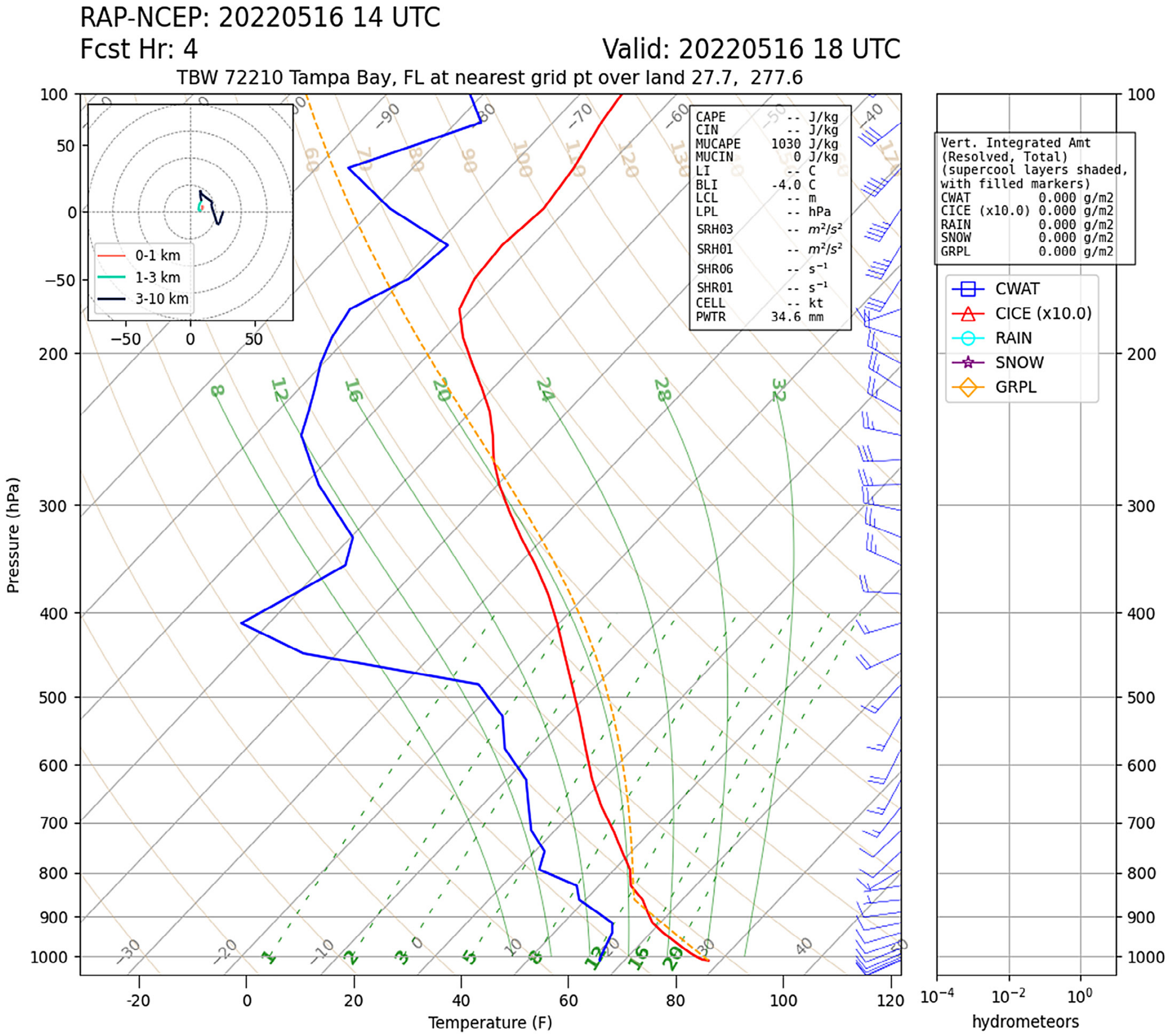
A sounding is a vertical profile of the atmosphere. Soundings allow forecasters to look at the vertical distribution of temperature, moisture, wind, and other features that are needed to predict severe convective weather. They are produced from radiosondes attached to weather balloons that launch twice a day from 92 stations across North America and the Pacific Islands. Their infrequency means hours go by between soundings and their geographic coverage leaves large areas uncovered, as shown in the map of launch sites below.



Map of the NWS Radiosonde Network showing balloon launch sites. Source: National Weather Service.

Computer forecast models, like RAP, fill these gaps with high-resolution model-generated soundings based on simulations that include ground-based and remote observations, but are not real observations like those taken by radiosondes. All models have some degree of uncertainty because of choices made in their development—this is one of the biggest challenges in science. To improve forecast reliability, many meteorologists take a "two heads are better than one" approach by combining soundings from multiple sources. This is where satellite-based soundings can help.

Model Soundings



Left: Launching a weather balloon carrying a radiosonde instrument. Source: NASA/Frankie Martin.
Above: Example RAP-NCEP model sounding for Tampa Bay, FL on May 16, 2022. Source: NOAA Global Systems Laboratory, Assimilation and Verification Innovation Division (AVID).

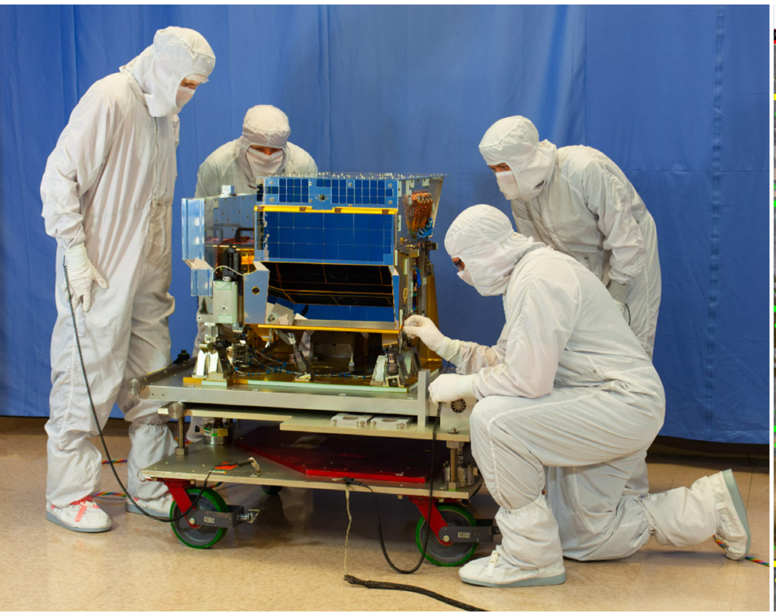
The NOAA Unique Combined Atmospheric Processing System (NUCAPS)

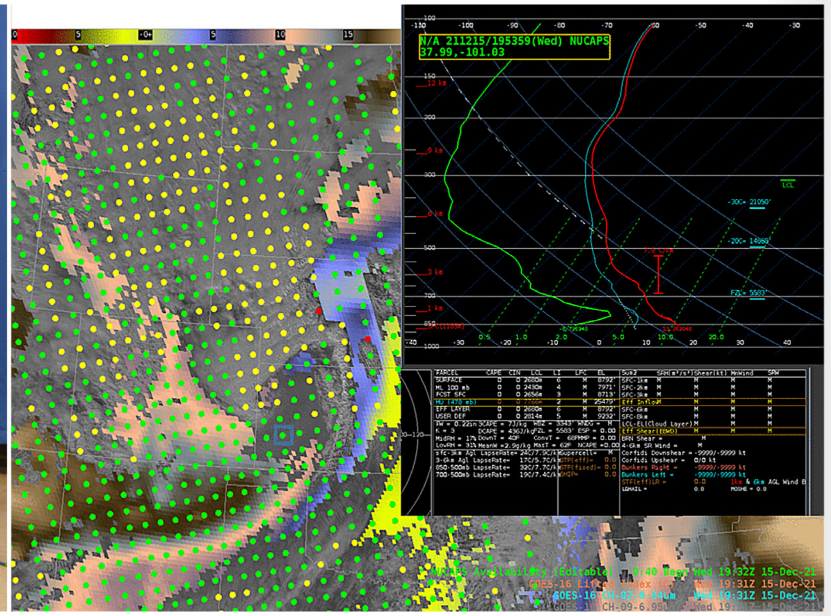
The NOAA Unique Combined Atmospheric Processing System (NUCAPS) combines data from the Cross-Track Infrared Sounder (CrIS) and Advanced Technology Microwave Sounder (ATMS) onboard JPSS satellites, as well as EUMETSAT MetOp weather satellites, to produce near real-time vertical profiles of temperature and moisture multiple times a day. Being independent of models, NUCAPS soundings are another tool for forecasters to compare to model data to improve their confidence in models. Since the sounders cover a 2,200 km wide swath and their observations are about 30 miles apart, they can fill in where radiosonde or ground-based data are sparse, like between balloon launch sites and over oceans. NUCAPS soundings are taken about the time that afternoon convection—the vertical transport of heat and moisture associated with storms—is starting across the Southern Plains, making them a valuable addition to storm nowcasting.

NUCAPS has been producing operational near real-time products and delivering them to the NWS Advanced Weather Interactive Processing System (AWIPS) since 2014. In AWIPS, forecasters can view and compare NUCAPS, radiosonde, RAP, and other model soundings. As a complementary tool, NUCAPS increases situational awareness of environmental conditions that lead to severe storms so forecasters can quickly see hotspots or areas of convective instability. NUCAPS also includes derived data, such as lapse rates and stability indices for severe weather potential.

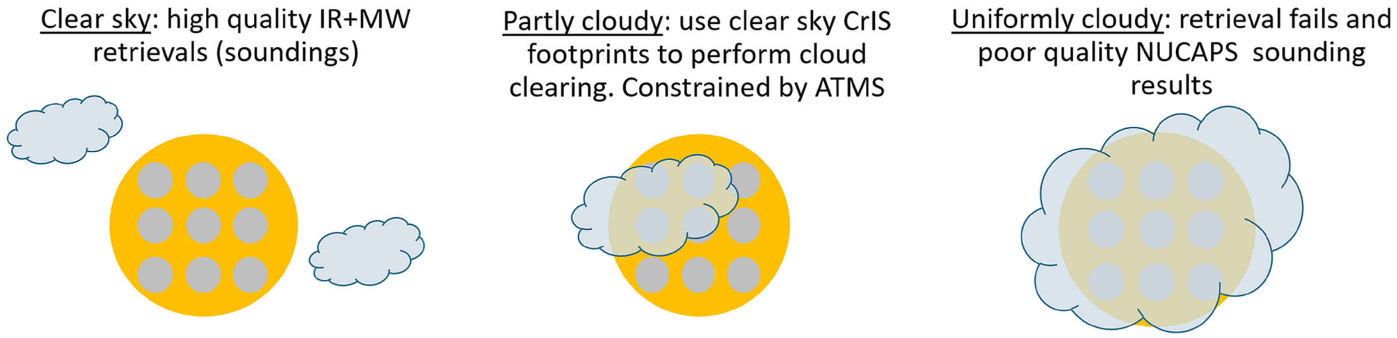
But there are caveats. NUCAPS CAPE values are calculated differently and are more complicated than model soundings (CAPE stands for "Convective Available Potential Energy" and is a measure of atmospheric instability). Learning the nuances of NUCAPS takes practice. For forecasters, "it comes down to knowing your region, what data works and doesn't work for your environment, and what models do well so that you can compare NUCAPS and see how it's performing," says Rutt. "Sometimes a max CAPE in NUCAPS is trying to correct for existing storms and it overcorrects, but there are cases where NUCAPS correctly pinpoints with a CAPE bullseye right where storms developed."

NUCAPS also does not include wind data, and cloudy conditions can impact data quality. Thick, uniform clouds can cause unrealistic values or retrieval failure, meaning that NUCAPS data is dependent on local weather conditions. Also, because satellite observations are taken from the top of the atmosphere, views of the atmospheric boundary layer—the part of the atmosphere 1-2 km above the earth's surface where most weather occurs—can be imprecise.



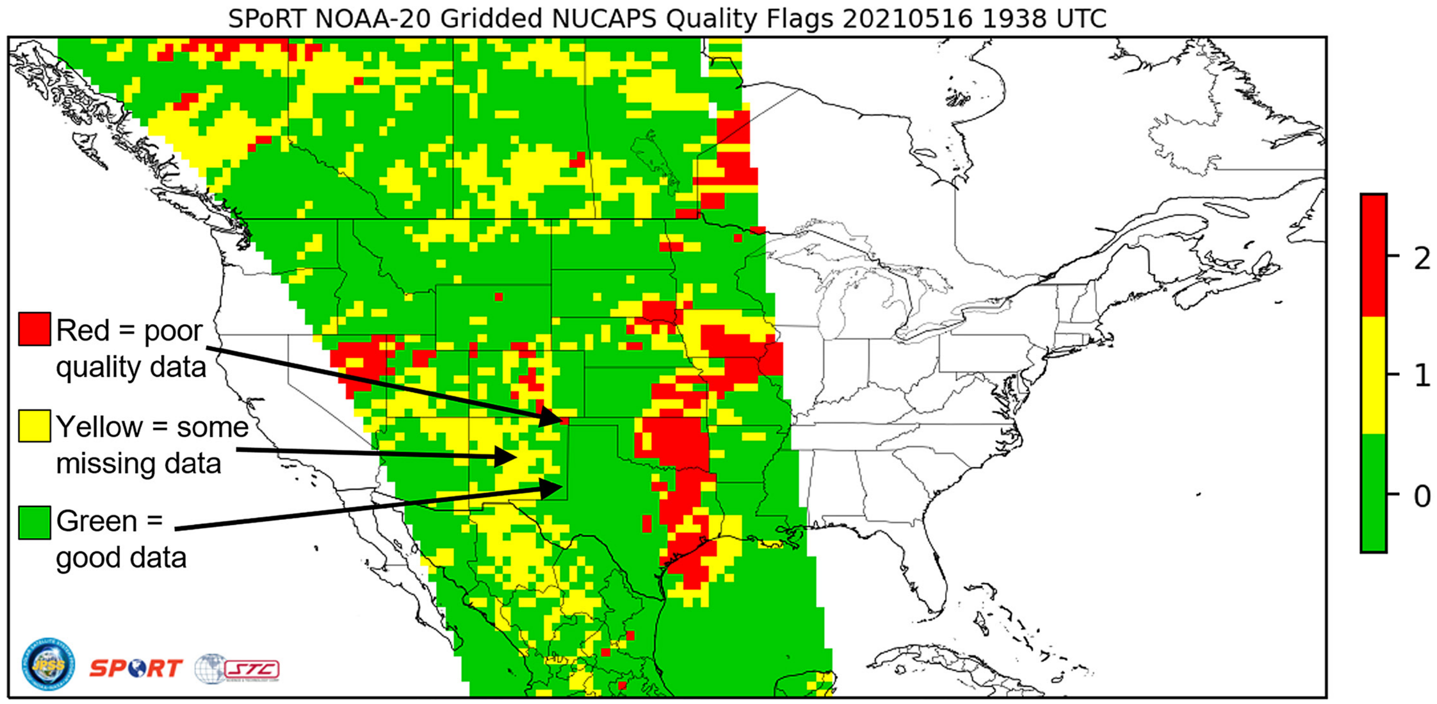


Left: The Cross-track Infrared Sounder (CrIS) instrument, one of two sounders onboard JPSS satellites. Source: NOAA National Environmental Satellite Data and Information Service (NESDIS). Right: Example Gridded NUCAPS sounding. Source: Cooperative Institute for Meteorological Satellite Studies (CIMSS) at University of Wisconsin-Madison.



The quality of NUCAPS soundings varies depending on cloud cover. Source: NOAA Hazardous Weather Testbed (https://hwt.nssl.noaa.gov/ewp/training_2017/HWT_GriddedNucaps_Training_final.pptx).

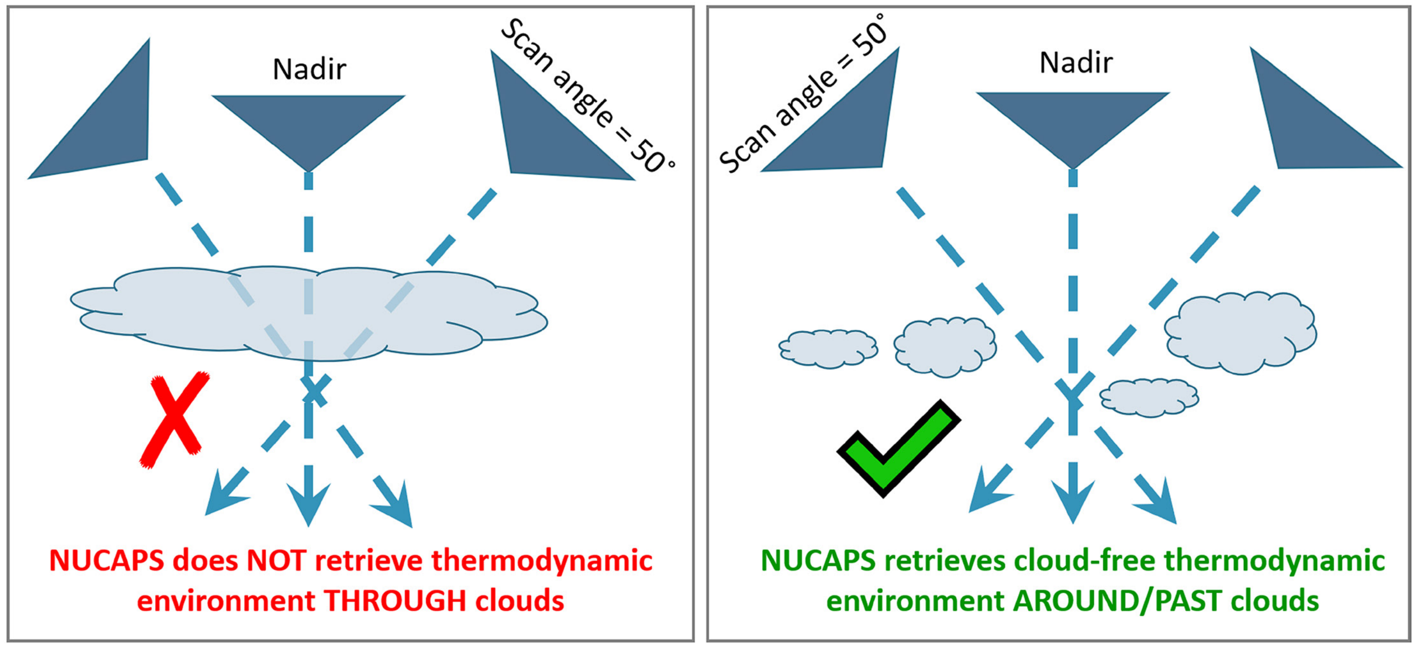
Within AWIPS, NUCAPS quality flags allow forecasters to quickly interpret data reliability before examining sounding profiles. Quality flags show whether a sounding is good (green), missing some data (yellow), or poor quality that should be questioned or ignored (red). In the example below, yellow quality flags are seen west of Texas where thunderstorms occurred on that day and cloud cover likely interfered with retrievals from CrIS, an infrared sounder that cannot penetrate thick clouds.



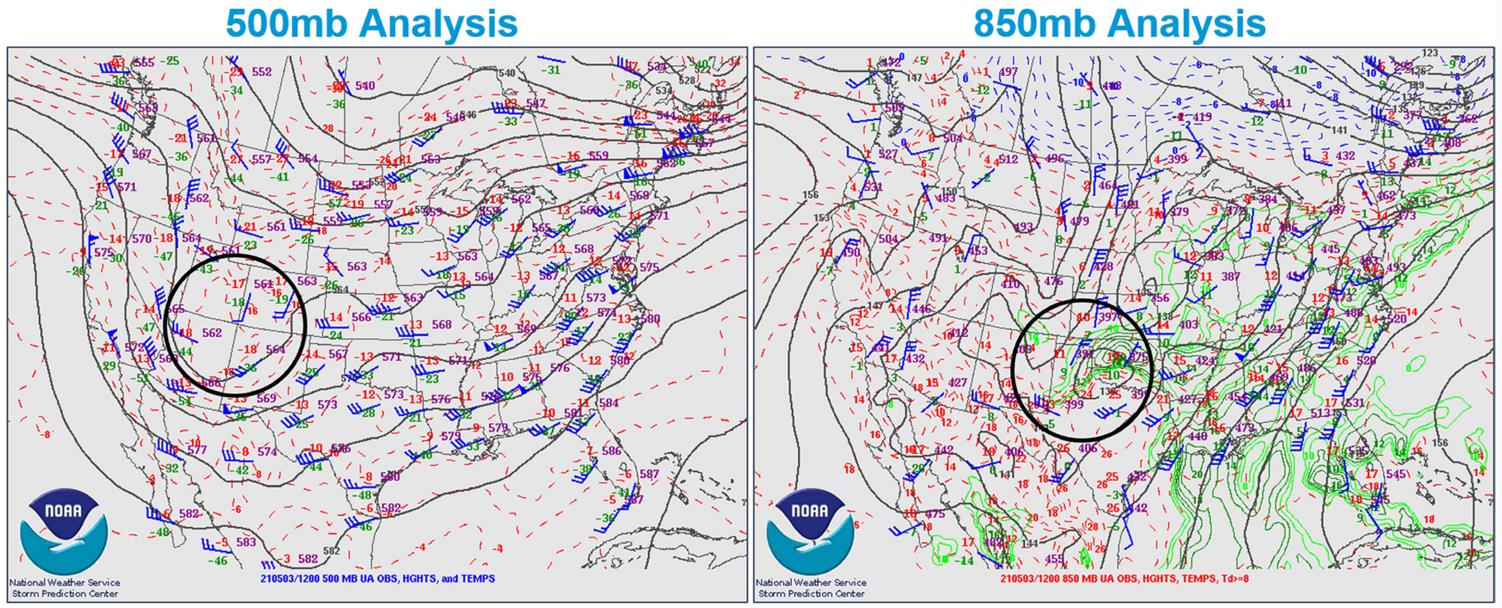
Gridded NUCAPS quality flags for May 16, 2021, at 2:38 PM CST (local time).

Data in yellow pixels is still usable because NUCAPS performs "cloud clearing" to allow retrievals from CrIS in partly cloudy conditions. Cloud clearing removes the cloud signal from infrared radiance–NUCAPS retrievals in these conditions should be thought of as observations around or past the clouds, not through the clouds.

CrIS is also sensitive to surface temperatures, although this and thick, uniform cloud cover are partly overcome by adding ATMS data to NUCAPS, which uses microwave radiation to penetrate most clouds beyond the top layers. Despite these limitations, NUCAPS "gives another viewpoint on storm initiation, strength, and intensity," Rutt says.



Cloud clearing approach used for NUCAPS retrievals from CrIS. Source: NOAA Hazardous Weather Testbed, (https://hwt.nssl.noaa.gov/ewp/training_2018/HWT2018_GriddedNucaps_Training.pdf).

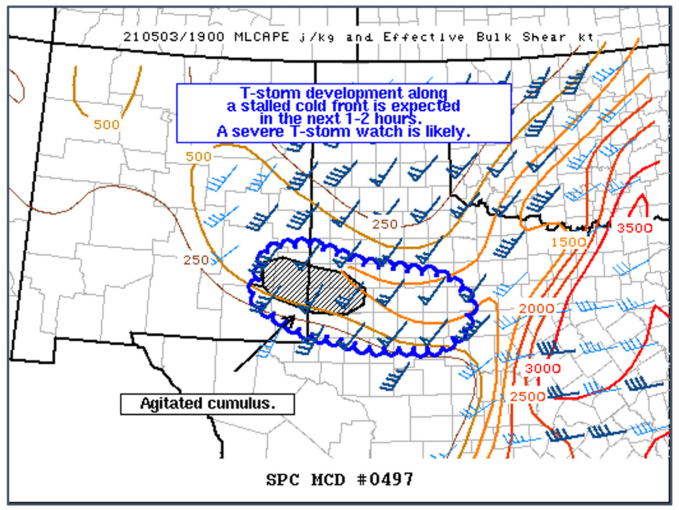


CLICK IMAGE TO ENLARGE. Constant pressure charts show selected weather conditions at different constant pressure altitudes (in millibars). They help determine the three-dimensional aspect of an atmospheric pressure system. These charts are from the morning of May 3, 2021, showing (left) the upper trough in the Four Corners and (right) a surface low across Northwest Texas/Southwest Oklahoma with a cold front draped across West Texas.

COMPARING NUCAPS TO FORECAST MODELS: TWO CASES OF WEST TEXAS STORMS

At the May 2022 JPSS Science Seminar, Rutt showed examples of how NUCAPS and other satellite products offer additional confirmation about the convective environment and higher resolution forecast models. One of these cases began on the morning of May 3, 2021, when an upper trough swung across the Four Corners where Arizona, Utah, Colorado, and New Mexico meet. Troughs are drawn-out regions of low pressure that typically occur in advance of a cold front, like in the constant pressure charts above. Just to the east, a surface low and cold front draped across the northern part of West Texas.

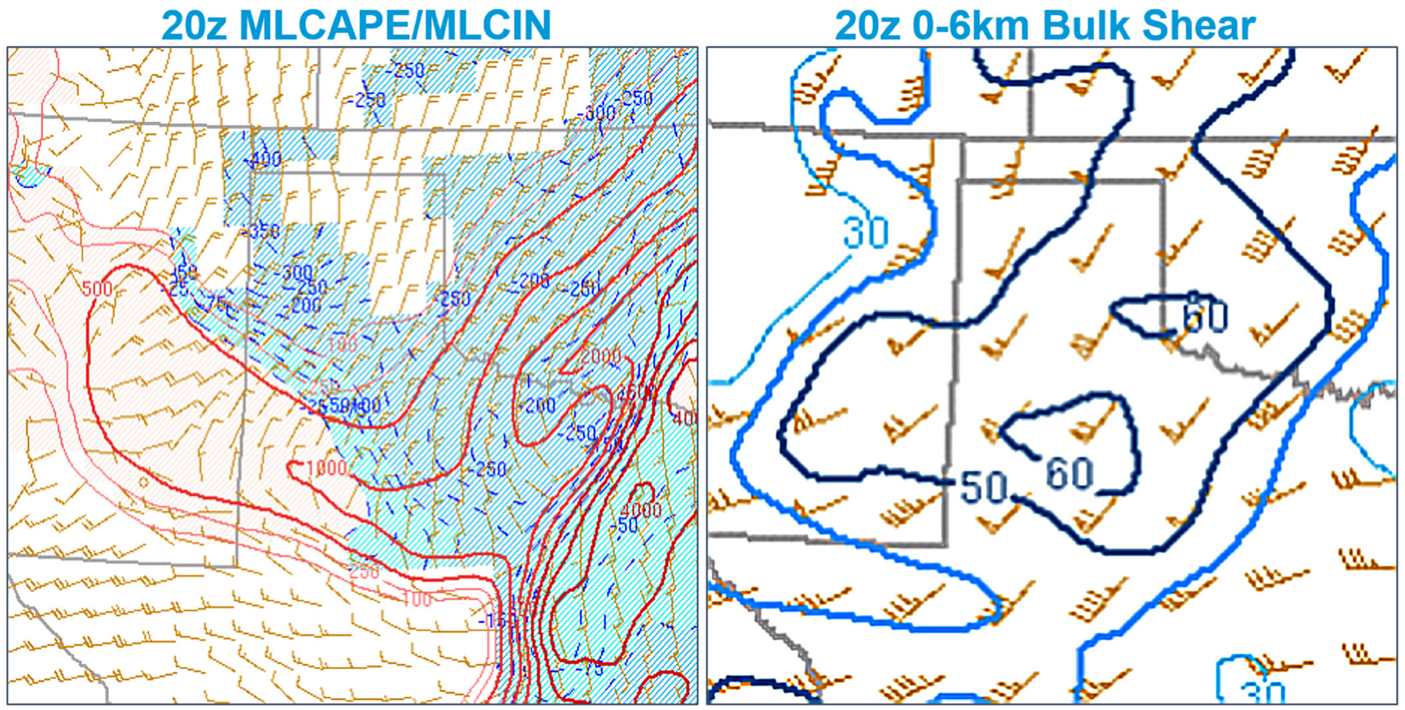
By the afternoon, the NOAA/NWS Storm Prediction Center (SPC) had issued a mesoscale discussion (below)—a short-term technical weather forecast/nowcast issued by SPC—for the potential for thunderstorm development along the stalled cold front. Shortly after, Rutt looked at the RAP model mesoscale analysis showing Mixed Layer CAPE



CLICK IMAGE TO ENLARGE.

(MLCAPE) and bulk shear wind (below) and noticed that "the higher MLCAPE values in East Texas near the Dallas-Fort Worth area—this area is capped," meaning there is a layer of warm, stable air thousands of feet up that is suppressing thunderstorms in the area. A higher value of CAPE signals that the atmosphere is more unstable—values between 1,000 to 2,500 Joules/kilogram (J/kg) mean moderate instability and thunderstorms can build quickly.

For the May 3 RAP soundings Rutt explains, "MLCAPE values are around 500 to 1,000 J/kg right along the stalled front in Northeast Texas, and if you look at the 0-6 kilometer bulk vertical shear [the change in wind in the 0-6 km layer closest to the ground], we had a shear of 50-60 knots around this area, so there was a lot of instability to support thunderstorms that could become strong to severe." A storm was brewing!



RAP soundings showing MLCAPE/MLCIN and 0-6km bulk shear wind values at 20Z on May 3, 2021.

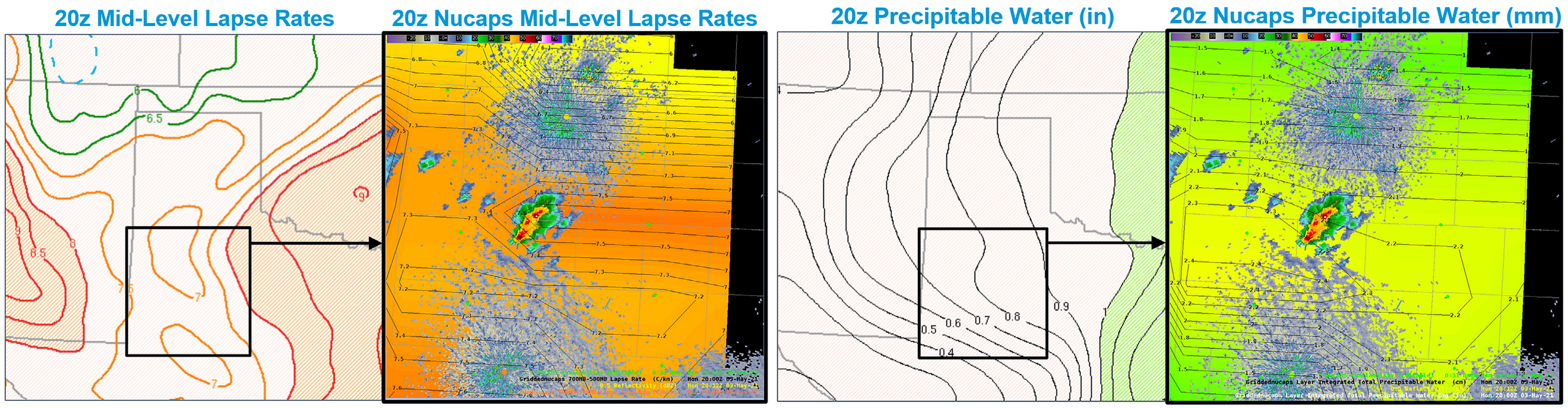
What is "Z" Time?

The notation "Z" is weather lingo for "Zulu" time, better known as Universal Coordinated Time (UTC), the time at the prime (zero) meridian—the line of 0° longitude. All aspects of meteorology are based on this global 24-hour clock. Weather maps, radar, and satellite images all have their time expressed in "Z".

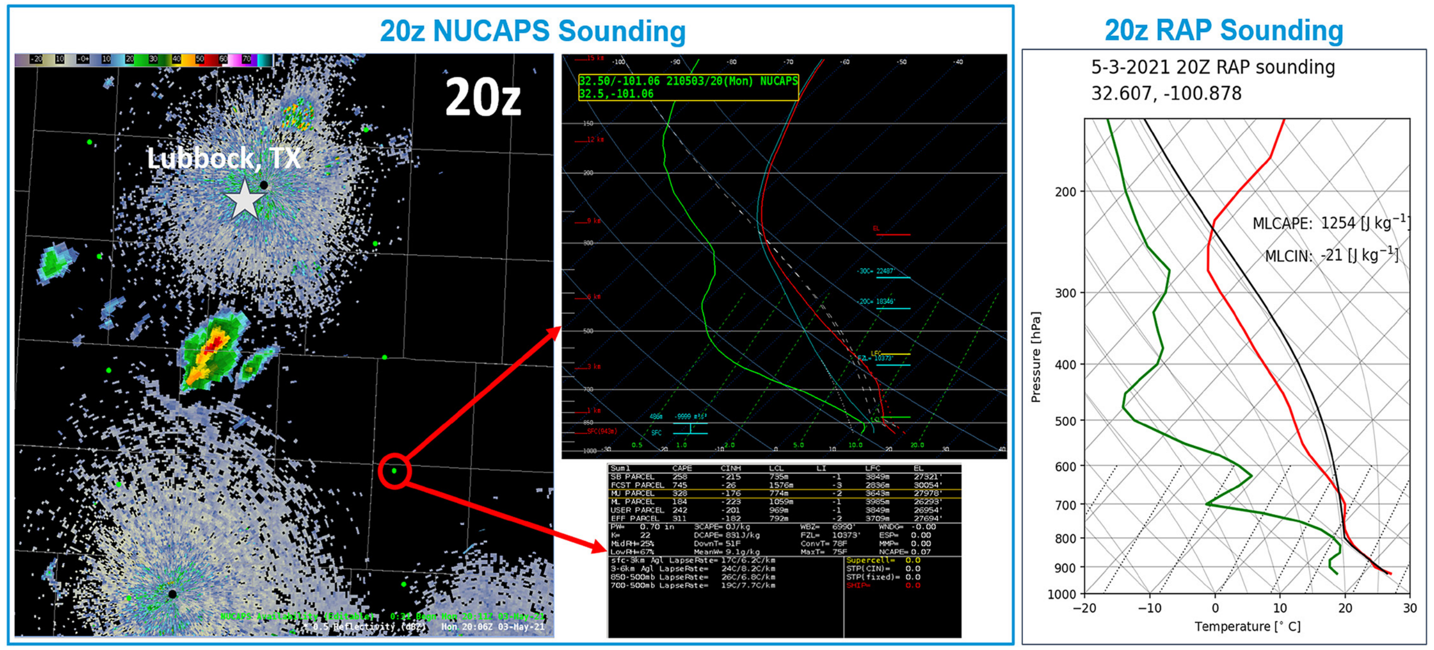
Still early in storm development, Rutt looked at mid-level lapse rates at 20Z (3:00 PM CST, local time) from RAP and NUCAPS for the area in and around the Texas Panhandle. The mid-level lapse rate—the rate that temperature changes with height at the 700-500 mb pressure level—is meant to identify regions where deep convection is more likely. The faster the temperature decreases with height, the “steeper” the lapse rate and the more unstable the atmosphere becomes. She also looked at precipitable water, which reveals the amount of moisture above a fixed point. It does not show how much it will rain but rather how much moisture is in the air that could turn into precipitation.

Comparing the higher resolution RAP model and NUCAPS observations (below), Rutt points out, “NUCAPS showed a corridor of higher lapse rates, which hinted at storm development right behind the stalled cold front and possibly back-to-back storms that might occur in this corridor of higher lapse rates.” A similar thing happened with precipitable water. Rutt continues, “NUCAPS precipitable water again shows a corridor of higher amounts along and slightly ahead of the stalled front with slightly better detail on the area of higher precipitable water than the higher resolution mesoanalysis (RAP) at the same time.”

Rutt evaluated a few NUCAPS and RAP soundings at 20Z for the areas ahead to the storm, east, and southeast of Lubbock (example at top of next page). “You can see generally good agreement between the two soundings in the overall shape of each profile with a cap and



Left: Mid-level lapse rates from RAP (L) and NUCAPS (R) at 20Z on May 3, 2021. Right: Precipitable water on May 3, 2021, from RAP (L, in inches) and NUCAPS (R, in millimeters).



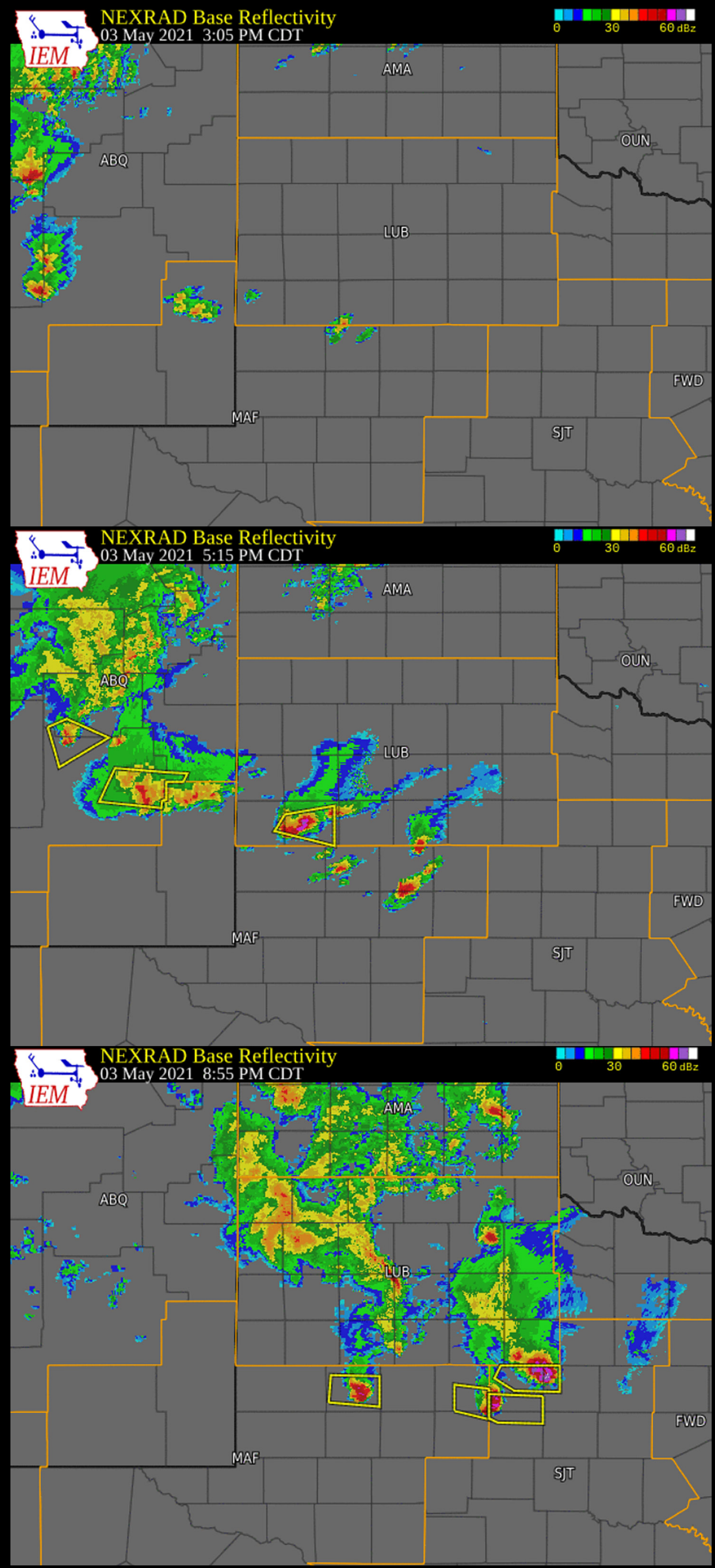
CLICK IMAGE TO ENLARGE. One dataset of NUCAPS and RAP soundings at 20Z on May 3, 2021, for a point southeast of Lubbock, Texas ahead of the stalled front. Note the similarities in profile shape between NUCAPS and RAP output.

subtle CIN present behind the stalled front,” explains Rutt (CIN stands for Convective INhibition and represents the “negative” area on a sounding that must be overcome before a storm can start). “The big difference between the two,” she notes, “is in the surface values—surface temperatures in NUCAPS are slightly lower than in the RAP and because of this, NUCAPS hints at higher CAPE values than what is realistic and vice versa with MLCIN.” Part of this is because NUCAPS calculates surface values differently than the RAP model. Rutt emphasizes, “It’s good to compare with actual surface temperatures to see which model lines up better.”

While generally similar, in this case there is a difference between NUCAPS and the higher resolution RAP model in the observational sense, especially near the surface. The previous mesoanalysis showed this area should have 500 to 1,000 J/kg of MLCAPE. Here, the RAP sounding shows this but NUCAPS struggles to reach 200 J/kg of MLCAPE. “We would expect instability to be highest along the front—we see this with the CAPE values around 1,000 in the RAP and negligible CIN values, but the NUCAPS sounding has a much lower presence of instability," says Rutt. While there are ways to improve NUCAPS data, its vertical retrievals will always be smoother than that of RAP, which contributes to its uncertainty. "You will never have the sharp vertical resolution in the mid-levels that you have with RAP soundings–that's just the nature of NUCAPS and how satellite observation is," she explains. Even so, NUCAPS has higher vertical definition than other satellite-derived soundings.

So, Was There Severe Weather?

Yes! Conditions were "the perfect storm"—moisture was trapped behind the stalled cold front, feeding the development of back-to-back storms, like NUCAPS had suggested. In the radar snapshots on the right, the progression of severe weather can be seen developing in the eastern part of New Mexico and continuing along the corridor of instability in West Texas as the day goes on. Tennis ball sized hail and winds up to 84 miles per hour were reported as the storms moved further east into North Central Texas.

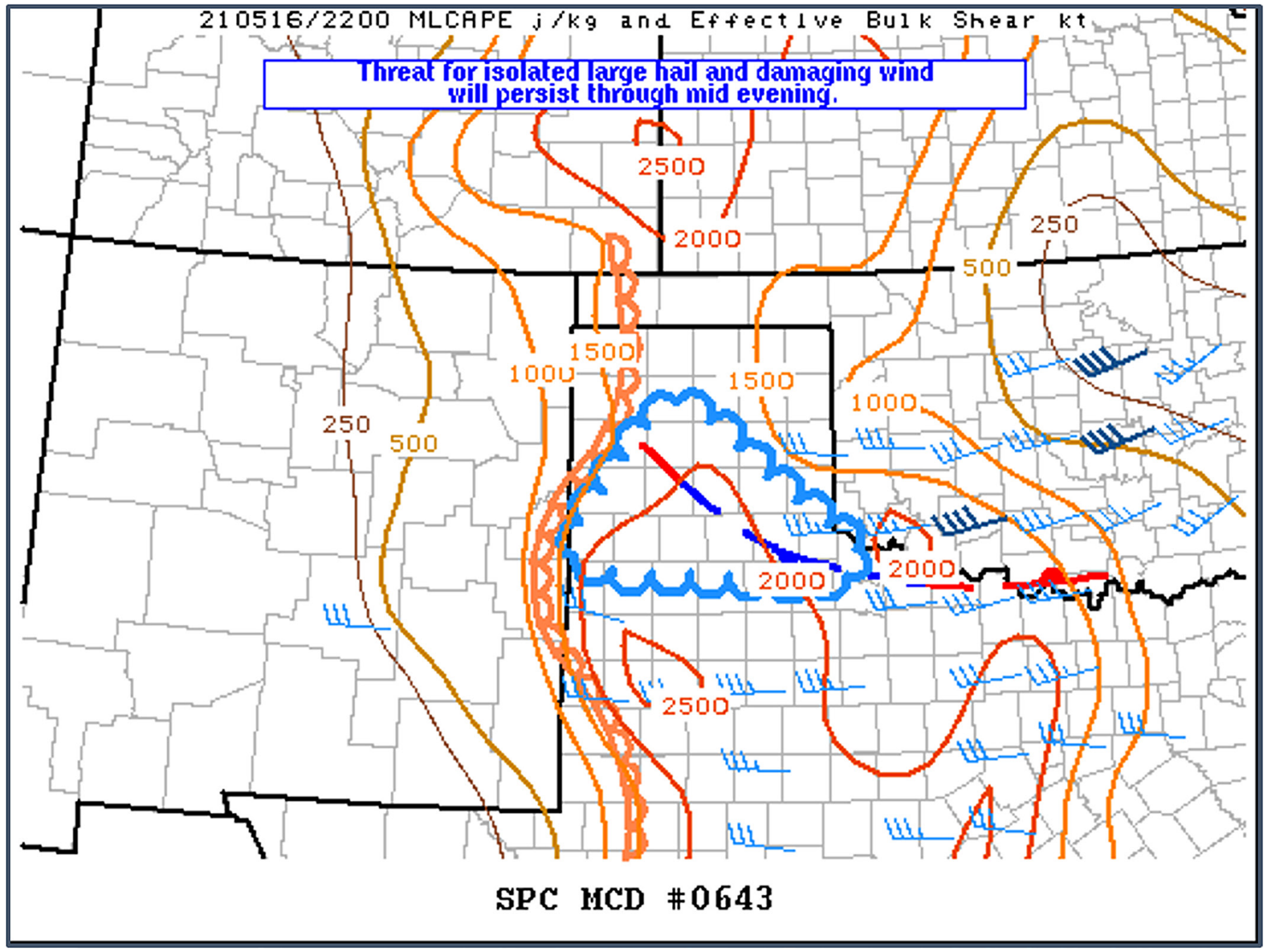


Right: Screenshots from NWS radar showing the progression of back-to-back thunderstorms on May 3, 2021, that moved from eastern New Mexico through West Texas.

Another Day, Another Storm

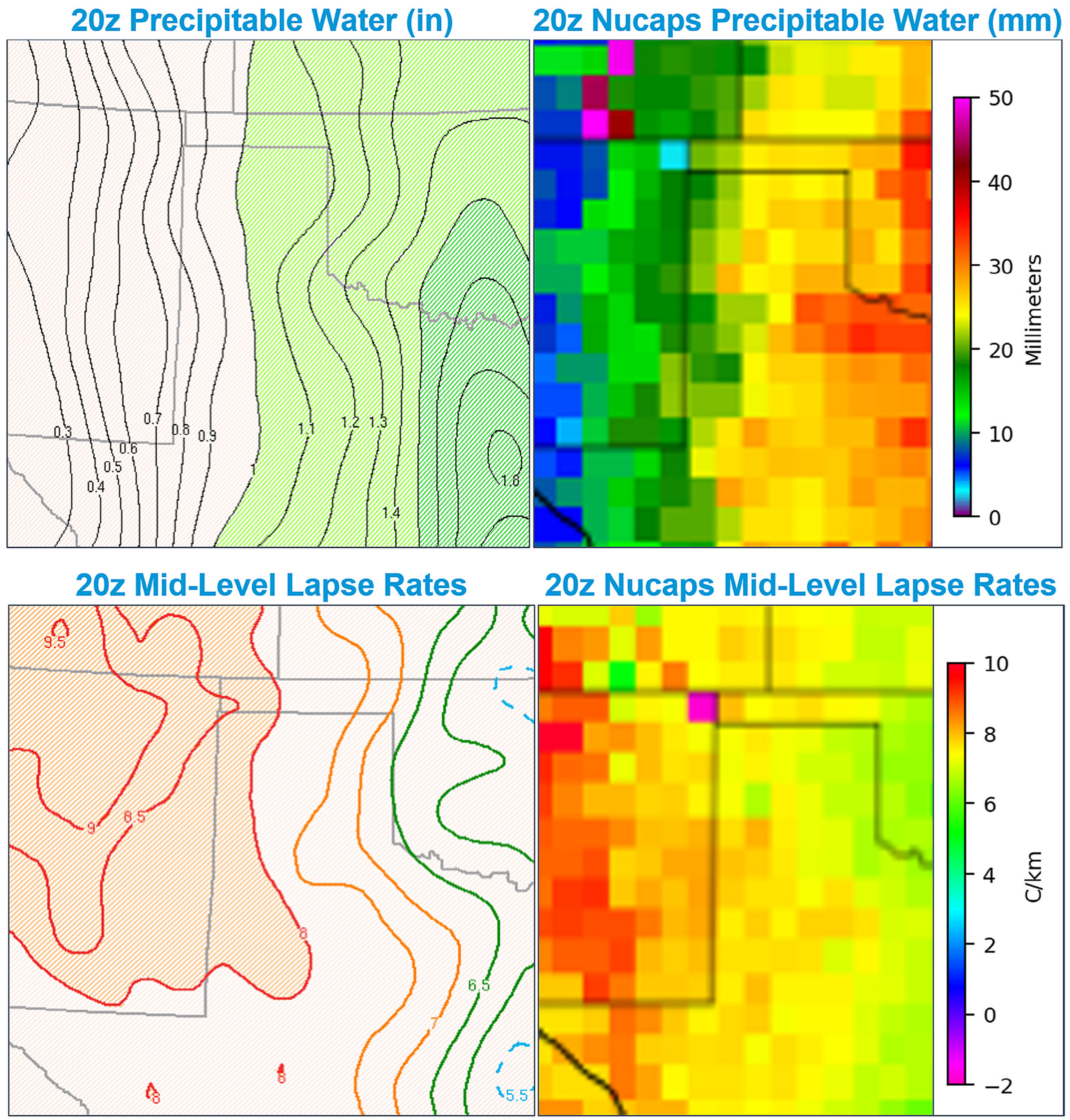
Being stationed in Amarillo, Texas has its benefits for a meteorologist—a lot of weather action! Rutt typically sees storms develop in West Texas around early afternoon when the dryline sets up. This boundary separating moist air and dry air is an important factor in storm frequency in the Great Plains. The dryline is most common in spring and early summer, and on May 16, 2021, Rutt observed another doozy of a storm pass through her area.

The morning hours of May 16, 2021 saw an upper low and a weak disturbance come across West Texas, causing a "lee low" to form off the eastern ridge of the Rocky Mountains—the "lee" side that faces away from westerly winds. This lee-side trough of elongated low pressure pushed into West Texas, providing a dryline setup, shown in the SPC mesoscale discussion below (the scalloped orange line). Instability increased farther east ahead of the dryline indicating severe storms would develop between Amarillo and Lubbock.



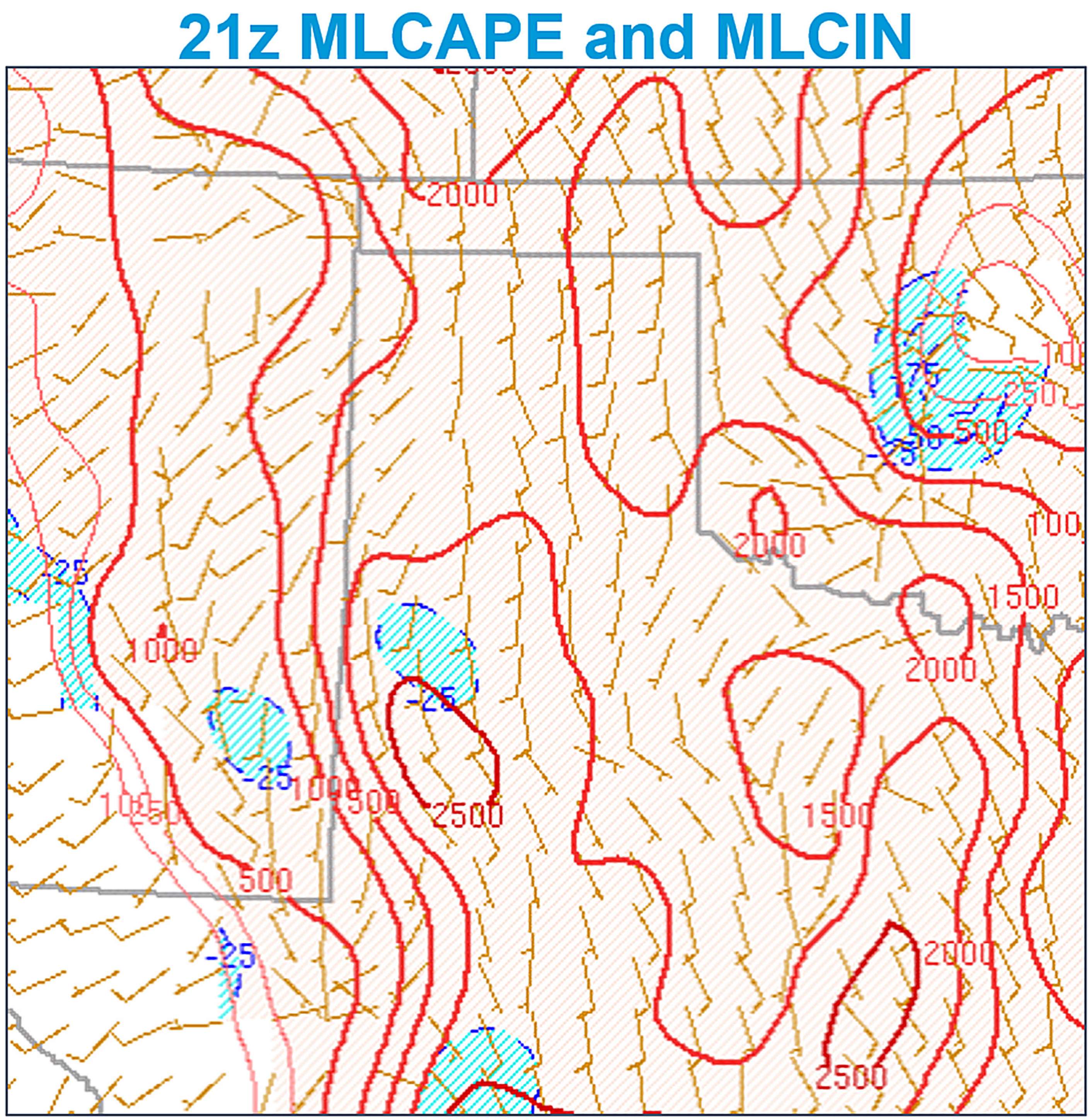
NWS mesoscale discussion for May 16, 2021, at 5:00 PM CST (local time). A dryline can be seen along the New Mexico-Texas border (scalloped orange line).

There was plenty of moisture in the area on this day. Looking at precipitable water at 20Z (below top), RAP and NUCAPS soundings match up well with both picking up drier air to the west and moisture to the east that define the dryline, hinting at where storms might occur in the afternoon. Lapse rates at 20Z (below bottom) tell a similar story where rates are steep to the west of the New Mexico-Texas border (west of the dryline). "NUCAPS shows this really well and is a good representation of mid-level lapse rates in this scenario," confirms Rutt.

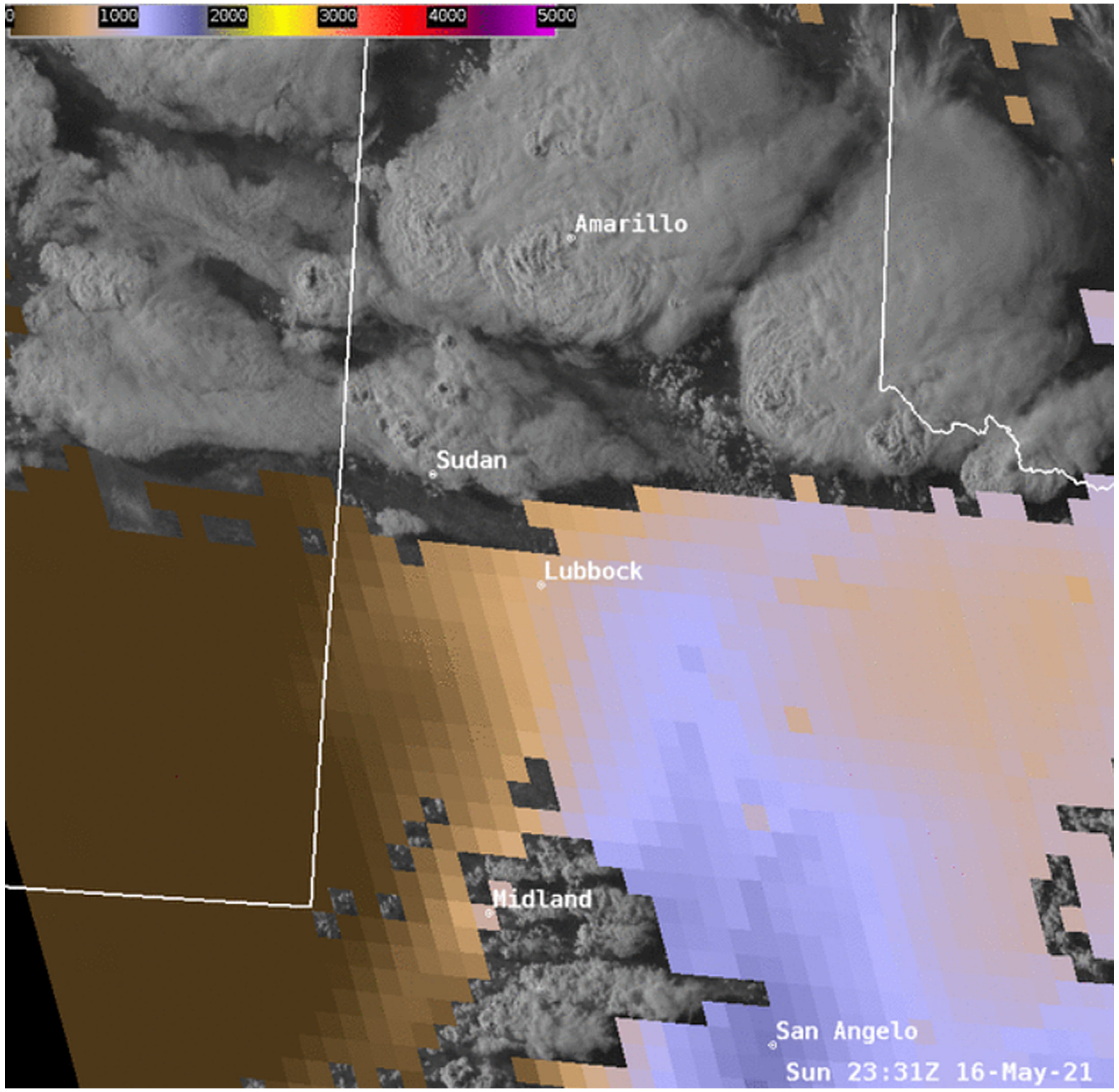


Top: Precipitable water at 20Z on May 16, 2021, from RAP (L, in inches) and NUCAPS (R, in millimeters). Bottom: Mid-level lapse rates from RAP (L) and NUCAPS (R) at 20Z on May 16, 2021.

In this case, retrievals from NOAA Geostationary Operational Environmental Satellites (GOES) were helpful in providing good situational awareness in this evolving situation. Looking at the RAP mesoanalysis for MLCAPE and MLCIN at 21Z (below left), there is a tremendous amount of CAPE—a bullseye of about 2,500 J/kg—which is enough to support thunderstorm development and possibly a supercell of rotating winds. GOES-East CAPE values (below right) about match RAP values but Rutt points out, "In GOES-East the bullseye is shifted a little east of what the mesoanalysis was showing, which gives us an idea that the area of instability might actually be shifted east—the dryline is very clearly on GOES and where we might expect storms to form in the afternoon." Underlying storms moving into the dryline and area of instability can be seen in GOES visible imagery.

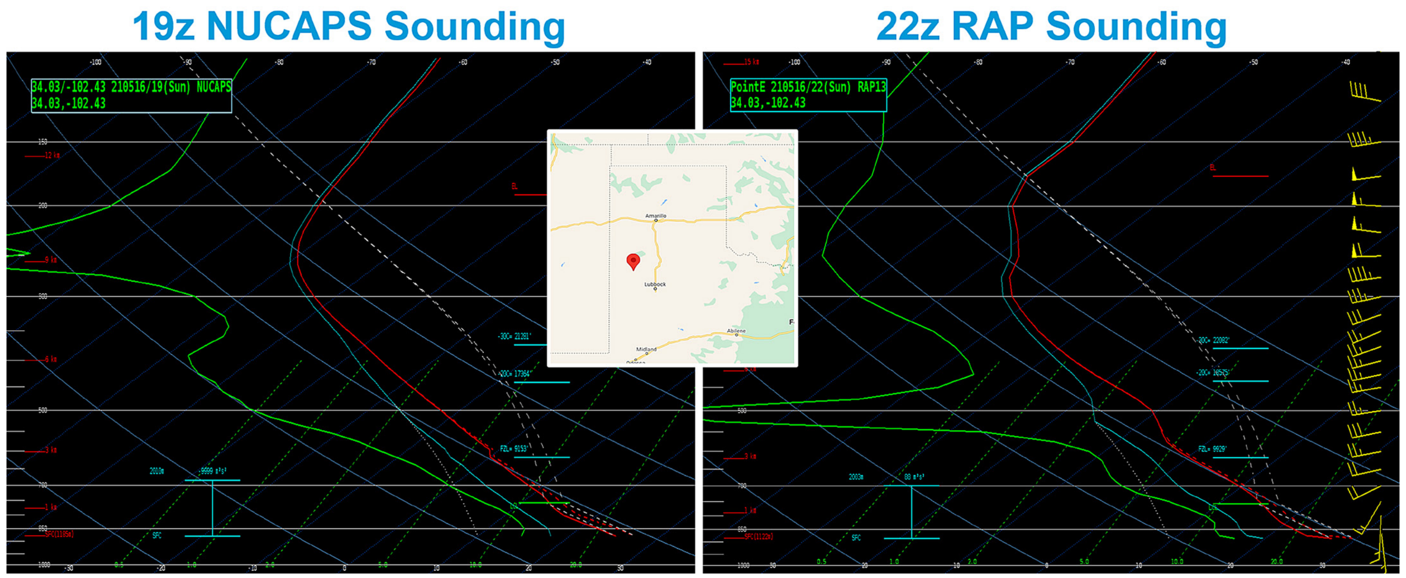


MLCAPE and MLCIN at 21Z on May 16, 2021 from RAP.



GOES-East visible imagery that shows overshooting tops at 23:31Z on May 16, 2021.

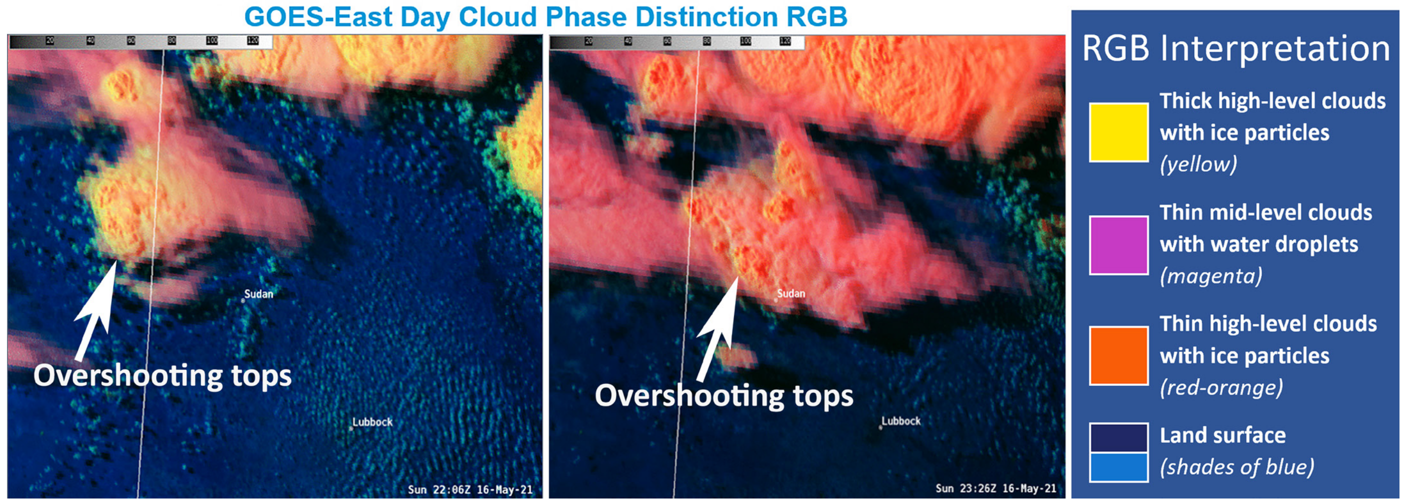
Like before, the RAP and NUCAPS soundings (below) are generally comparable—their timing is different because of data availability but the profiles give a similar sense of the environment. "At 19Z you're looking ahead of the storm development and you can see good steep lapse rates throughout the profile, the CAPE is at ample amounts," says Rutt. The RAP model shows low-level shear winds pointed south-southwest through the profile that hints at a mesocyclone—a rotating part of a thunderstorm about two to six miles across. Rutt reiterates, "NUCAPS data was pretty close to what the higher resolution RAP models were trying to pinpoint for what was going to happen with the line of storms over the next few hours."



CLICK IMAGE TO ENLARGE. Comparison of NUCAPS and RAP soundings for May 16, 2021, at a point near Sudan, Texas, northwest of Lubbock.

What Happened?

GOES-East Day Cloud Phase Distinction RGB imagery (top of next page) gives a clear view of what happened—strong thunderstorms developed along the dryline just as NUCAPS and RAP predicted. They continued to strengthen as they progressed to the east with some rotation north of Lubbock. Signs of updrafts and overshooting tops—dome-like protrusions that shoot out of the top of thunderstorms—help evaluate how the storm is developing. Here, the overshooting tops are continuous, indicating this storm is severe. And severe it was! These storms produced a tornado northwest of Lubbock near Sudan, Texas where the NUCAPS and RAP soundings showed high CAPE values, warning of an unstable atmosphere and a potential for volatile storms. A job well done by NUCAPS and RAP!



CLICK IMAGE TO ENLARGE. GOES-East Day Cloud Phase Distinction RGB imagery for Northwest Texas on May 16, 2021 at 5:06 PM CST, local (left) and 6:26 PM CST, local (right).

PERSPECTIVE

The case studies presented by Rutt reinforce what others have found—that NUCAPS is a good supplementary source of temperature and moisture information in areas, and at times, not well covered by the NWS radiosonde network. But Rutt says she is not yet comfortable solely relying on its data: "Sometimes NUCAPS does really well in giving what the environment looks like, but other times NUCAPS struggles on surface details." One way that forecasters can improve surface data in NUCAPS is to manually change it based on observations from other sources. The JPSS Proving Ground Risk Reduction (PGRR) program is looking at ways to automate the addition of actual or modeled observations of the lower atmosphere in future versions of NUCAPS to further address this challenge.

NUCAPS is one of many tools in the forecaster's toolbox. Like any tool, it has strengths and limitations, but when used alongside other data sources it offers additional insight and helps fill data gaps. NUCAPS quality flags provide the user with information about retrievals that may be impacted by clouds, weather, or another issue. To be of greatest value, forecasters must carefully consider these flags to help determine where and when a particular sounding can be useful in a quickly changing environment.

Besides its merit in locating pre-convective weather systems, NUCAPS soundings are also useful for aviation, air quality, fire weather, and cyclone applications. For example, in the winter months, frigid air temperatures at high altitudes can cause airplane jet fuel to gel, known as "cold air aloft," an obvious safety issue. Vertical temperature profiles from NUCAPS are helpful in finding freezing cold air pockets in near real-time so pilots can go around them. Also, NUCAPS provides vertical profiles of ozone and trace gases like carbon dioxide, methane, carbon monoxide, and volcanic sulfur dioxide to assist forecasters in issuing more effective hazardous air quality alerts. Plans are ongoing to update NUCAPS algorithms to improve retrieval performance and look at the impact of using radiance and noise equivalent differential radiance to produce soundings. ✦

STORY SOURCE

The information in this article is based, in part, on the April 18, 2022, JPSS science seminar presented by Kaitlin Rutt, meteorologist for the NOAA National Weather Service Forecast Office in Amarillo, Texas.

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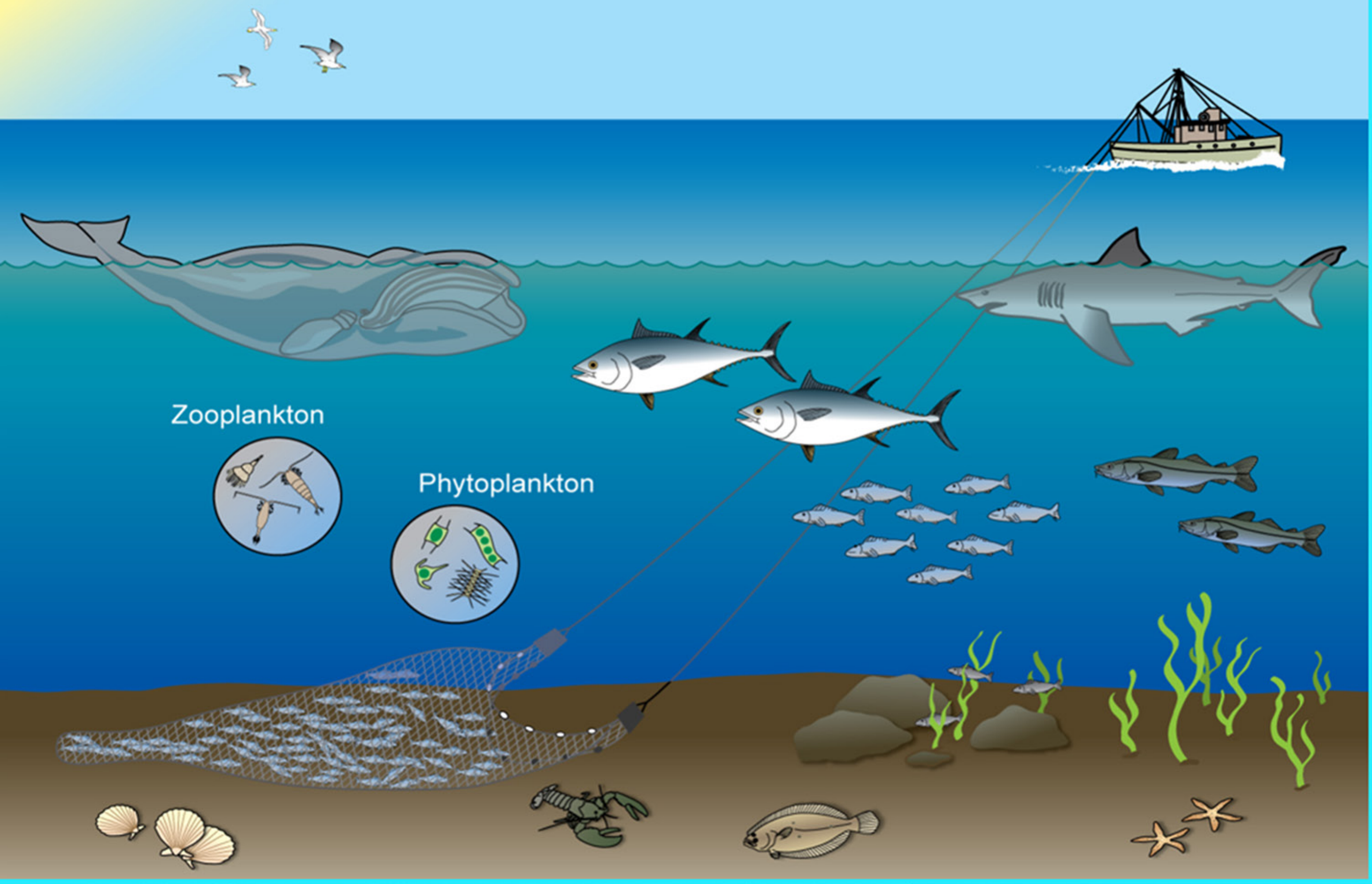
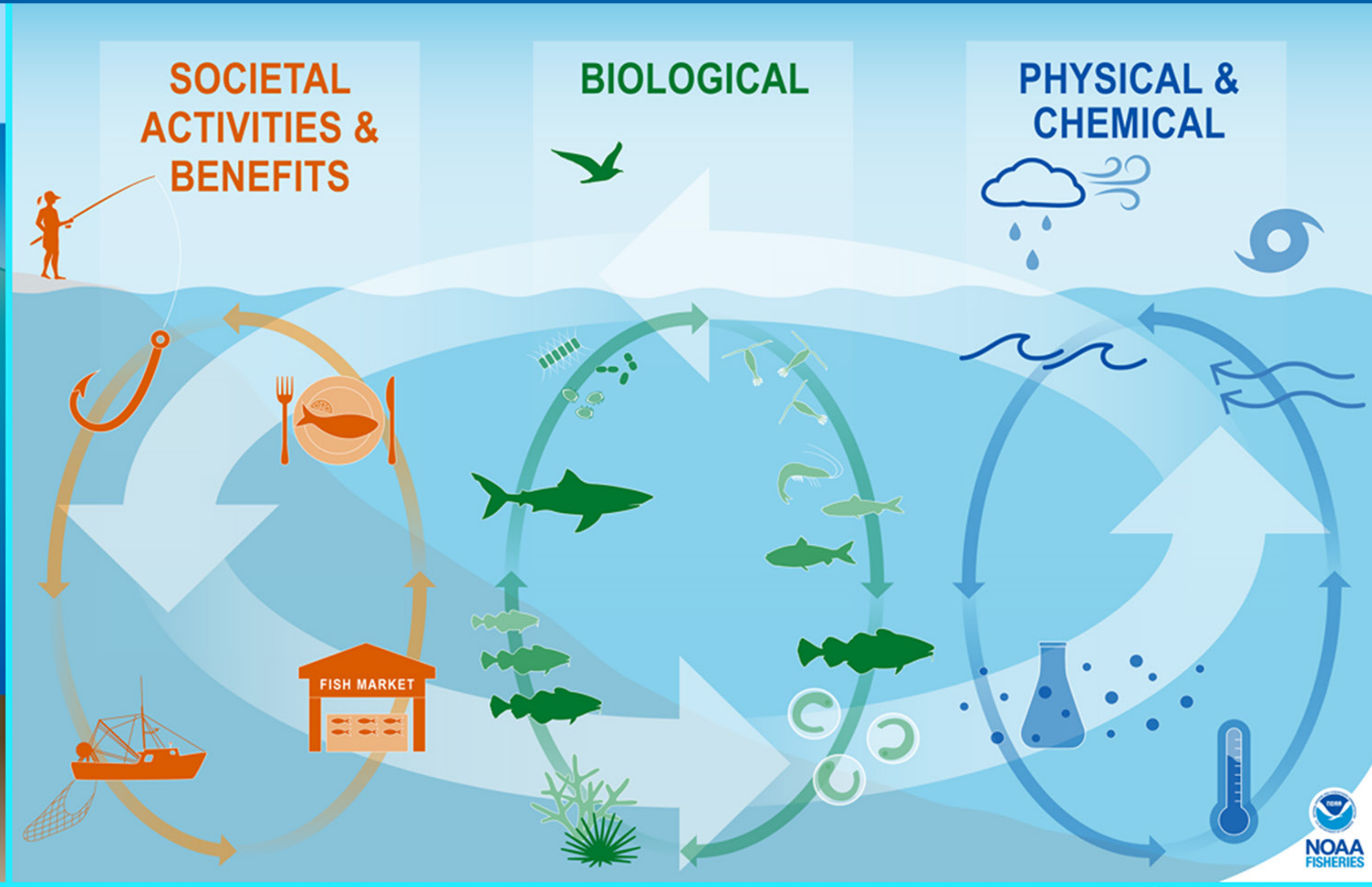
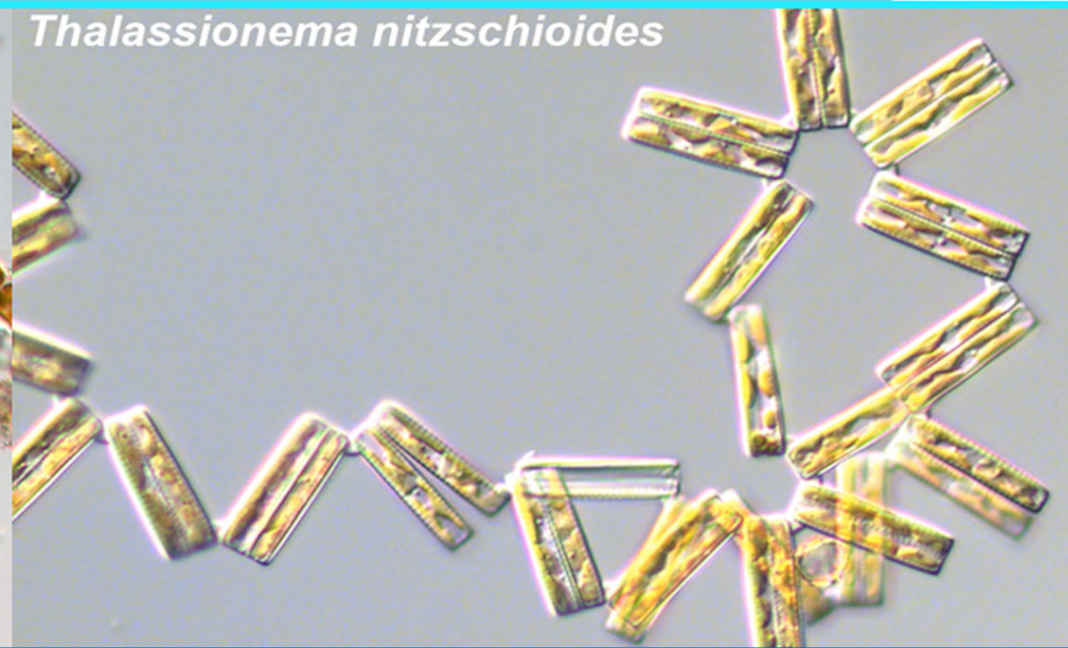
Estimating Phytoplankton Size Class in the Northeast U.S. Continental Shelf Using Regionally Tuned Ocean Color Algorithms







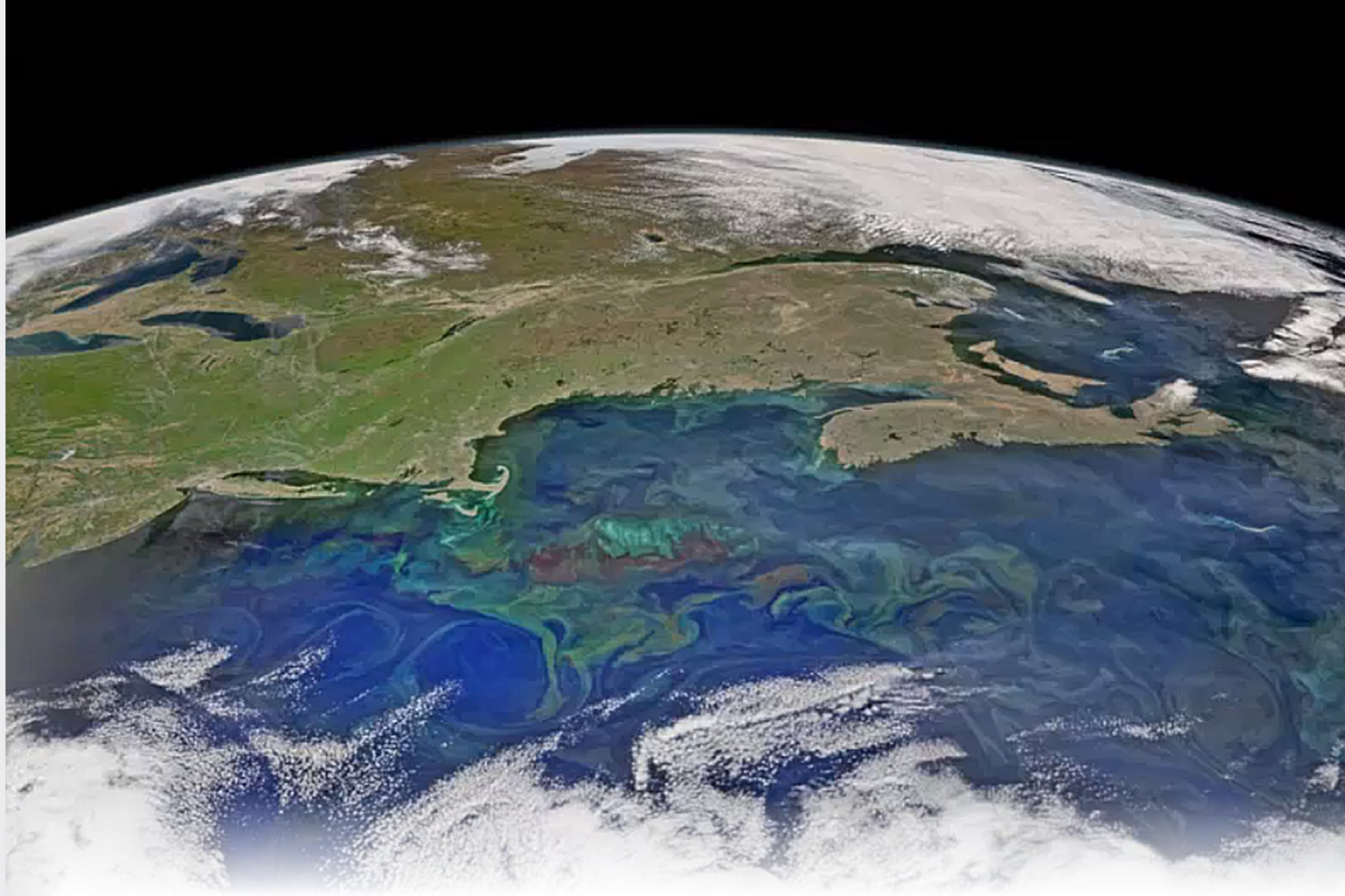
Top left: Representation of a fishery ecosystem from the base of the food web (phytoplankton and zooplankton) to humans. Source: Michael Fogarty, NOAA Fisheries Northeast Fisheries Science Center and Jack Cook, Woods Hole Oceanographic Institution. Top right: Societal, biological, physical, and chemical factors are the multiple system drivers that influence marine ecosystems through a variety of different pathways. Source: NOAA Fisheries. Bottom row: Examples of phytoplankton species found in the Northeast U.S. continental shelf. Source: NOAA Fisheries.

Phytoplankton are microscopic plant-like organisms that live in top layers of the ocean and freshwater environments. Diverse in size and function, these influential organisms are the foundation of the marine food web, serving as a source of nutrition for a variety of sea creatures. Marine phytoplankton have a close relationship with the commercial and recreational fishing industries—for example, zooplankton (a primary consumer) eat them, small fish eat zooplankton, larger fish eat smaller fish, and so on up the food chain—and the economic impact is significant. In 2019[1] alone, fishing supported 1.8 million U.S. jobs and generated $255 billion in sales and $117 billion in value added impacts (contributions made to the gross domestic product).

Phytoplankton also play an important role in the Earth's carbon cycle, acting as a "biological carbon pump" by removing about 1 billion tons of carbon per year from the air through photosynthesis. As phytoplankton absorb carbon they are eaten by larger marine organisms, which consume the carbon and take it further down into deeper ocean layers, effectively removing it from the atmosphere. But the ocean is changing—it is getting warmer, currents are shifting, mixing and stratification patterns are different, and together these changes can affect all aspects of phytoplankton. Given how vital phytoplankton are to the food web, environment, and the economy, it is critical to understand how they are changing so that fisheries can adapt their management strategies.

Tiny But Mighty

*The word "**phytoplankton**" comes from the Greek phyto (plant) and plankton (made to wander or drift). Phytoplankton use the **green pigment chlorophyll** to capture sunlight and photosynthesis to turn it into chemical energy. They are the **foundation of the aquatic food web** and consume as much carbon dioxide as forests making them a **critical regulator of climate change**.*

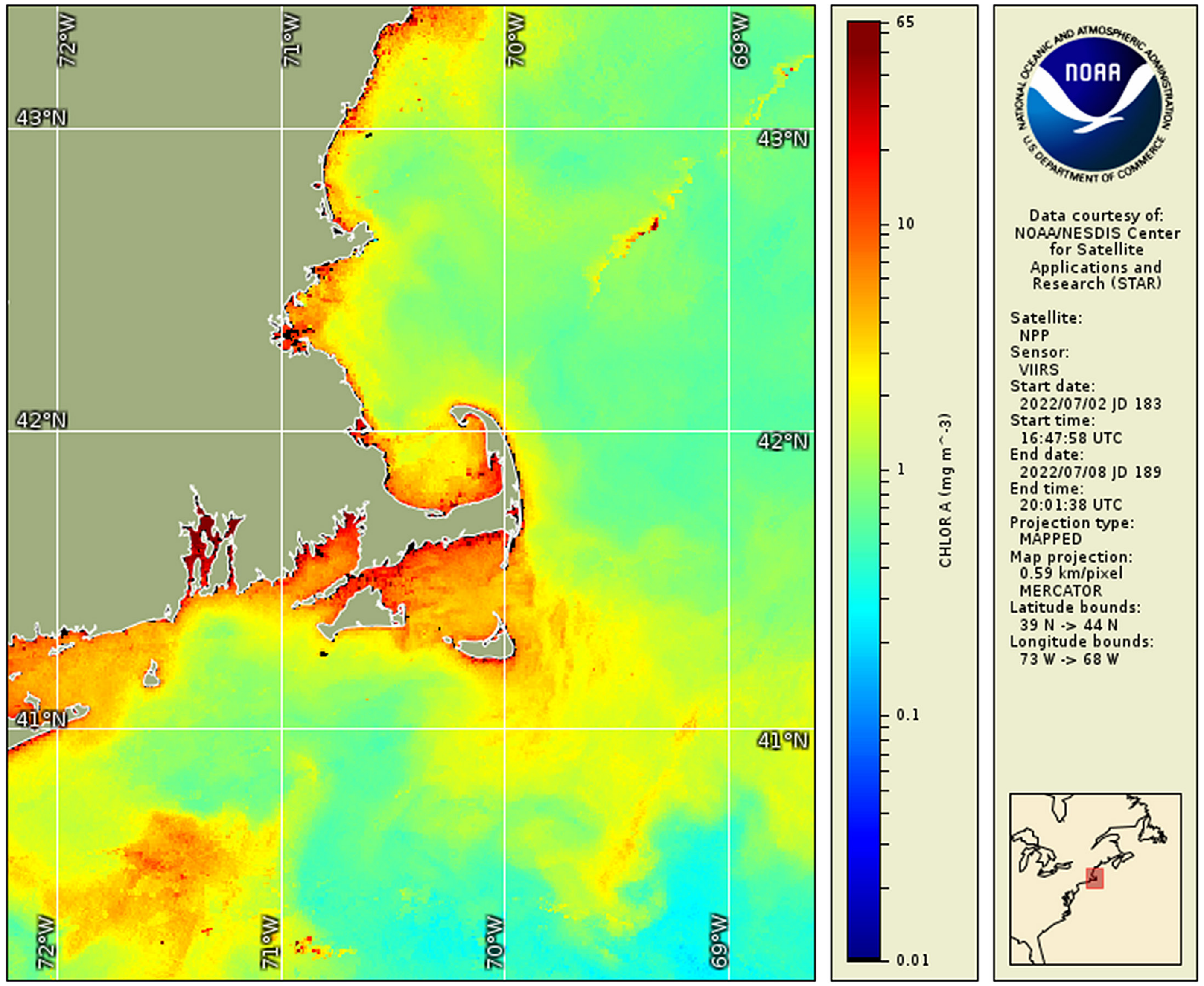


A VIIRS True Color image from May 14, 2015 showing a spring phytoplankton bloom (green) in the Northeast U.S. Continental Shelf region. Spring blooms are a key seasonal feature of the North Atlantic region and are a significant source of energy for the entire ecosystem.

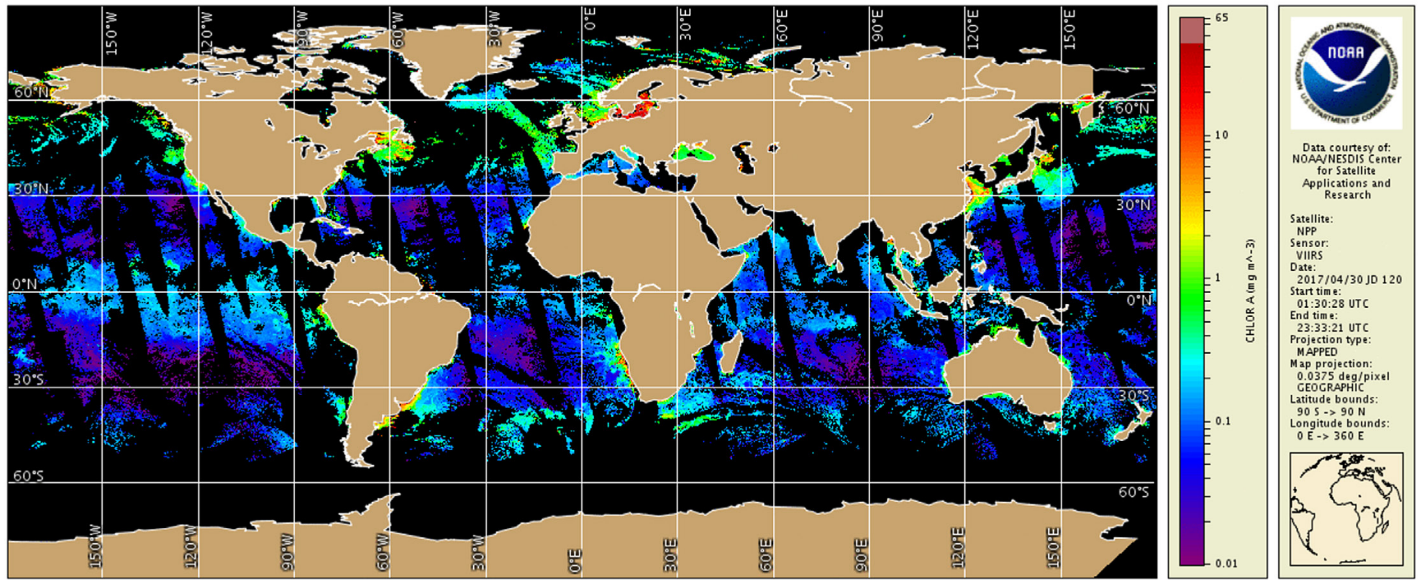
REMOTE SENSING OF PHYTOPLANKTON COMMUNITIES

Traditional methods of observing phytoplankton communities rely on water sampling and sensors onboard ocean vessels or moored platforms (*in situ* data). While helpful in determining the scale of marine organism activity, this approach is limited in time and space with remote areas of the ocean being largely unobserved due to the difficulty and expense in getting access. Simply put, *in situ* sampling cannot compete with satellite sensors in obtaining the vast amount of data needed for observing long term ecosystem changes. To put this into perspective, Dr. Kimberly Hyde, a biological oceanographer with the NOAA Northeast Fisheries Science Center (NEFSC), explains, "It would take a research ship moving 10 knots for more than five years to collect the same amount of data captured in this single image" (above) of a spring phytoplankton bloom in the North Atlantic, taken with the JPSS Visible Infrared Imaging Radiometer Suite (VIIRS) on May 14, 2015.

Remote sensing of phytoplankton first showed promise with the 1978 launch of the experimental Coastal Zone Color Scanner (CZCS) aboard the NASA/NOAA Nimbus 7 satellite. The CZCS was a proof-of-concept multi-channel radiometer that could measure the reflectance of phytoplankton pigments at certain wavelengths of light. The ratio of intensity at blue versus green wavelengths is linked to chlorophyll-a concentration, the main pigment of photosynthesis, which is an index of the amount of phytoplankton biomass in water. Showing promise, the CZCS sensor led to several follow-on ocean color missions starting in 1997 with NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS), ushering in an era of continuously measured chlorophyll-a in the global ocean. Currently, VIIRS is one of several remote sensors providing daily and weekly global chlorophyll-a estimates.



Example output from the VIIRS (Suomi-NPP) 7-day chlorophyll-a product for July 2, 2022 to July 8, 2022 for the Massachusetts and Rhode Island Bays. The product is processed with the NOAA OC3 algorithm and near-infrared (NIR) atmospheric correction. Source: NOAA CoastWatch East Coast Node.



CLICK IMAGE TO ENLARGE. Example time series of daily global chlorophyll concentration distribution from April 29, 2017 to May 29, 2017 (screenshot shows April 30). Global daily chlorophyll concentration distribution images are generated in the NOAA CoastWatch Okeanos operational system. Source: NOAA Office of Satellite and Product Operations, www.ospo.noaa.gov/Products/ocean/color/viirs/noaa20/index.html.

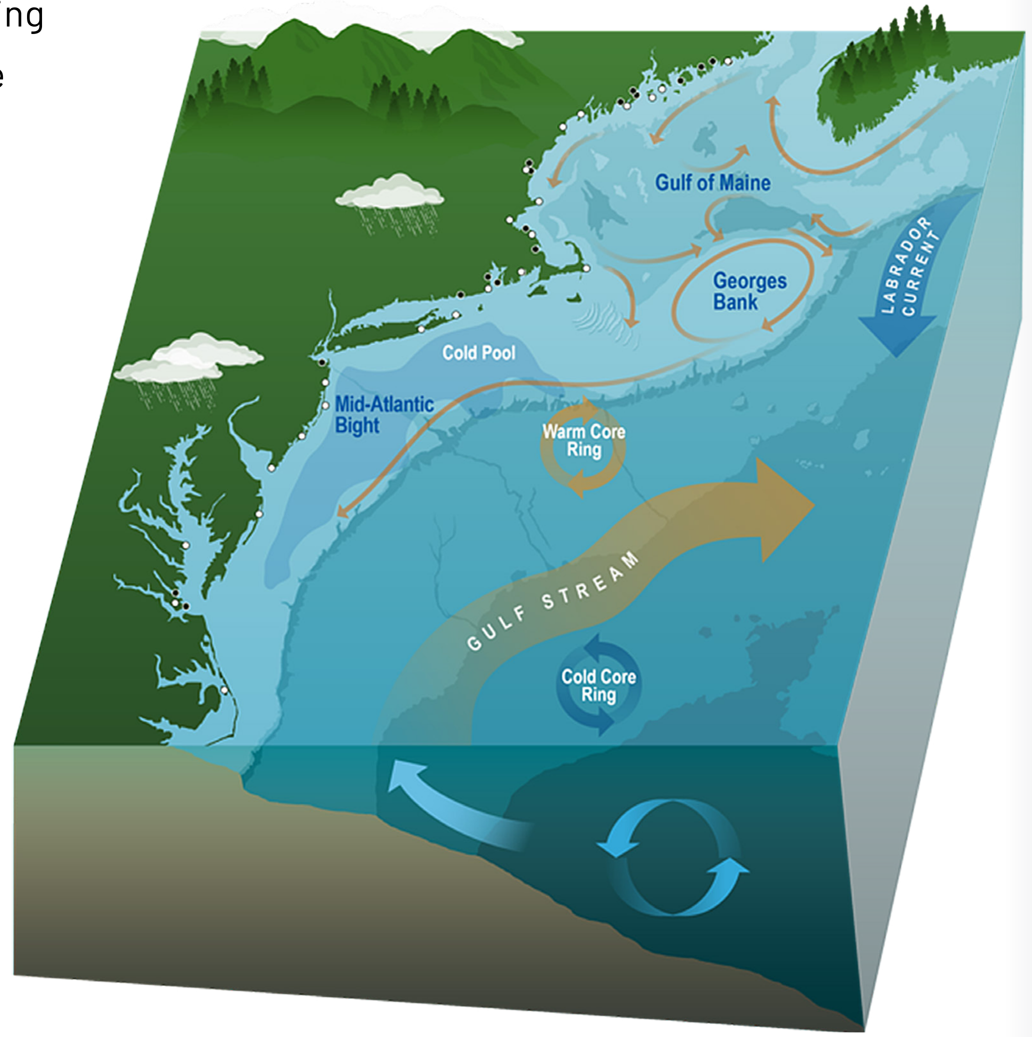
The remote monitoring of phytoplankton allows researchers to make sense of large-scale and long-term patterns and identify ways to increase resilience and reduce risk of ecosystem decline or collapse. But chlorophyll-a concentration (phytoplankton abundance) is not enough to understand the consequences of environmental change on the base of the marine food web. Understanding phytoplankton community composition and size distribution is also needed to better predict timing and extent of ecosystem production. Several satellite-derived ocean color algorithms are available that estimate phytoplankton functional type and size class, but on a global scale across deep seas. Why is this a problem? As Dr. Hyde explains, these algorithms "were developed for the global ocean and not for coastal and continental shelf regions where the optical properties and phytoplankton composition are different from the open ocean."

Why does this matter? The answer, in part, is that many localized coastal communities rely on commercial and recreational fishing to support their economies—industries dependent on a healthy phytoplankton population in the nearshore environment, like that of the Northeast U.S. Continental Shelf. This region is one of the world's most productive marine ecosystems but is also one of the fastest warming on the planet. Detecting and tracking changes over time is critical for understanding the impact to primary productivity and fisheries. To address this, Hyde and her colleagues regionally tuned several existing satellite ocean color algorithms to determine the best one for monitoring phytoplankton in the Northeast U.S. Continental Shelf. At the May 2022 JPSS Science Seminar, she and her NOAA NEFSC colleague, Dr. Ryan Morse, provided an update on their work that includes major contributions from Dr. Colleen Mouw, Kyle Turner[2], and Audrey Ciochetto from the University of Rhode Island, Graduate School of Oceanography.

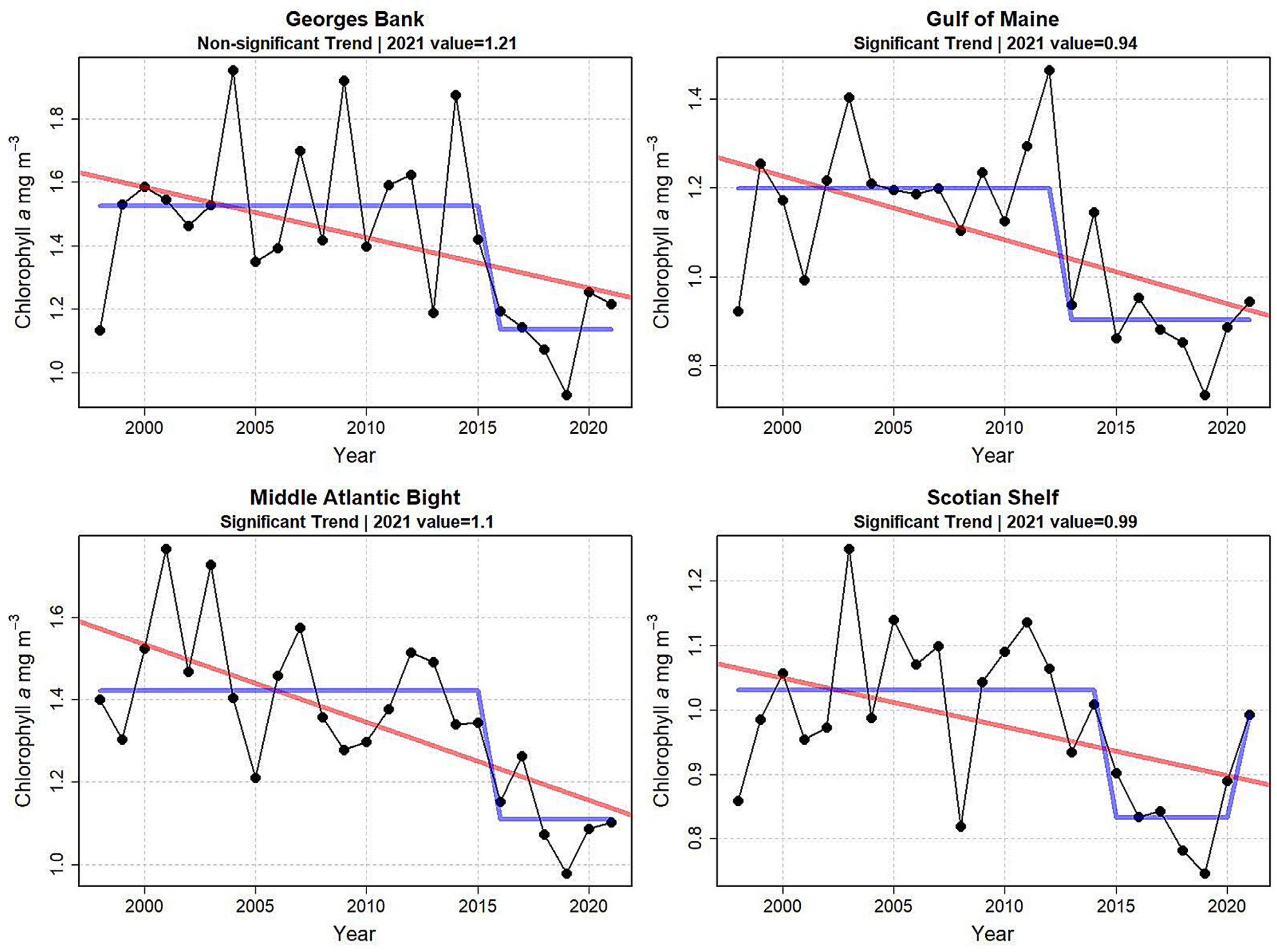
FROM GLOBAL TO REGIONAL: IMPROVING OCEAN COLOR ALGORITHMS IN THE NORTHEAST U.S. CONTINENTAL SHELF

The Northeast U.S. Continental Shelf extends from Cape Hatteras, North Carolina to the Gulf of Maine. This highly dynamic and productive ecosystem supports several important fisheries that depend on phytoplankton as fuel for the marine food web. The importance of commercial fishing in this area is considerable. In 2019, the industry generated about $2 billion in landings[3] revenue and supplied nearly 350,000 jobs, making phytoplankton vital to the coastal communities in this region.

But this ecosystem is changing, which is of great concern because shifts in the timing, location, or species composition of phytoplankton blooms can have dramatic impacts on carbon cycling and the fate of important commercial and protected species. Phytoplankton rely on the availability of light and nutrients, and as



The geographic area of the Northeast U.S. Continental Shelf region. It includes the Mid-Atlantic Bight, Georges Bank, and the Gulf of Maine. The region is influenced by the Gulf Stream from the south and the Labrador Current from the north.



CLICK IMAGE TO ENLARGE. Mean chlorophyll concentration for the first six months of each year. The red lines show the linear trend, the titles indicate the trend's significance, and the blue lines represent change points. Credit: NOAA Fisheries, https://www.fisheries.noaa.gov/new-england-mid-atlantic/ecosystems/current-conditions-northeast-us-shelf-ecosystem-fall-2021.

surface temperatures increase, so does stratification, which limits mixing of deep water nutrients to the surface. In addition, the spring bloom is becoming smaller in magnitude as the graphs above show that total chlorophyll-a concentration is trending down in the Northeast U.S. Continental Shelf.

The timing of blooms is also changing. Blooms are starting earlier leading to mismatches with zooplankton and other creatures that feed on them, which show up later in the year. These missed feeding opportunities impact food web stability. Evidence also suggests that phytoplankton in the Northeast U.S. Continental Shelf are becoming smaller—this is meaningful because a size shift can have significant effects on the food web, too. Size is a fundamental trait that defines phytoplankton's role in the ecosystem and serves as a key indicator of marine ecosystem health. Phytoplankton size affects carbon cycling, growth rate, and the amount of energy transfer to organisms higher up the food chain. Hyde

Food Webs

Food webs represent the ***flow of food energy*** *and* ***feeding relationships*** *between organisms. Primary producers, like phytoplankton, are at the lowest trophic level. The next highest level is made up of organisms that feed on primary producers. Succeeding groups feed on the groups before them. The path can form either a one-way flow (chain) or a complex food web.*

explains, "The significant changes in phytoplankton biomass and production we are observing are propagated up through the food web and ultimately control fisheries production—larger phytoplankton are more efficiently transferred up the food chain, while the energy from smaller phytoplankton species is mostly tied up in the microbial loop." These different pathways in the food web are key reasons why Hyde's research team is using regionally tuned ocean color algorithms to understand changes in phytoplankton community composition in this important region.

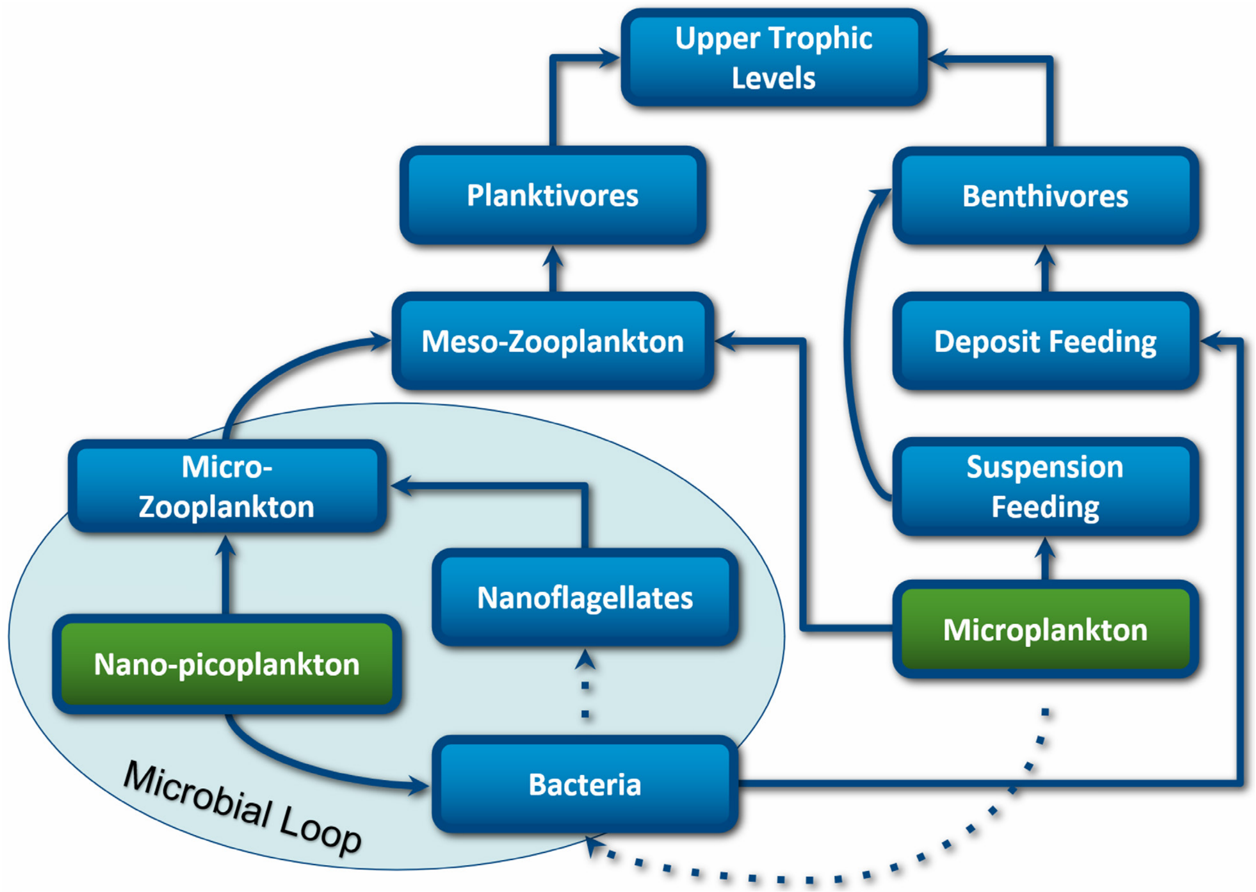


Diagram showing different pathways in the food web. Larger phytoplankton (micro-) are more efficiently transferred up the food chain, while the energy from smaller phytoplankton (nano- and pico-) are mostly tied up in the microbial loop where bacteria and microzooplankton feed on them and recycle nutrients. In this way, dissolved organic carbon is returned to higher trophic levels via its incorporation into bacterial and zooplankton biomass, which is consumed by higher trophic level species.

Satellite-derived Phytoplankton Functional Type Algorithms

In the last 10-15 years there has been a lot of progress in the development of satellite ocean color products, especially phytoplankton functional type (PFT) algorithms. Satellite-derived PFT algorithms are grouped by their output classification—phytoplankton taxonomic class (PTC), phytoplankton size class (PSC), or particle size distribution (PSD)—and algorithm development type (abundance-, radiance-, absorption-, or scattering-based), as shown in the diagram. For their study, Hyde's team focused on detecting PSCs with abundance- and absorption-based algorithms, two of the most frequently used for phytoplankton size classification.

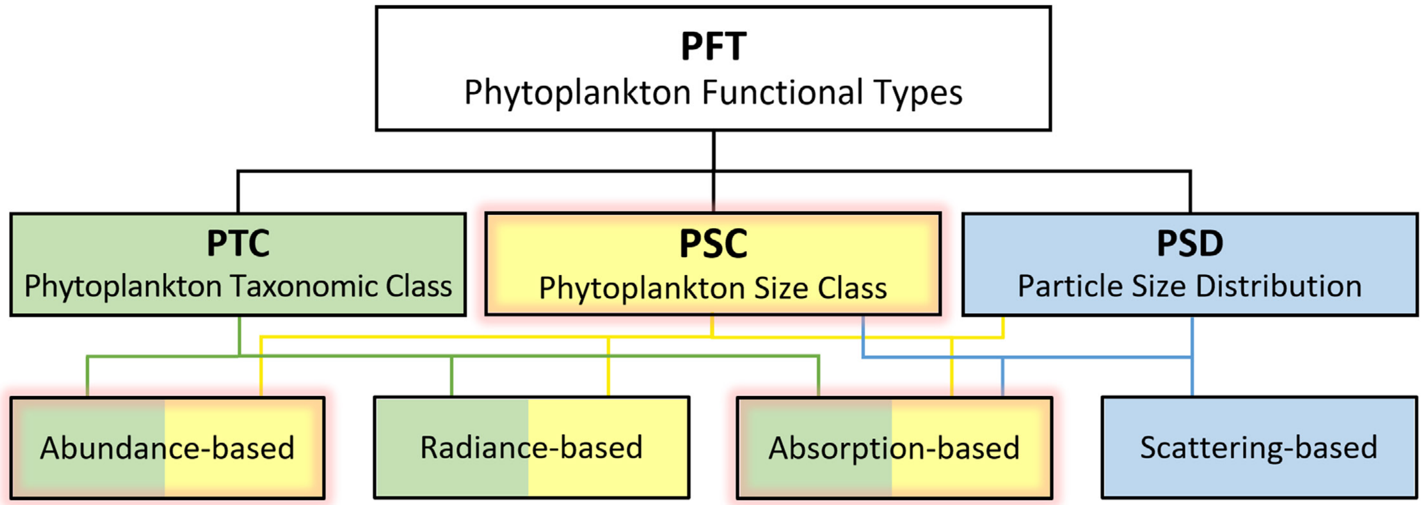
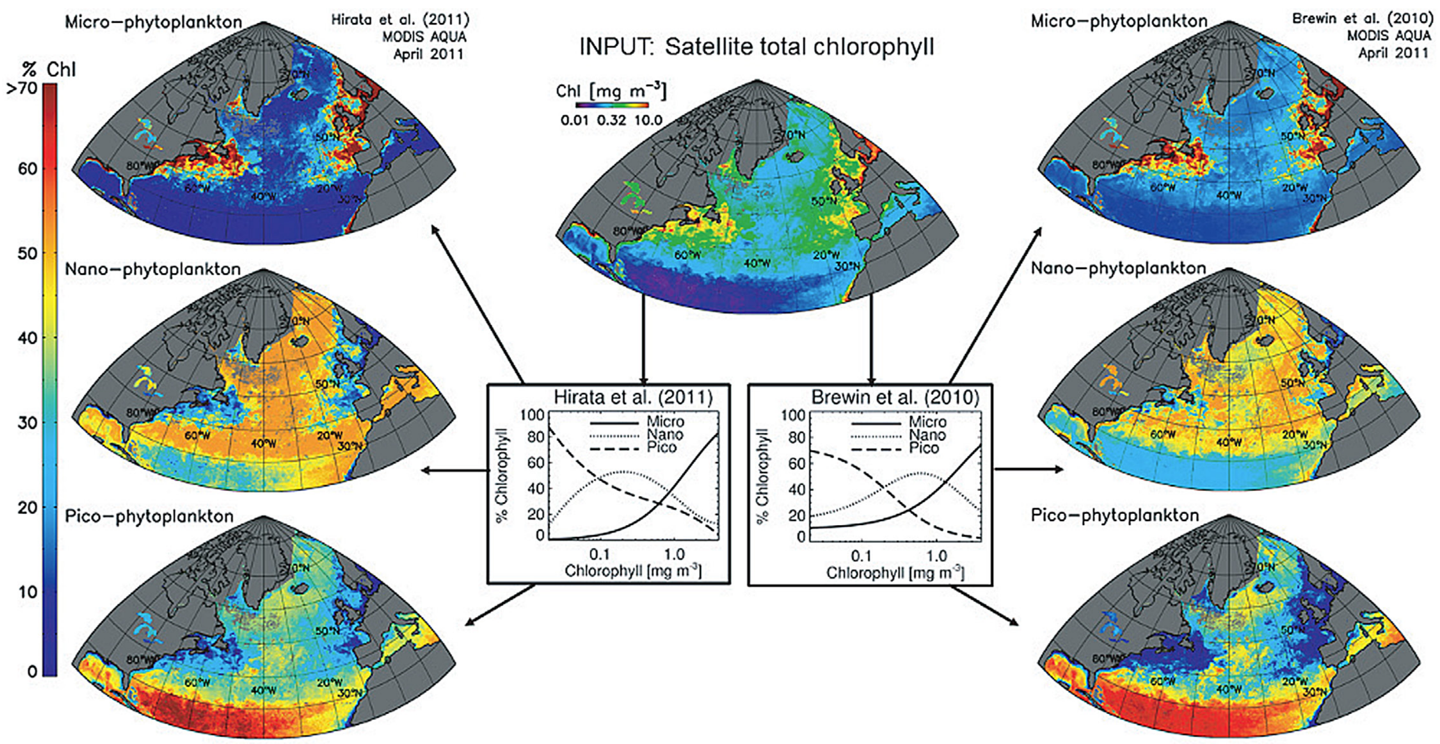


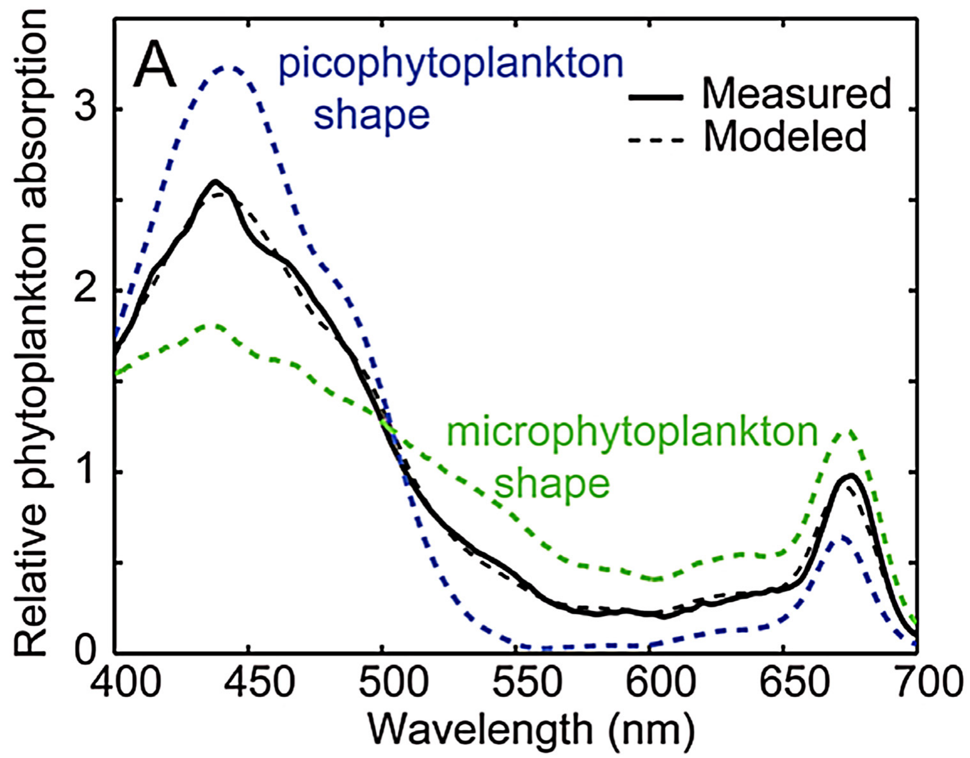
Diagram of various phytoplankton functional type (PFT) algorithms grouped according to their output classification (PTC, PSC, or PSD) and algorithm development types, which are classified according to their theoretical basis: abundance-, radiance-, absorption-, and scattering-based approaches. Color indicates the output classification of phytoplankton taxonomic class (PTC, green), phytoplankton size class (PSC, yellow) or particle size distribution (PSD, blue). Source: Mouw et al. 2017.

Satellite-derived PSC algorithms typically assign phytoplankton to one of three "size" groups: picophytoplankton (0.2–2.0 μm), nanophytoplankton (2–20 μm), or microphytoplankton (20–200 μm) (by comparison, the width of a human hair averages about 70 μm). Abundance- and absorption-based PSC algorithms differ in theoretical basis and satellite data inputs. Satellite abundance-based PSC algorithms use chlorophyll as an indicator for phytoplankton cell size. This approach is based on the association between changes in chlorophyll-a concentration and changes in phytoplankton cell size or biomass. A higher chlorophyll-a concentration is usually associated with larger (micro-) phytoplankton. While easy to implement, this approach mostly relies on the relationship between diagnostic pigments (from diagnostic pigment analysis, a standard reference method for determining the ratio of pico-, nano-, and microphytoplankton in a population) and observed chlorophyll-a concentration (from *in situ* samples) that can vary with regional changes. As a result, this approach "requires on-going recalibration as environmental change alters phytoplankton assemblages," says Hyde.



CLICK IMAGE TO ENLARGE. Diagram showing the application of two abundance-based algorithm models to satellite data. The two methods are illustrated using a mapped Level 3 monthly chlorophyll image from NASA's MODIS instrument onboard the Aqua satellite for April 2011. Source: International Ocean-Colour Coordinating Group 2014.

In contrast, satellite absorption-based PSC algorithms are not dependent on chlorophyll-a concentration as an indirect estimate of cell size. Instead, they rely on direct observations of optical signals (reflectance) measured by remote ocean color sensors. Instruments such as VIIRS look at variations in the amount of visible light absorbed by phytoplankton to estimate cell size. Smaller cells are better at absorbing light than larger cells, with the most noticeable change in absorption efficiency at about the 440 nm wavelength, the blue region of the visible light spectrum. However, this approach is open to physiological variability where it can be hard to retrieve small changes in spectral shape or magnitude and to distinguish phytoplankton from other particles with similar absorption signatures, especially in the optically complex waters of the Northeast U.S. Continental Shelf.

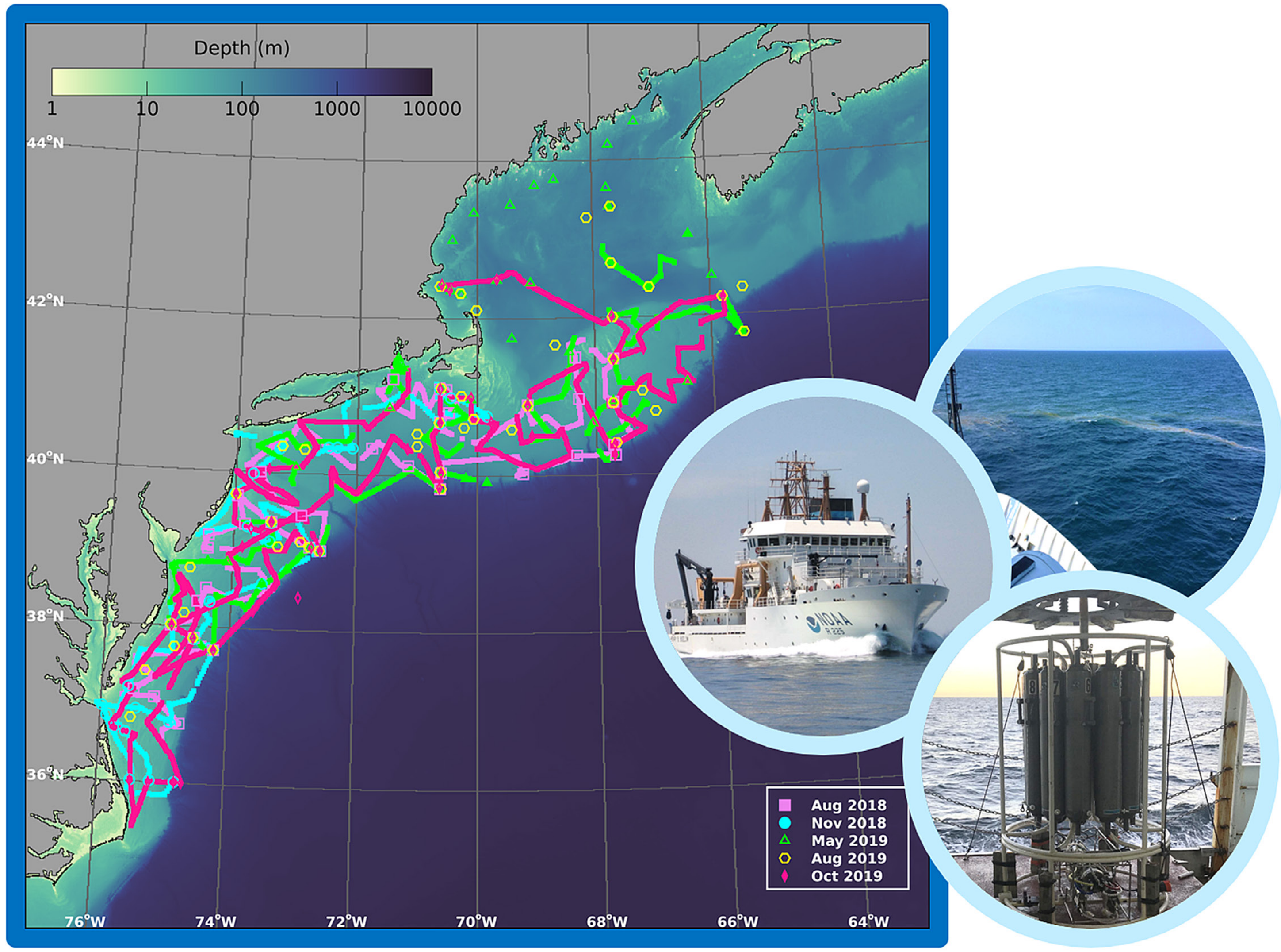


Example of absorption-based algorithm using satellite-based reflectance as the data input.

With some exceptions, satellite-derived PSC algorithms focus on the global ocean, and most are not recommended for use in waters less than 200 meters deep (close to shore). Since abundance- and absorption-based PSC algorithms have their own pros and cons, Hyde's team looked at the performance of each type on a regional level to determine if either or both could be optimized to account for local variations. Their objective was three-fold: (1) find the "best" PSC algorithm for the Northeast U.S. Continental Shelf, (2) compare absorption-based and abundance-based type algorithms, and (3) determine if global models can be regionally improved using *in situ* observations. But to do so, they needed data, and lots of it.

Compiling Ocean Color Time Series Data

Evaluating the performance of any remotely sensed product requires "truth" data for comparison. In this case, the team turned to *in situ* measurements from the Northeast U.S. Continental Shelf waters. Keep in mind that optical properties, pigments, nutrients, and environmental data have different characteristics close to shore versus in the open ocean. To get regional *in situ* data, two team members participated in a selection of survey cruises in 2018 and 2019. The cruises were part of the NOAA Northeast Fisheries Science Center (NEFSC) Ecosystem Monitoring (EcoMon) program[4], which has been collecting plankton and hydrographic data for the Northeast U.S. Continental Shelf since 1992. In addition, the team compiled historical *in situ* data from NASA SeaBASS and NOAA's World Ocean Database—archives of *in situ* oceanographic and atmospheric data—to get good spatial and seasonal data coverage of the region.

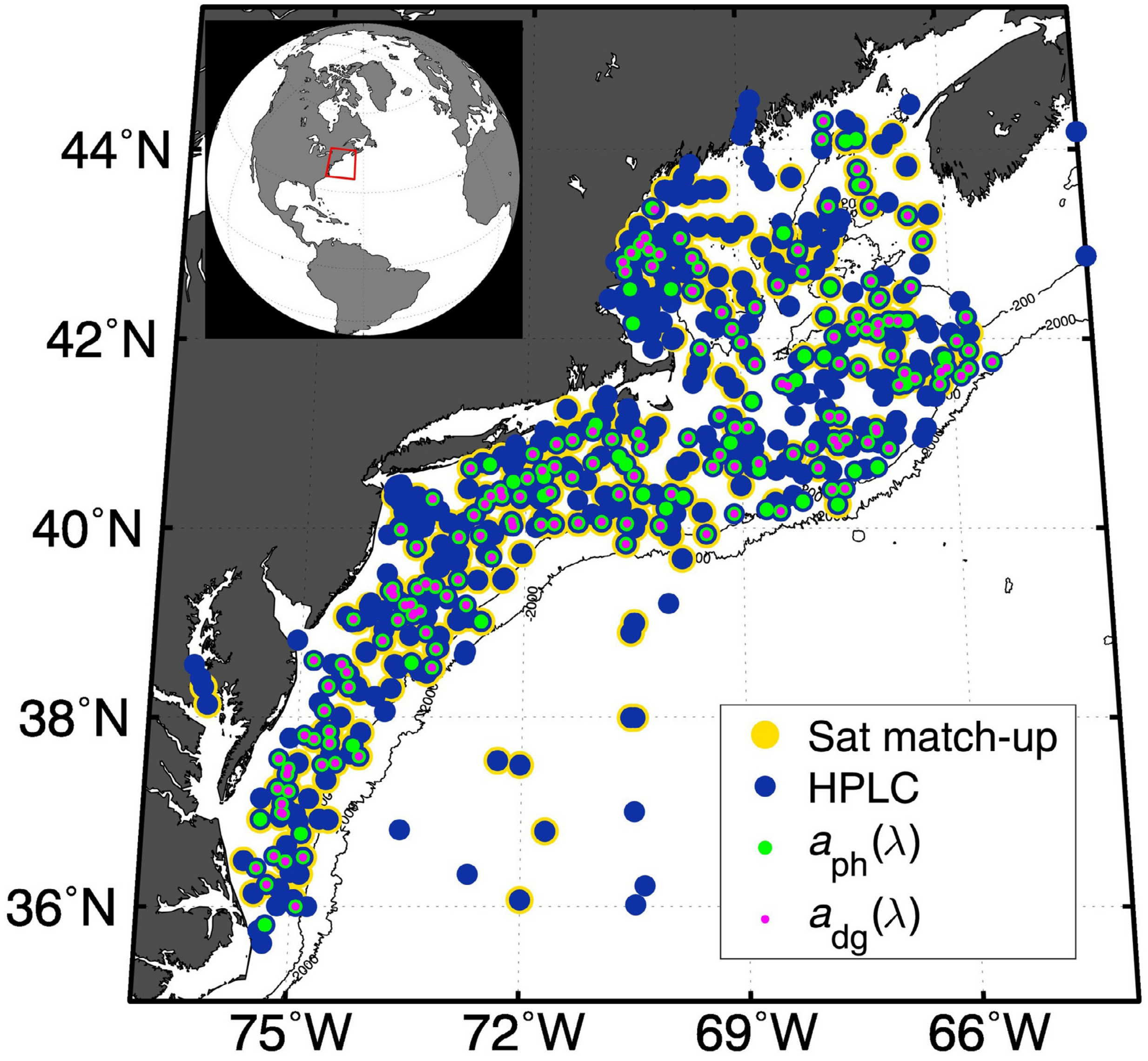


The research team participated in several NOAA Northeast Fisheries Science Center (NEFSC) Ecosystem Monitoring cruises in 2018 and 2019 to collect in situ data for the Northeast U.S. Continental Shelf region. Shown here are sampling locations.

They also needed satellite ocean color data to optimize (re-parameterize, that is, regionally tune) and validate PSC algorithm output for the Northeast U.S. Continental Shelf. Regional estimates of spectral remote sensing reflectance, chlorophyll-a concentration, spectral absorption of phytoplankton, colored dissolved organic matter (CDOM), and non-algal particles (NAP) were pulled from the European Space Agency (ESA) Ocean Colour Climate Change Initiative product (OC-CCI, v4.2). OC-CCI is a blended product—it merges ocean color data from many satellite sensors to provide consistent, timely, high quality, and high resolution data. The version used combines data from JPSS VIIRS (onboard Suomi-NPP), NASA's Moderate Resolution Imaging Spectroradiometer (MODIS-Aqua) and SeaWiFS, and ESA's Medium Resolution Imaging Spectrometer (MERIS).

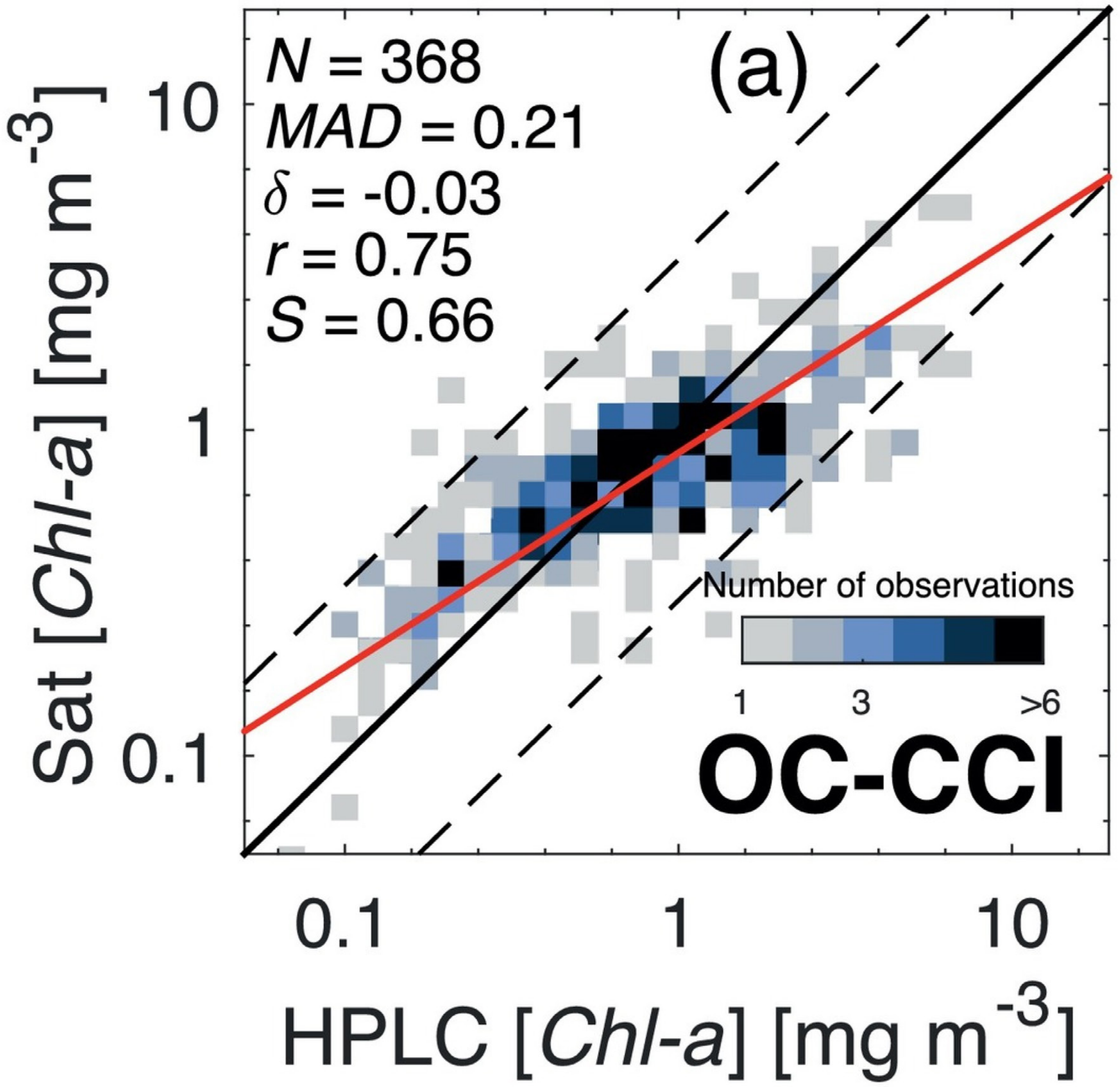
The OC-CCI product spans the entire length of the modern ocean color data record, from 1997 to the present, providing a more complete time series than any individual satellite sensor can offer. Individual sensors, like VIIRS, have a shorter timescale—VIIRS onboard Suomi-NPP has only been collecting data since 2011. By merging data from many sensors, OC-CCI helps fill data gaps that occur with individual sensors from cloud interference, swath width, and other factors. The bottom line: continuation of data across time is critical. No one satellite sensor can provide the entire story and Hyde and her colleagues needed as many suitable ocean color data sources as they could find, which is why they selected OC-CCI as their satellite data source.

Another reason OC-CCI was chosen was because it matches up well with ground-based sampling points. Because of differences in space and time there were not many matchups between VIIRS-derived data and *in situ* data for this study, meaning that VIIRS alone could not be used for optimizing and validating PSC algorithms. But using OC-CCI, the team was able to match and validate an adequate number of satellite data points to *in situ* samples (below). They found that nearly half (47%) of OC-CCI satellite-derived chlorophyll-a data points matched with *in situ* data. These *in situ* matchups served as the PSC algorithm validation dataset. The unmatched *in situ* data were used to regionally fine tune a selection of PSC models (parameterization dataset).



Locations of the in situ data (blue, green, and red dots) and satellite match-ups (yellow dots) used in this study. HPLC refers to chlorophyll pigment, $a_{ph}(\lambda)$ refers to the spectral absorption of phytoplankton, and $a_{dg}(\lambda)$ refers to colored dissolved organic matter (CDOM), and non-algal particles (NAP). The 200m and 2000m isobaths from the 2019 General Bathymetric Chart of the Oceans are shown for reference. Source: Turner et al. 2021.

PSC algorithm output is only as good as the data that is fed to the model, so Hyde's team also validated the OC-CCI product in the Northeast U.S. Continental Shelf—regional performance versus global—to make sure it was suitable as an input for the region. While they found that on a regional level the OC-CCI product overestimates chlorophyll-a at low concentrations and underestimates chlorophyll-a at high concentrations (when compared to *in situ* measurements), this is a known bias with abundance-based algorithms and was expected. OC-CCI product performance was consistent with ESA product validation, and the product was found to be a reliable data source.

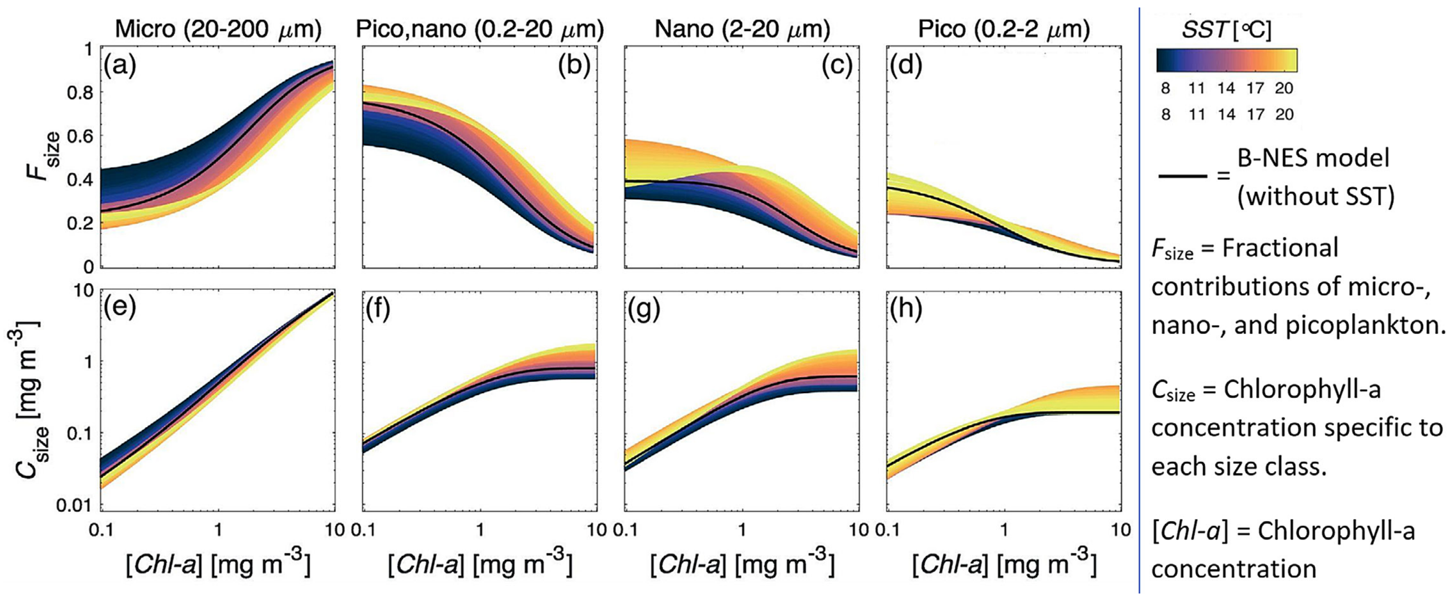


Comparison of chlorophyll-a concentration estimated with OC-CCI (Sat [Chl-a]) and in situ measurements (HPLC [Chl-a]). The solid black line is the 1:1 line, dashed black lines indicate the 1:1 line ±30%, and the red line is the Type-II regression line. N denotes the number of match-ups, MAD denotes the mean absolute difference, δ denotes the bias, r denotes the correlation coefficient, and S denotes the regression slope. The darker colored boxes indicate more observations so that most samples were of average concentration. Source: Turner et al. 2021.

Evaluating and Validating Regionalized Phytoplankton Size Class Algorithms

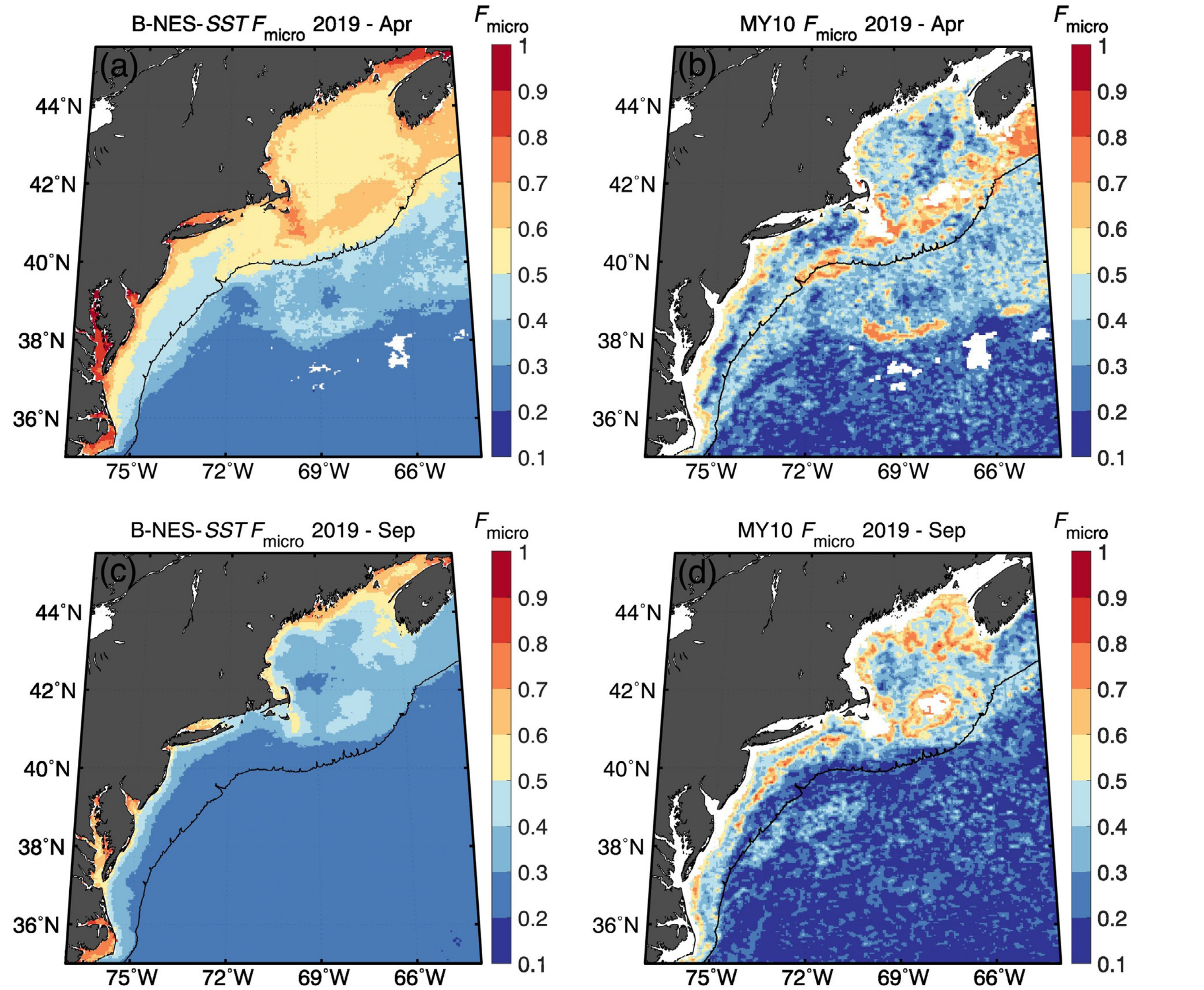
The team applied several statistical approaches to assess and compare the impact of regional tuning (regionalization) on a selection of existing PSC algorithms—in other words, how well do the models perform with *in situ* and/or satellite data as inputs (chlorophyll-a concentration and other variables) for the Northeast U.S. Continental Shelf region. Abundance-based PSC models and absorption-based PSC models were evaluated and validated separately.

They found that for abundance-based algorithms (using *in situ* data as the input) regionalization did not significantly improve performance of the models in the region. But something interesting happened when satellite-derived sea surface temperature (SST) was added to the mix—abundance-based algorithm accuracy significantly improved across all phytoplankton size classes. In the graphs below, the color gradient illustrates how algorithm performance varies with SST, meaning that sea surface temperature is likely an influencing factor in the regionalization of abundance-based PSC algorithms, a finding that is consistent with other study results.



Comparison between the "B-NES" abundance-based PSC algorithm without SST (black line) and the "B-NES" abundance-based PSC algorithm with SST added (color gradient). Modeled F_{size} (a-d) and C_{size} (e-h) from the B-NES-SST model are plotted as a function of chlorophyll-a concentration ([Chl-a]), with the color gradient illustrating the changes in the model when model parameters vary as a function of sea surface temperature. The black line indicates the sea surface temperature-independent model, with a single set of model parameters (B-NES). Source: Turner et al. 2021.

The performance of absorption-based algorithms was close to that of the abundance-based models. Most notably, the best performing of the absorption-based group ("MY10"[5]) had similar performance to the regionalized abundance-based model with SST added ("B-NES-SST"). Their similarities and differences are shown below in the satellite imagery comparison for F_{micro}, the fractional contributions of microplankton (below). Ultimately, Hyde and her colleagues determined that the best algorithm for optically complex regions like the Northeast U.S. Continental Shelf was the "B-NES-SST" model because it is easy to implement and benefits from the addition of sea surface temperature.



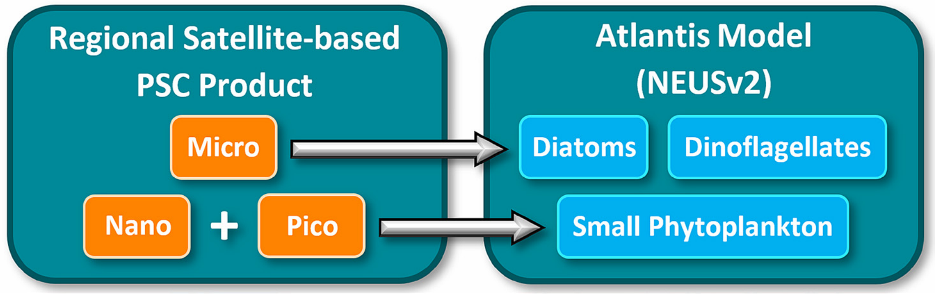
Ocean color imagery monthly composites showing variations in spatial-seasonal features of phytoplankton size classes in the Northeast U.S. Continental Shelf. The images are a comparison of monthly F_{micro} imagery from the B-NES-SST and MY10 algorithms for April 2019 (a, b) and September 2019 (c, d). The MY10 algorithm applies a 2-D average filter, masks pixels that exceed defined thresholds of [Chl-a] and a_{dg}(443) (plotted in white), and bins F_{micro} to increments of 0.1. The color scale for the B-NES-SST imagery was modified to match the output of the MY10 algorithm. The black line indicates the 400 m isobath to mark the approximate location of the shelf break. Source: Turner et al. 2021.

While regional tuning alone did not significantly improve PSC model performance, the researchers concluded that sea surface temperature enhances abundance-based PSC prediction accuracy overall. "Inclusion of sea surface temperature into an abundance-based algorithm framework significantly improves phytoplankton size class estimates, and absorption-based models in their original configuration (not optimized) perform as well as the regionally optimized abundance-based models with sea surface temperature included," notes Hyde. Additional details about the regional performance of the algorithms included in this study can be found in the publication: *Optimization and assessment of phytoplankton size class algorithms for ocean color data on the Northeast U.S. continental shelf.*[6]

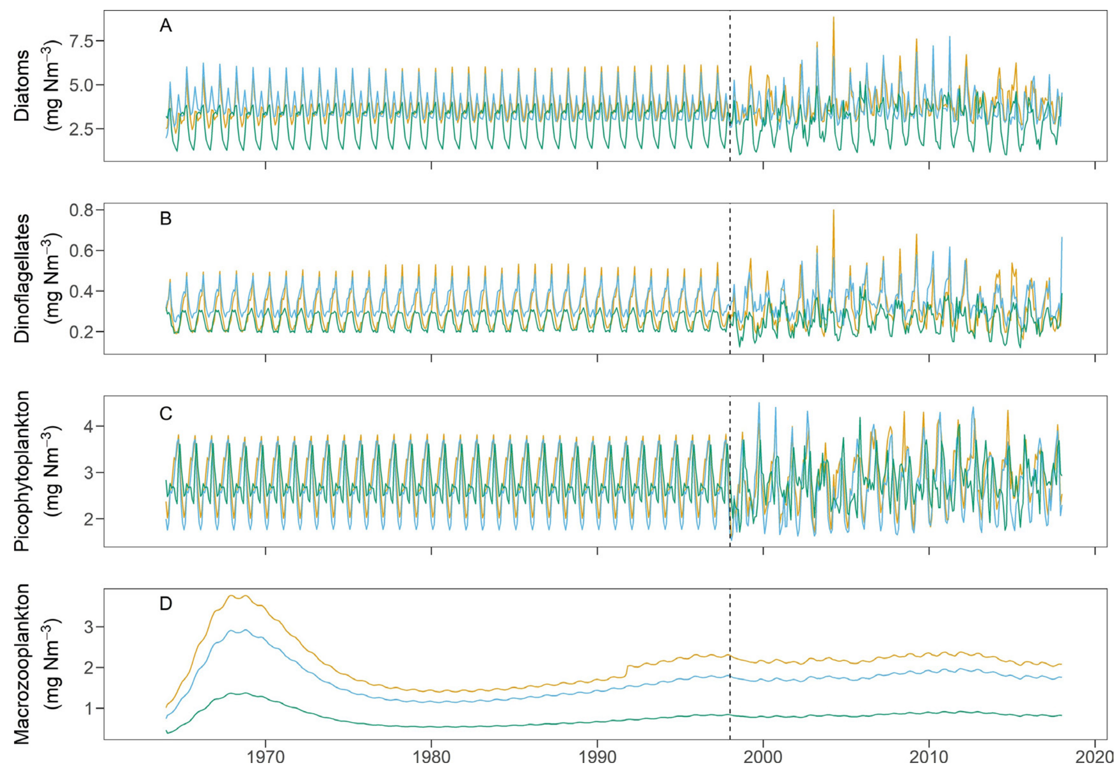
APPLICATIONS OF REGIONALLY TUNED PHYTOPLANKTON SIZE CLASS DATA

Having determined the best satellite-derived PSC algorithm for the Northeast U.S. Continental Shelf, this new regionalized data can be used to promote more accurate and timely decision making. Phytoplankton size class is now part of models that look at interannual variability, which is reported in the annual NEFSC State of the Ecosystem Reports for the Northeast U.S. Continental Shelf[7], as well as in other outreach materials provided to local decision makers, like fisheries management councils. PSC data is also being used in risk assessment and scenario planning. As the ecosystem changes, assessment models and biological reference points for specific fisheries also need to change. Chlorophyll and primary production data from ocean color sensors (by way of PSC algorithms) are needed to assess trends over time and look for correlations with fishery stock performance. "We're trying to take a more holistic approach to understanding how ecosystem changes are affecting fisheries and how we should alter our management advice," Hyde says.

The new phytoplankton size class data is also being used to force the Northeast U.S. Atlantis ecosystem model, which considers all aspects of the marine ecosystem and is used to address multiple fisheries and climate related questions. "Forcing" is a method used in modeling to improve model performance. In this case, "we are 'forcing' the [Atlantis] model to use real phytoplankton data instead of the model calculating the phytoplankton variables using other parameters, such as light, nutrients, and temperature," Hyde explains. Specifically, they are using the new phytoplankton size class data to inform lower trophic level forcing of phytoplankton groups, which was the subject of a recently published paper, *A northeast United States Atlantis marine ecosystem model with ocean reanalysis and ocean color forcing.*[8]



Using data from the regionalized PSC algorithm along with "spin up" climatology data from the 1960s to 1998, the researchers generated a time series for each phytoplankton size class that is valuable for ecosystem studies (example below). Climatology is the study of the Earth's climate, typically defined as weather conditions averaged over a period of at least 30 years. Climatology data is important because it shows how the climate is changing and offers clues about what the future may hold. In this case, the time series generated provides more realistic input and much better results for the lower trophic levels in the Atlantis model. Hyde emphasizes, "The most important thing is to have these long term time series' to better understand the ecosystem changes over time."



Monthly standardized biomass for select Atlantis model (NEUSv2) functional groups and for each ecological production unit (Georges Bank - orange, Gulf of Maine - blue, and Mid-Atlantic Bight - green). Panels show biomass as a volume-standardized concentration (mgN m−3). Vertical lines show the end of the defined spin-up period. Source: Caracappa et al. 2022.

NEXT STEPS

Within NOAA Fisheries there is a strong focus on ecosystem-based approaches to management, as well as an emphasis to monitor changes in the oceans including how climate change impacts phytoplankton species composition and the marine food web. "When looking at the ecosystem it is important to understand that there are multiple ecosystem level drivers including bottom up physical and chemical influences as well as top down biological processes," says Hyde. To support this, she and her colleagues are taking their work a critical step further by using the new phytoplankton size class data from the regionalized PSC algorithm to look at changes in phytoplankton composition distributions over the satellite record going back several decades. "Now that we have almost a quarter century's worth of ocean color data," she explains, "we can observe these long term patterns, changes in the timing and spatial extent and the duration and magnitude of blooms." This is of critical importance for understanding the impact to the marine food web over time and incorporating that information into fisheries management.

Given the critical role of phytoplankton in the food web and their diverse functions across different taxonomic groups, this research is important to advance fisheries modeling and better inform decision making. The critical data produced supports the NOAA Fisheries mandate to ensure the productivity and sustainability of fisheries and fishing communities through science-based decision-making and aligns with the NOAA Climate and Fisheries Initiative to better understand and adapt to changing ocean conditions that are affecting the base of the food web.

THE FUTURE OF OCEAN COLOR SATELLITES

The next generation of ocean color satellites are being launched, starting with Joint Polar Satellite System-2 (JPSS-2, renamed NOAA-21 after it reached orbit) on November 10, 2022, the second of NOAA's latest generation of polar-orbiting environmental satellites. Onboard is a new VIIRS instrument that promises better data than previous versions thanks to its redesigned focal plane arrays and improved performance metrics. NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite, scheduled for launch in 2024, is even more exciting. It will provide enhanced spatial and temporal resolution and hyperspectral capability, meaning it looks beyond the rainbow by measuring enough wavelengths to approximate the full spectrum of light, including ultraviolet and near-infrared bands. PACE's Ocean Color Instrument (OCI) will be the most advanced for observing ocean color in NASA's history and will greatly improve characterization of the complex waters of the Northeast U.S. Continental Shelf by providing more accurate detection of phytoplankton functional groups. "For more accurate discrimination of phytoplankton groups, hyperspectral data are essential. I'm very excited to see what we will be able to do with the data coming from NASA's PACE sensor," says Hyde. With these advancements, NOAA Fisheries and others can better understand and manage the impacts of ecological shifts in the critical Northeast U.S. Continental Shelf region. ✦

STORY SOURCE

The information in this article is based, in part, on the May 16, 2022 JPSS Science Seminar "Phytoplankton Size Class Distributions on the Northeast U.S. Continental Shelf" presented by Dr. Kimberly Hyde, Operations Research Analyst and biological oceanographer, and Dr. Ryan Morse, Research Scientist, of the NOAA Northeast Fisheries Science Center (NEFSC), Narragansett, RI, with contributions from Dr. Colleen Mouw (University of Rhode Island Graduate School of Oceanography); Kyle Turner (City University of New York); Audrey Ciochetto (University of Rhode Island Graduate School of Oceanography); Julia Lober (Tufts University); Teemer Barry (University of Maryland Eastern Shore); Chris Melrose (NOAA NEFSC); and Somang Song, Rowan Cirivello, and Virginie Sonnet (University of Rhode Island Graduate School of Oceanography). This article also references the work of Joseph Caracappa (NOAA NEFSC).

FOOTNOTES

1 The most recent data available from NOAA Fisheries.
2 Currently at City University of New York.
3 Landings are the total number or weight of all marine species captured, brought to shore, and sold or transferred to another person or party.
4 https://www.fisheries.noaa.gov/feature-story/monitoring-northeast-shelf-ecosystem
5 Mouw, C.B. and Yoder, J.A. (2010). Optical determination of phytoplankton size composition from global SeaWiFS imagery. Journal of Geophysical Research, 115:C12018. https://doi.org/10.1029/2010JC006337
6 https://doi.org/10.1016/j.rse.2021.112729
7 https://www.fisheries.noaa.gov/new-england-mid-atlantic/ecosystems/state-ecosystem-reports-northeast-us-shelf
8 https://doi.org/10.1016/j.ecolmodel.2022.110038

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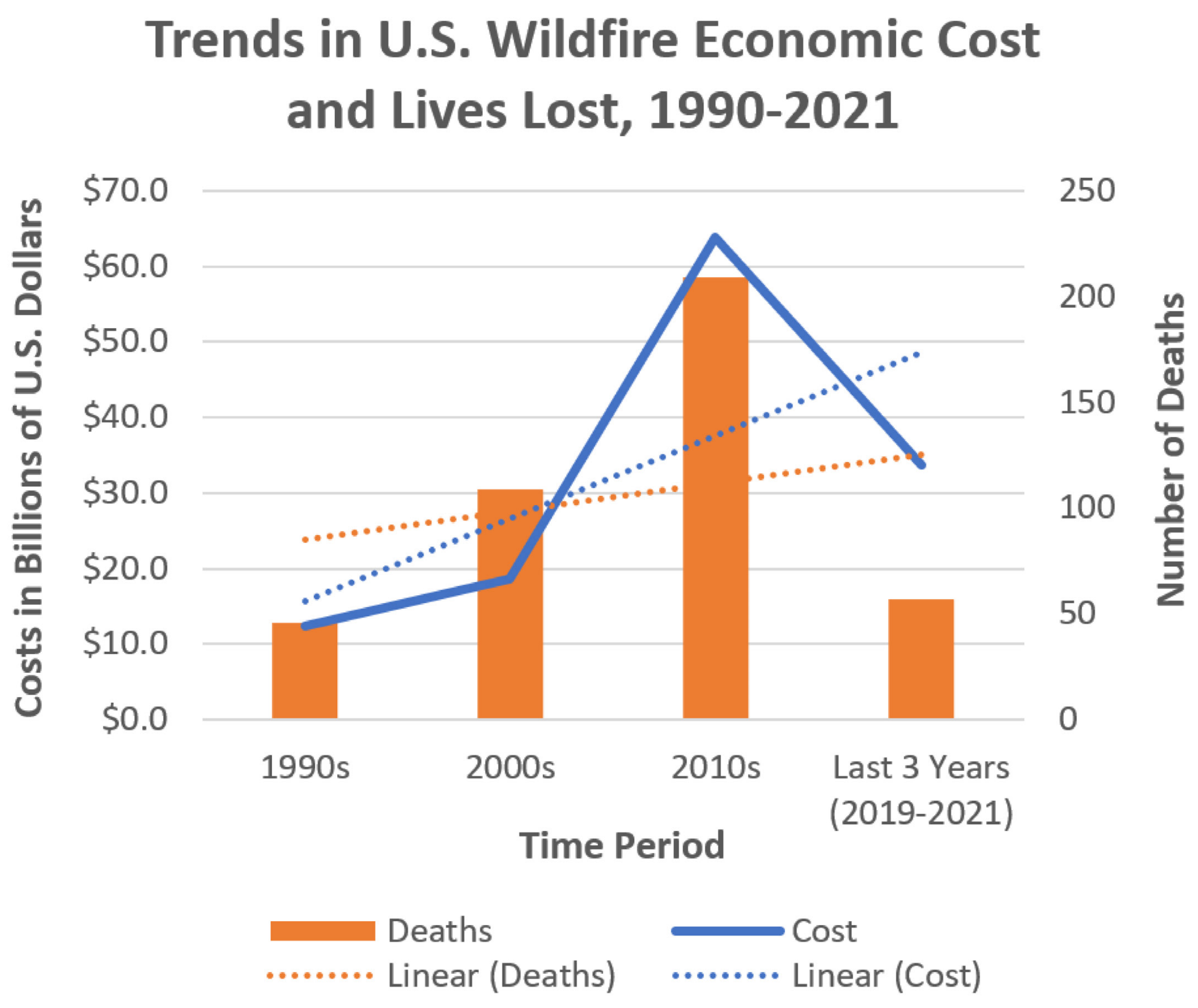
FEATURE 7

Fire Light at Night:

Quantifying Fire Combustion Phase Using the Visible Infrared Imaging Radiometer Suite (VIIRS)

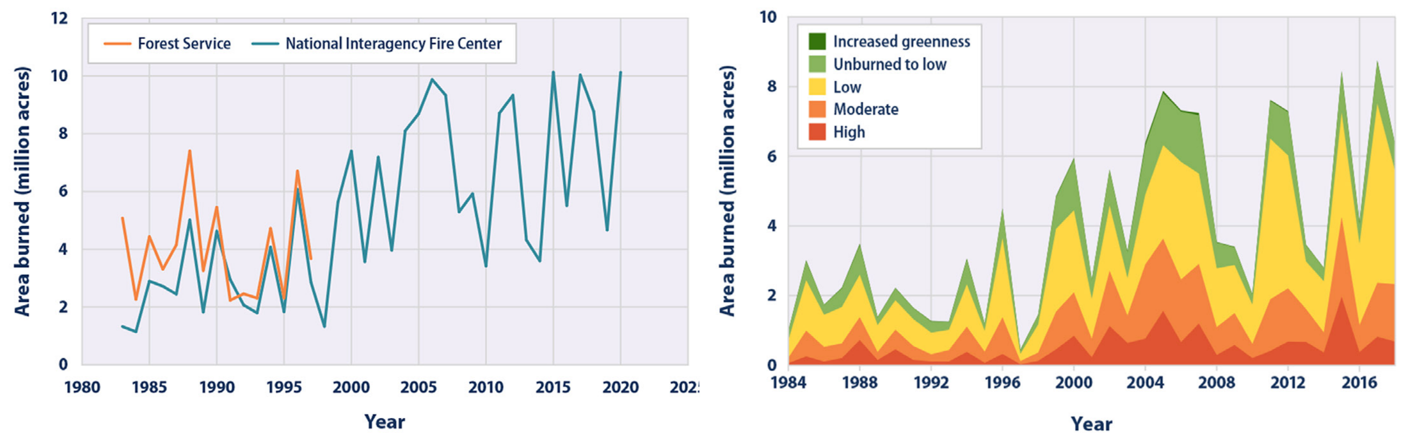
The Woosley Fire burns brush and timber through the night near Malibu, California, November 2018. Source: Peter Buschmann, USDA Forest Service. https://csl.noaa.gov/projects/firex-aq/science/goals.html



Data source: NOAA National Centers for Environmental Information (www.ncei.noaa.gov/access/billions/summary-stats).

In recent years, wildfire has dominated headlines around the globe. Wildfire frequency, extent, and severity are increasing, meaning that more people and communities are impacted than ever before. Wildfire harms human health, property, and livelihoods. From 1990 to 2021 wildfires caused 418 deaths and $123.6 billion in economic losses ($10.8 billion in 2021 alone!) in the U.S., and these statistics are trending upward as shown by the dotted lines (linear trend) in the graph.

Another troubling trend: wildfire season is lengthening. In the U.S., what was typically a four-month season has stretched to seven months or more, starting earlier and ending later. More acreage is burning at a higher intensity than in previous decades, as evidenced by the data graphs at the top of the next page,, and studies make it clear that climate change is a contributing factor. With this comes



CLICK IMAGE TO ENLARGE. Left: Annual wildfire-burned area (in millions of acres) from 1983 to 2020. The two lines represent two different reporting systems though the U.S. Forest Service stopped collecting statistics (orange line) in 1997. Right: The distribution of acreage burned by large wildfires, based on the level of damage caused to the landscape—a measure of wildfire severity. "Unburned to low" indicates no or low burned areas and "increased greenness" indicates increased vegetation growth after a fire was extinguished. Large wildfires are defined as fires with an area larger than 1,000 acres in the western U.S. and 500 acres in the eastern U.S. The total acreage shown on the left is slightly less than the total on the right because the right graph is limited to large fires. Source: U.S. EPA (https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires).

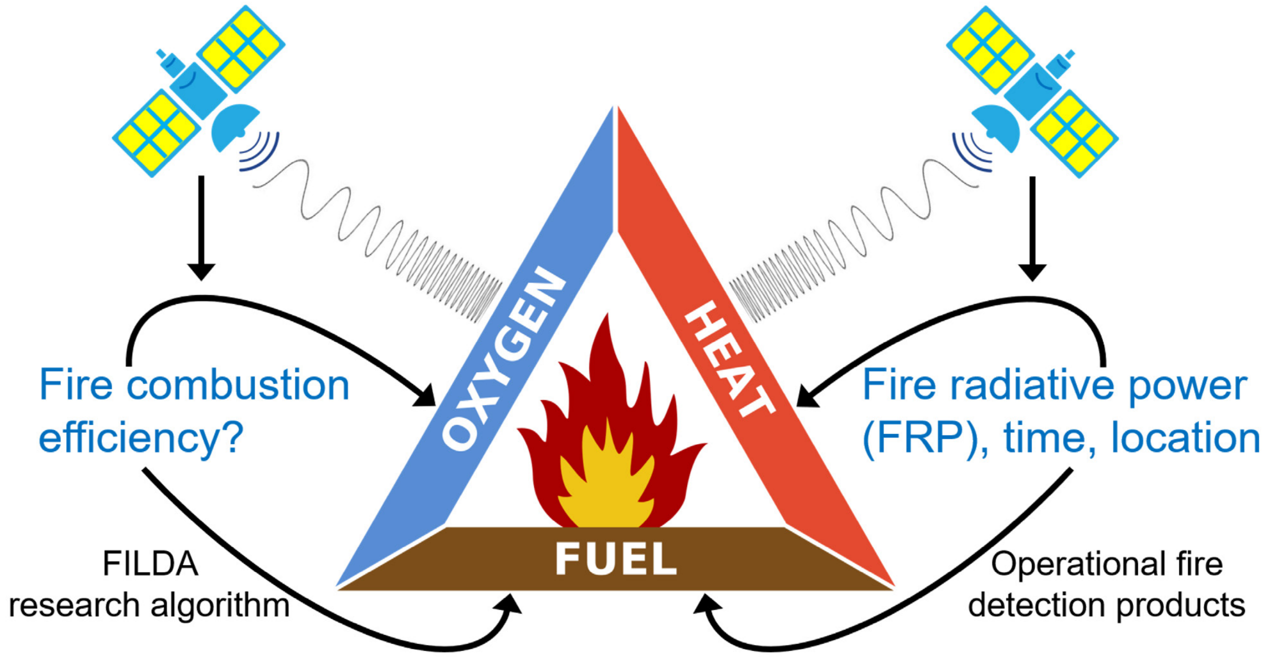
an increase in biomass burning that can cause hazardous air quality and a surge in hospitalizations. Unhealthy air conditions can persist for days or weeks, and wildfire smoke can travel hundreds of miles impacting communities far from the source.

Wildfires are also growing more intense at night, a time that used to mean slower growth from cooler temperatures and higher humidity. But the night air in some regions of the U.S. has become hotter and drier causing little relief during the overnight hours. Case in point: since 2003, the western U.S. has seen nighttime fire intensity increase by 28%. This is worrisome because it is difficult to monitor cooler and smaller fires in the dark with existing operational fire detection methods, which means responders may wake to find that a fire spread overnight in unexpected directions—the dreaded "sunrise surprise."

Climate change, extreme weather, and shifting fire regimes are challenging the status quo and new tools are needed to better characterize fires and their emissions. While many operational satellite data products detect and describe active wildfires, none quantitatively characterize the fire combustion phase. Using data from JPSS' Visible Infrared Imaging Radiometer Suite (VIIRS), Dr. Jun Wang, James E. Ashton Professor in the College of Engineering at the University of Iowa, Interim Chair of the Department of Chemical and Biochemical Engineering, and Assistant Director of the University of Iowa Technology Institute, answered this challenge. Professor Wang and his team developed a novel algorithm that describes the fire combustion phase at the satellite pixel level to improve emission estimates and fire detection at night. At the October 2021 JPSS Science Seminar, Wang shared progress and insights from the development and validation of the new research algorithm called the FIre Light Detection Algorithm (FILDA), as well as related research using VIIRS Day/Night Band to track fire emissions at night that will be discussed in summary.

WHAT THE FIRE COMBUSTION PHASE TELLS US

Fire has three elements: heat, fuel, and oxygen. For agencies to successfully battle fire and smoke, they need meaningful information about these elements, some of which can be measured from space. Current satellite-derived active fire products can estimate fire radiative power (the amount of total radiant energy emitted by a burning fire), fire location, fire size, and fire temperature—all important for understanding heat and fuel types. But less is known about how oxygen and fuel interact, which affects the fire combustion phase (whether a fire is flaming or smoldering) and fire combustion efficiency (the degree to which combustion is completed). Why does this matter? Two reasons: first, the combustion phase impacts how, where, and when firefighters and agencies respond. Second, combustion efficiency influences the accuracy of fire emission factors, which are critical inputs for models used to develop wildland fire emission inventories.



"In the literature, the fire combustion phase is often quantified in terms of modified combustion efficiency, MCE, which is the ratio between the amount of carbon dioxide emitted from a fire and the sum of carbon monoxide and carbon dioxide from that fire," explains Wang. The larger the MCE, the more complete the combustion, meaning that more carbon dioxide (CO_2) is emitted compared with other pollutants like carbon monoxide (CO), soot, organic carbon, particulates, and others. An MCE of 1 means that all carbon emitted was converted to CO_2—there is 100% combustion efficiency, complete combustion.

MCE has a significant impact on fire emission factors. For example, as MCE increases from 0.85 to 0.96, the emission factor for sulfate can grow 10 times larger, while the emission factor for organic carbon can shrink 10 times smaller. Wild swings in both directions! Wang emphasizes, "The importance of fire phase [MCE] for estimating fire emissions cannot be overstated." The issue is that MCE is difficult to estimate remotely for wildfires where flaming and smoldering occurs at once because satellite sensors "see" a mixture of both in each "fire pixel"—the satellite pixel where fire is detected. The FILDA product aims to tackle this problem.

MCE as a Proxy

*Combustion efficiency (CE) is a measure of how effectively a fire converts carbon in the fuel to carbon dioxide (CO_2) emissions. Calculating CE is not practical because it requires measuring all the carbon released during a fire. Instead, a proportion is used as a proxy—**modified combustion efficiency (MCE)**. MCE is the proportion of total carbon emitted by a fire released as CO_2.*

$$MCE = \frac{CO_2}{(CO + CO_2)}$$

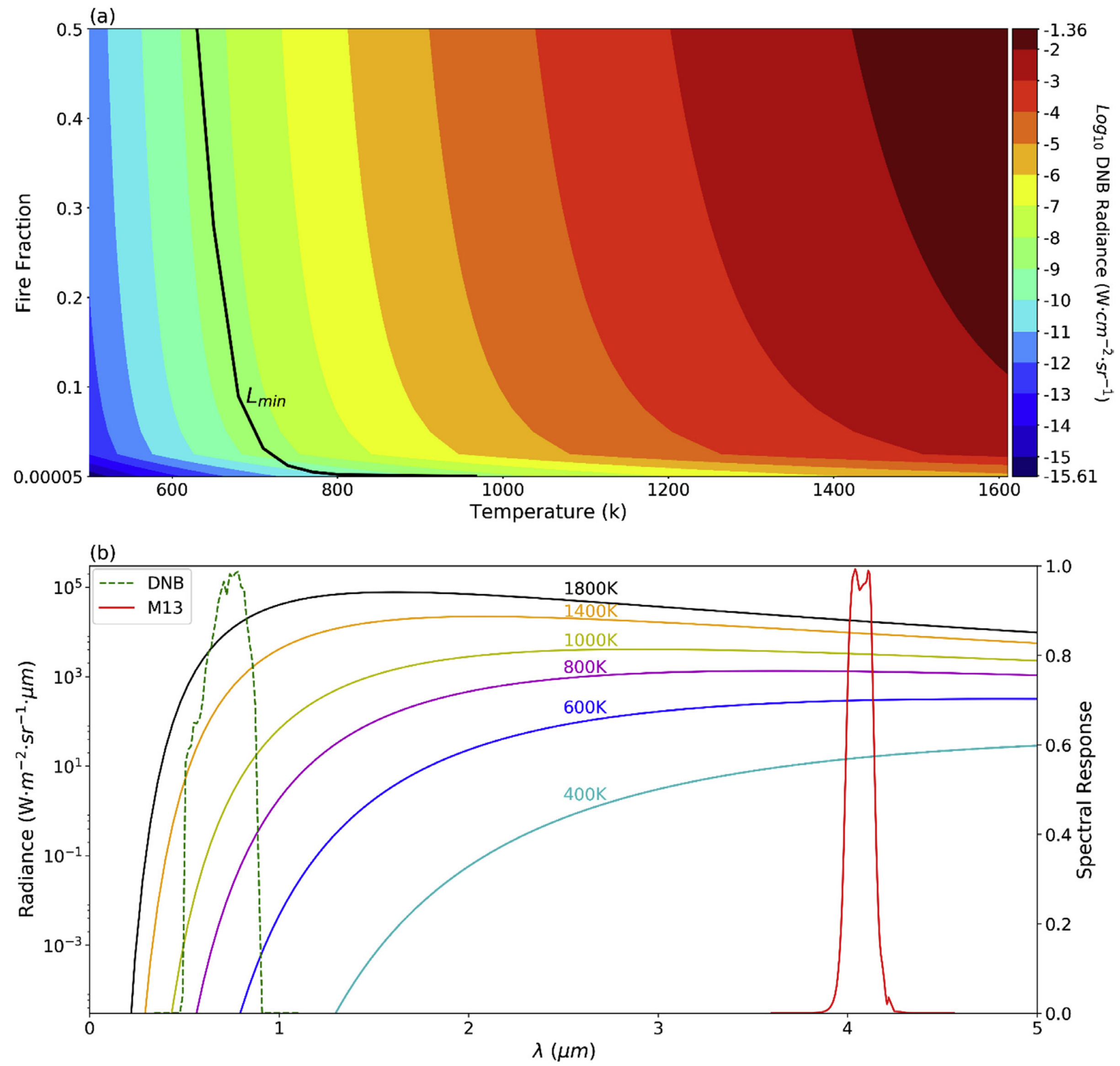
Fire Light: Flaming Versus Smoldering

The fire combustion phase is controlled by temperature, relative humidity, available oxygen, and fuel content. Light is an indication of the fire combustion phase and combustion completeness (efficiency). The flaming phase of a fire occurs above the ground where oxygen is plentiful, while the smoldering phase occurs near or at the surface where oxygen is limited. Smoldering is a slow, low temperature, flameless form of combustion of a solid fuel, like vegetation and wood, unlike flaming, which is high temperature and spreads easily with the wind.

By definition, a fire in the flaming phase emits visible light. Fire that does not emit visible light is defined as smoldering. Wang explains, "This is the key criteria for a flaming fire, it must have visible light, which are shorter wavelengths compared to smoldering fire that has no visible light because it emits radiation at longer wavelengths." Combustion efficiency is based on the principle that if a fire emits light, then it is flaming. More visible light means a greater amount of flaming. Knowing this, Wang saw the potential to link fire light to MCE using satellite data.

USING VIIRS TO CALCULATE FIRE COMBUSTION EFFICIENCY

The VIIRS instrument has three sets of bands that collect observations across visible and infrared (IR) wavelengths at two spatial resolutions, 375 meters (m) and 750 m. High resolution image bands (I-bands) and moderate resolution bands (M-bands) mostly measure infrared (IR) radiation, while the Day/Night Band (DNB) measures visible and near-infrared light. What makes the Day/Night Band unique is its ability to detect low levels of visible light in cloud-free conditions, meaning that it is sensitive to visible light from flaming fires at night. It can detect visible light intensity as low as the equivalent of a fire of 650 Kelvin (710°F/377°C) and 50 square meters (0.0001 area fraction in a Day/Night Band pixel). While 650 Kelvin does not sound like a low temperature, forest fires average about 1000 Kelvin (1472°F/800°C). With its high dynamic range, the Day/Night Band also detects white-hot fires burning at more than 1800 Kelvin (2780°F/1527°C). These capabilities are illustrated by the plots below.

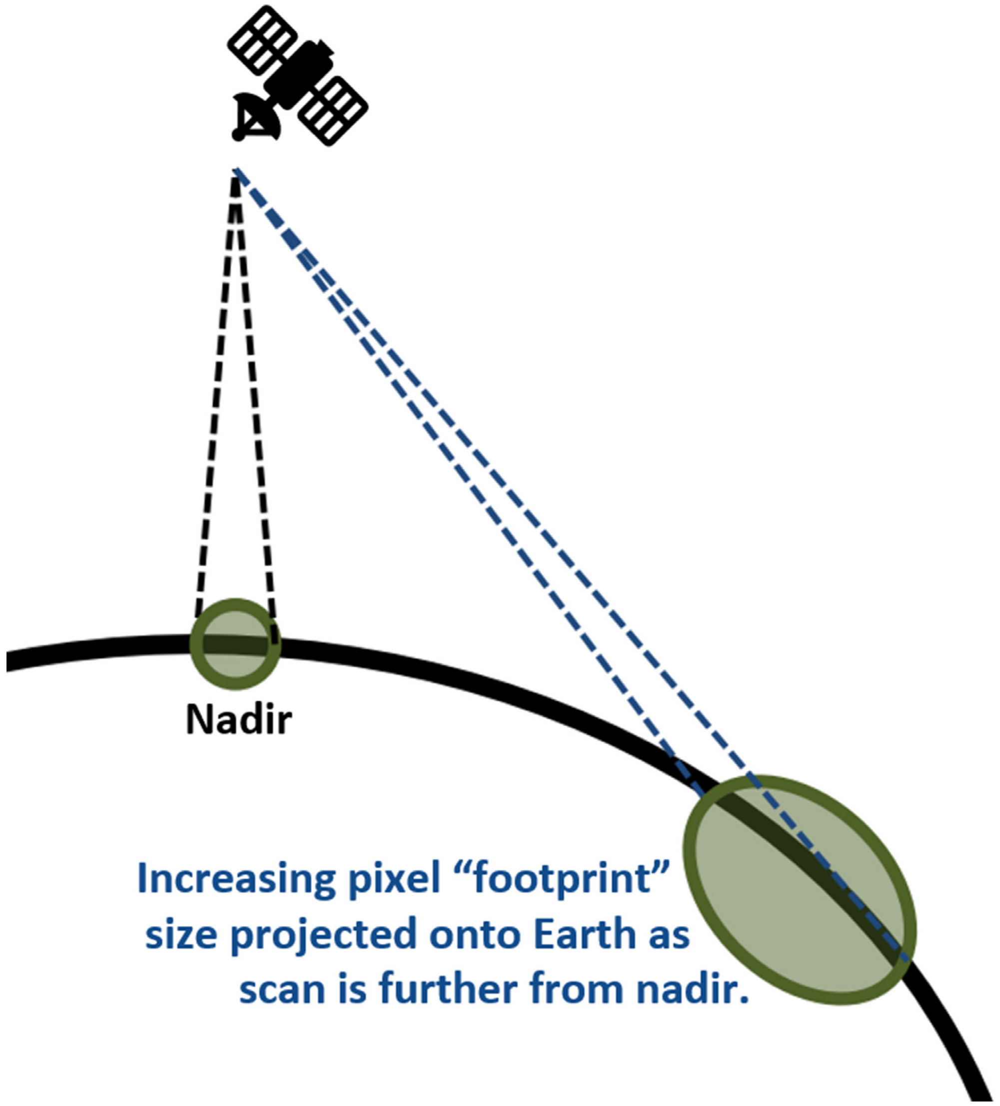


Top (a): Contour plot of simulated VIIRS Day/Night Band (DNB) radiances for different fire temperatures and fractions during nighttime (assuming no lunar or other illumination) using Unified Linearized Vector Radiative Transfer Model. The black line shows the minimum radiance (L_{min}) that DNB sensor can detect. The fires that fall into the left side of the black line are not detectable by DNB sensor. Bottom (b): Plot of VIIRS Day-Night band (DNB) and 4 μm moderate-resolution band #13 (M13) spectral responses along with different Plank curves for different temperatures. DNB is highly sensitive to high temperature (flaming) fires in the night while M13 is sensitive to all fire temperatures. M13 measures mid-infrared radiation while DNM measures visible light. Source: Wang et al. 2020.

VIIRS Day/Night Band imagery on June 12, 2012, showing the High Park Fire alongside city lights from Fort Collins, Greeley, and Loveland, Colorado.

The point is that detection of both small, cool fires and intense, large fires can be improved at night by using the visible light measured from VIIRS. Wang and his team realized this back in 2012, shortly after VIIRS first launched, when they saw the High Park Fire in Colorado clearly visible on VIIRS Day/Night Band nighttime images. The researchers got excited, and Wang wondered, "Can we use that to calculate the fire combustion efficiency?" The short answer is yes; the long answer is that it is complicated.

To Wang, the physics seemed promising because more light means more flaming. But several challenges were met in translating this concept to MCE. First, fires detected in a fire pixel (at the satellite pixel level) are a mix of flaming and smoldering parts and determining the fraction of each at a subpixel level is tricky. Second, to link fire light to MCE, the ratio of visible energy to total radiative energy needs to be known. Third, visible and total radiant energy are measured using different VIIRS bands (Day/Night Band versus M-band) that have differences in their pixel sizes and must be harmonized. To deal with these issues, the team blended and standardized the mismatched VIIRS bands, developed a method to calculate the ratio of visible energy for each VIIRS fire pixel (more on that later), and linked the visible energy fraction values to MCE and emission factors used for global modeling.

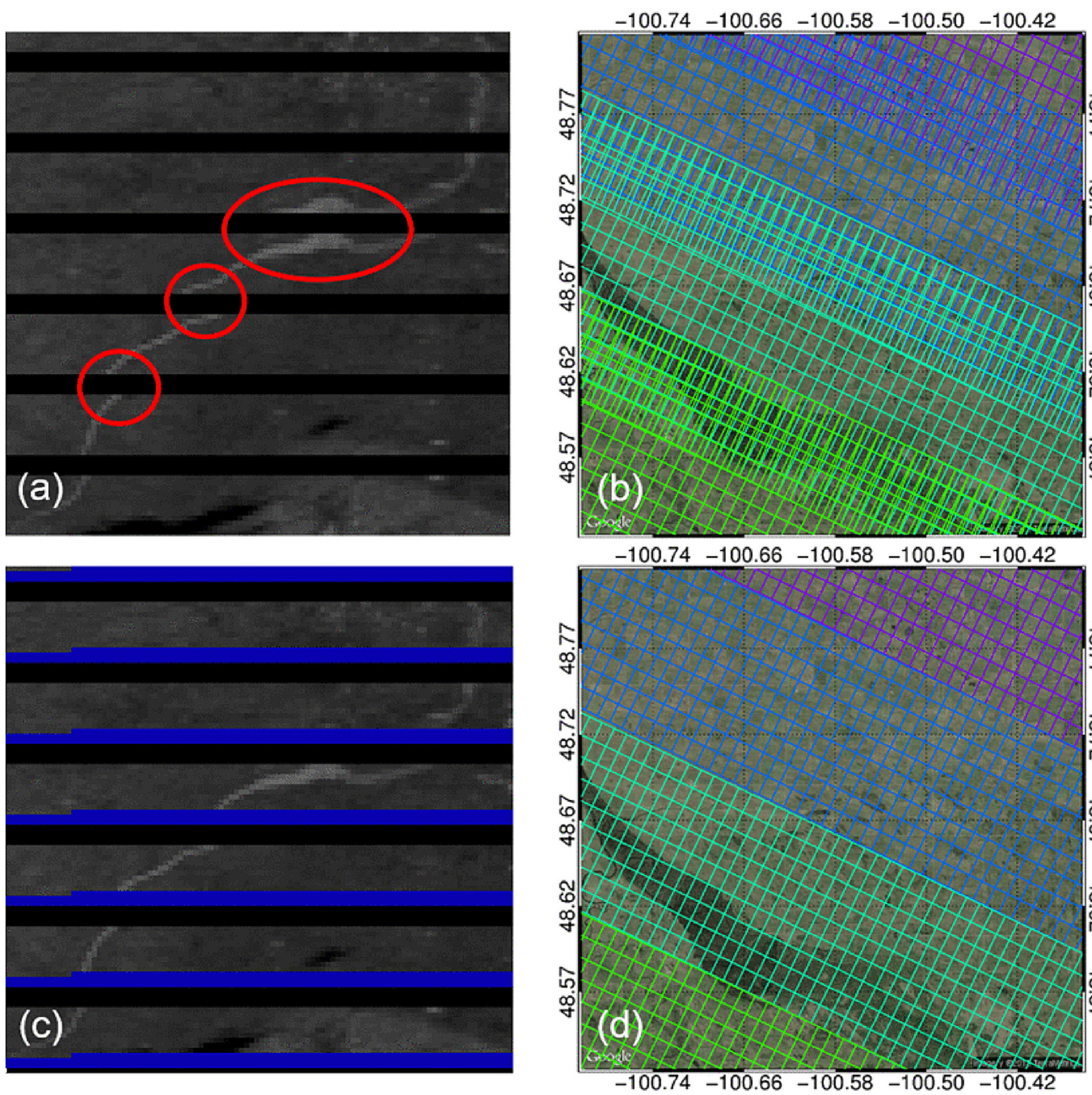


Adapted from Seaman 2013, https://rammb.cira.colostate.edu/projects/npp/Beginner_Guide_to_VIIRS_Imagery_Data.pdf.

Dealing With the Challenges of VIIRS Data

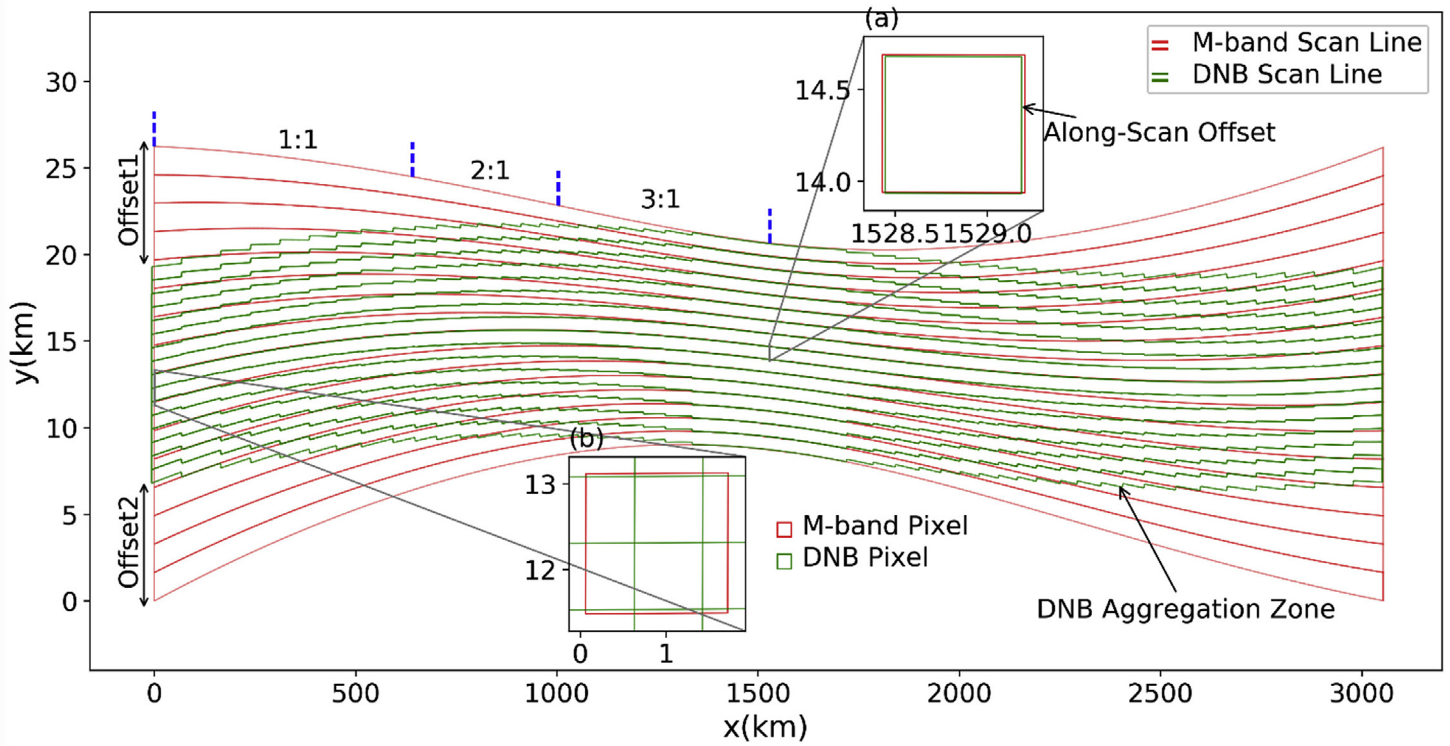
VIIRS pixels distort along the edge of its swath because of scan geometry and the Earth's curvature. Known as the "bow-tie effect," this distortion is especially pronounced the further away the scan is from nadir, the downward-facing viewing geometry, because the scanning process causes pixel size to grow as scan angle increases, which is shown in the illustration.

As a result, pixels from consecutive scans overlap along the edge of the swath, resulting in extra data. These overlapping pixels must be removed to avoid double counting detected fires in a fire pixel. Some of this happens during onboard processing, but much of it was completed by an efficient algorithm that Wang and his team designed and can be automated with computers. In the figure below, the top row shows overlapping, redundant data for a VIIRS scene. The bottom row is the same scene after overlapping regions were removed. Without overlap correction, the same pixel might be counted twice near the edge of the scan.



Correcting for pixel overlap. (a) VIIRS unprojected 4μm moderate-resolution band #13 (M13) scene before corrections. The red outlines highlight the duplicated river areas, and black lines are the bow-tie deleted areas done onboard VIIRS. (b) Pixel footprints for the M13 VIIRS scene including overlap (before corrections) with different colors representing different scans. (c) Image in (a) after corrections with additional overlapping regions removed (blue). (d) Projected scans after corrections. Source: Polivka, et al. 2016.

This is particularly noticeable for the VIIRS M-band. To address this, Wang applied aggregation schemes to compute the pixel growth and enlargement of the ground footprint at the edge of a scan, which can be seen in the plot below (Offset1 and Offset2). This is done so that the width and length of each pixel are accurately calculated throughout the scan zone.



VIIRS M-band/Day/Night Band (DNB) scan zone for the whole swath projected on a flat plane. The DNB scan line is shown in green; the M-band scan line is shown in red. The DNB pixels keep the same size throughout the whole scan while the M-band pixel size grows as a function of scan angle. Near the edge, there is an offset (Offset1 & Offset2) of 8 scan lines between DNB and M-band. Subset (a): the zoom-in view of the nadir M-band and DNB pixels in which the denoted along-scan empty space between M-band and DNB pixels is due to their nominal spatial resolution mismatch. Subset (b): the zoom-in layout of the edge M-band and DNB pixels. Each large near-edge M-band pixel can overlap with up to 12 DNB pixels from 4 different DNB scan lines. Note, the different scales for X and Y axes makes the figure exaggeratedly look curvy. Source: Wang et al. 2020.

Complicating things more, VIIRS M-band and Day/Night Band are mismatched at the pixel level. Wang's plan was to merge these bands, so these differences needed to be resolved, which they did by mapping Day/Night Band pixels to M-band pixels so that they matched in space and time. They also did other work to mechanically align data collected by Day/Night Band versus other bands since Day/Night Band is focalized differently. Overall, it took the team about two years to address the complex challenges encountered with VIIRS data.

Computing Modified Combustion Efficiency With the Fire Light Detection Algorithm (FILDA)

The point of this work was to enable Wang to use measurements from M-band (operational product) and Day/Night Band as inputs to the FILDA product. FILDA quantifies the fire combustion phase for each fire pixel to improve fire detection and characterize combustion efficiency at night. It does so by using fire radiative power (FRP) from M-band and visible light power (VLP) from Day/Night Band to calculate visible energy fraction (VEF), a measure of the relative portion of flaming versus smoldering phase within each fire pixel retrieved from the VIIRS 750m Active Fire Product. VEF is the ratio of VLP to FRP and is used to calculate MCE.

Definitions

Fire Radiative Power (FRP): *Total radiative power in all wavelengths due to all fires in a pixel.*

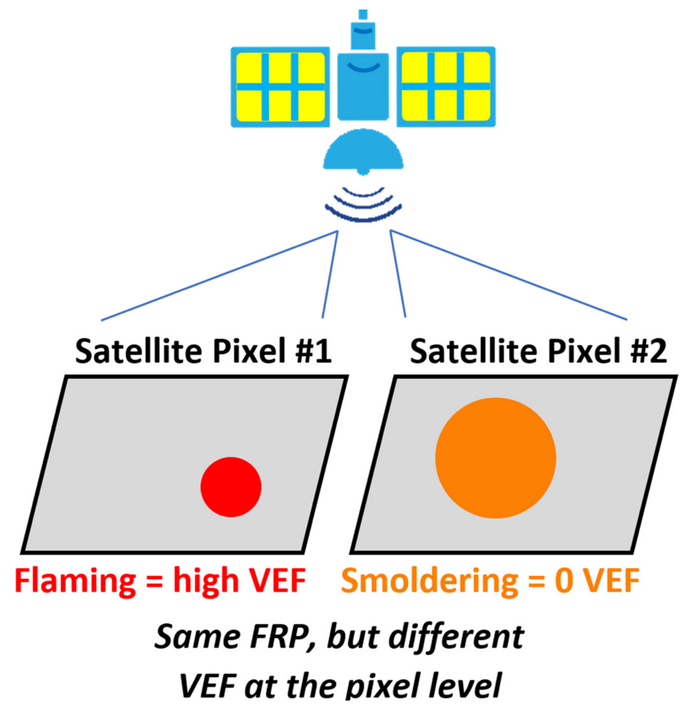
Fire Visible Light Power (VLP): *Radiative power in the visible wavelengths due to all fires in a pixel.*

Visible Energy Fraction (VEF): *The ratio of visible light power (VLP) to fire radiative power (FRP) that quantifies fire combustion phase per fire pixel. VEF is the FRP of the visible spectrum.*

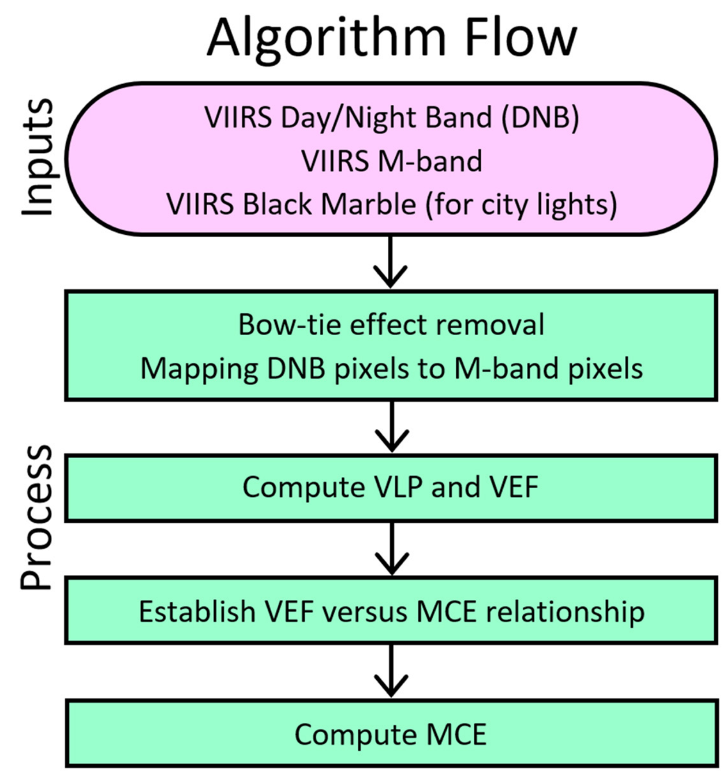
$$VEF = \frac{VLP}{FRP}$$

But why is VEF needed? Current operational satellite-derived fire products, like VIIRS Active Fire Products, use FRP to characterize active fires and quantify burning biomass emissions. While FRP provides an estimate of total radiant energy generated by fires in a satellite pixel, VEF describes how much of that radiant energy is visible light, that is, the fraction of fire that is flaming. A smoldering fire emits hardly any radiation in the visible spectrum, so VEF is zero for smoldering fires. In contrast, Wang explains, "For flaming fires, the higher the VEF value, the more complete the combustion because more radiant energy from the fire is due to flaming." VEF provides crucial information about the fire combustion phase and combustion efficiency that FRP has difficulty providing.

To illustrate this point, in the image on the right, satellite pixel #1 represents a small fire area and high temperatures (flaming) and satellite pixel #2 represents a large fire area and cooler temperatures (smoldering). While both fires might have the same or similar FRP, the VEF would significantly differ—the flaming fire (#1) would have a high VEF value while the smoldering fire (#2) would have an insignificant or zero VEF value. FRP tells little about combustion, but VEF reveals a lot.



Once VEF is known, MCE can be calculated. Once MCE is known, fire emission factors can be estimated and used to calculate the amount of CO_2, CO, black carbon, and other pollutants that are being emitted from wildfires. This data is desired by climate modelers and fire agencies because it is more tangible than emission factors derived from FRP.

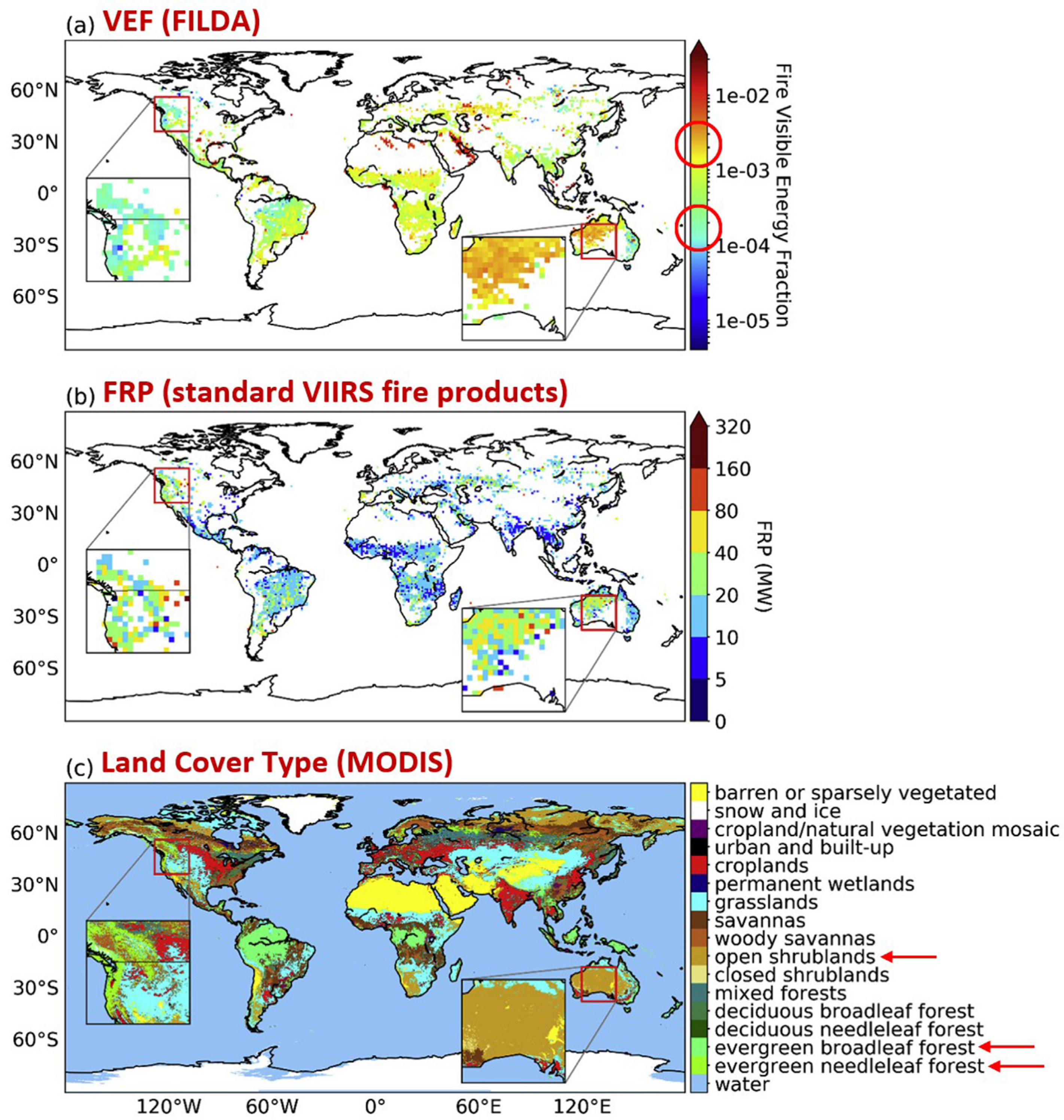


While the physics is clear, Wang and his colleagues have been working on this research algorithm for the better part of a decade, as their goal is to streamline the FILDA algorithm step by step so that it can be efficiently applied globally for fire detection. This work not only helps improve emissions inventories, but it also goes a long way in providing valuable information about the fire combustion phase needed by responders to better understand fire line (or flame) movement, extent, and ferocity.

Global Characterization of Fire Combustion Efficiency From Space—A First!

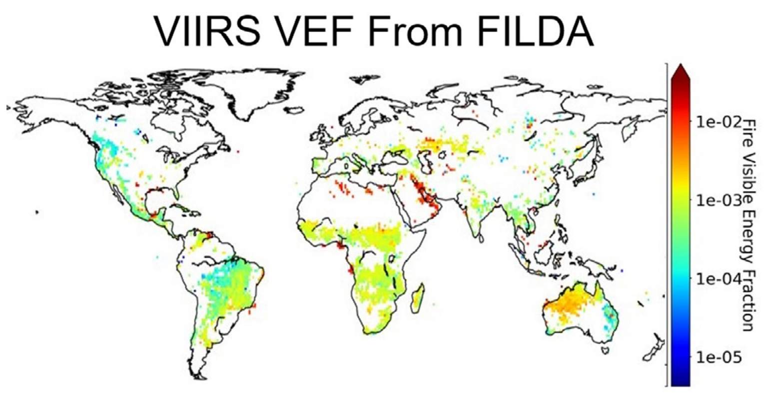
While evaluating FILDA, Wang made a fascinating observation when he calculated VEF and mapped the fire combustion phase across the globe (right, top and middle images). Here, the highest VEF values (red) point to gas flares along the west coast of Africa, Northern Africa, and the Middle East, which makes sense because gas flares are flaming and have very high complete combustion. Things get interesting when zooming into California and Australia (call out boxes), regions with long and intense fire seasons. VEF is much higher in Australia than in California. Why? Wang found an answer in land surface type.

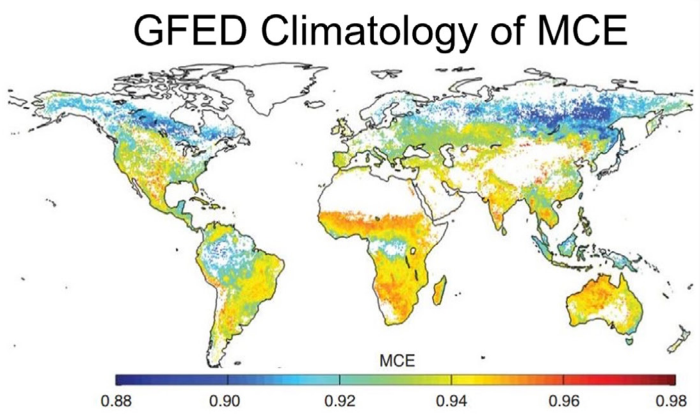
VEF values (top image) mimic land cover (bottom image). "VEF in shrubland in Australia are much higher than the VEF values of evergreen forests in North America, which is consistent with the literature," says Wang. In other words, brush fires burn a lot hotter and have higher combustion efficiency than forest fires, which is consistent with VEF values. On the other hand, FRP in these regions do not show this difference (middle image). FRP are similar between regions in terms of how much radiant energy is emitted, which is expected given the definition of FRP (total radiant energy emitted by a fire at all wavelengths).



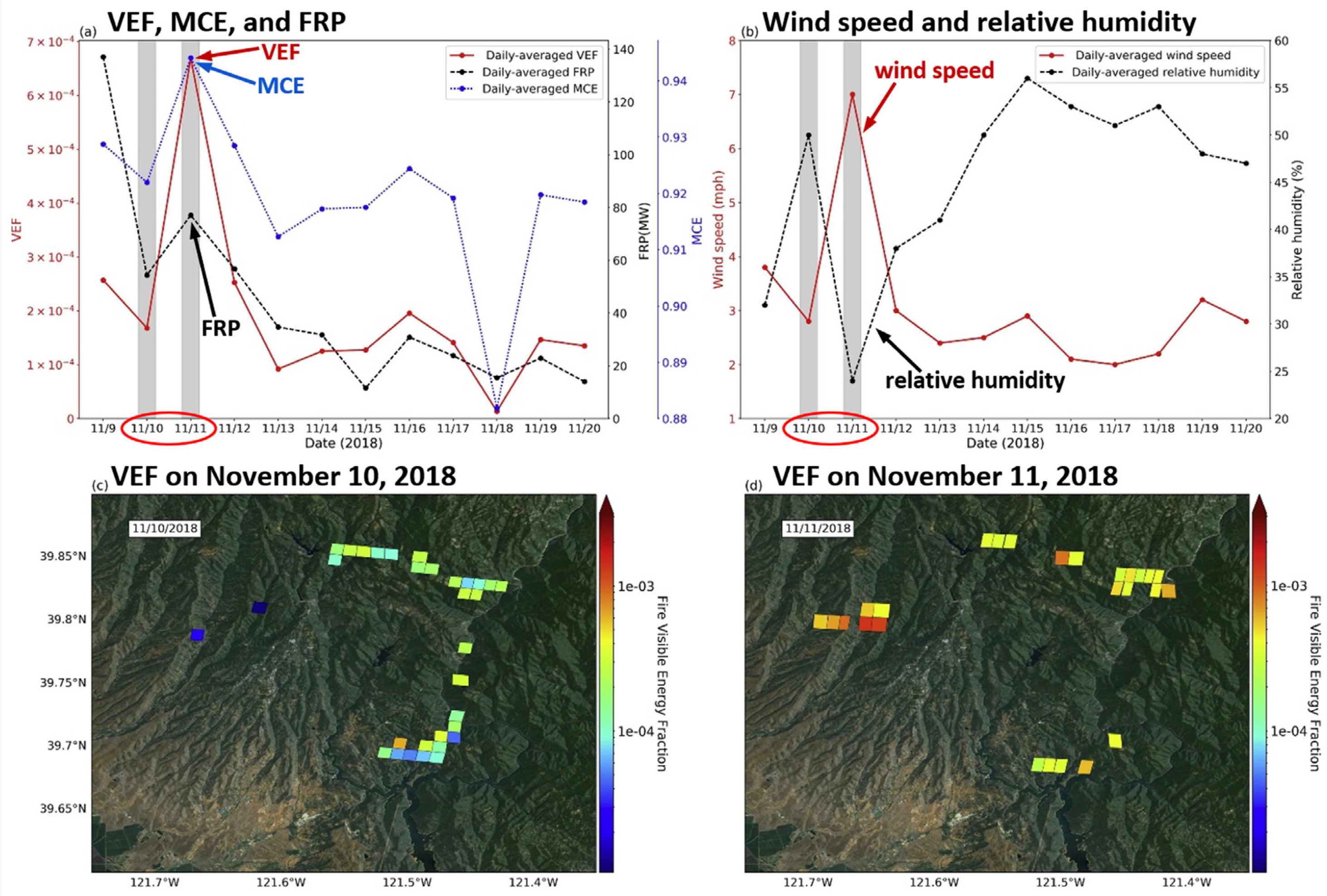
Top (a): Global map of VEF for 2017. Each 1° grid represents the average VEF value for the year 2017. The VEF map shows the transition from forest land cover type in North America (lower VEF) to shrublands in Australia (higher VEF). The red grids (highest VEF) are mostly corresponding to the gas flares while the lowest VEF (blue color) are where the evergreen forests are located. Middle (b): Global map of FRP for 2017. Each 1° grid represents the average nighttime FRP value for the year 2017. The FRP map does not capture the fire combustion phase differences based on the land cover type as the FRP spread for shrubland and forest are similar. Bottom (c): Global landcover map generated based on the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Climate Modeling Grid for the year 2017. The land cover categories are according to the International Geosphere-Biosphere Programme (IGBP) scheme. Source: Wang et al 2020.

Taking it a step further, Wang compared global VEF with Global Fire Emissions Database (GFED) climatology of MCE, the best knowledge available from fire emission and climate modelers. What he found was good correlation between values, which was statistically validated and is shown in the comparison images below.





"VEF clearly shows the influence of biome types on MCE—these matchups indicate that land cover has an impact on combustion efficiency," says Wang. This was the first global characterization of fire combustion efficiency from space, providing validation that VEF from the FILDA product more accurately and completely describes the MCE variation of different vegetation types.

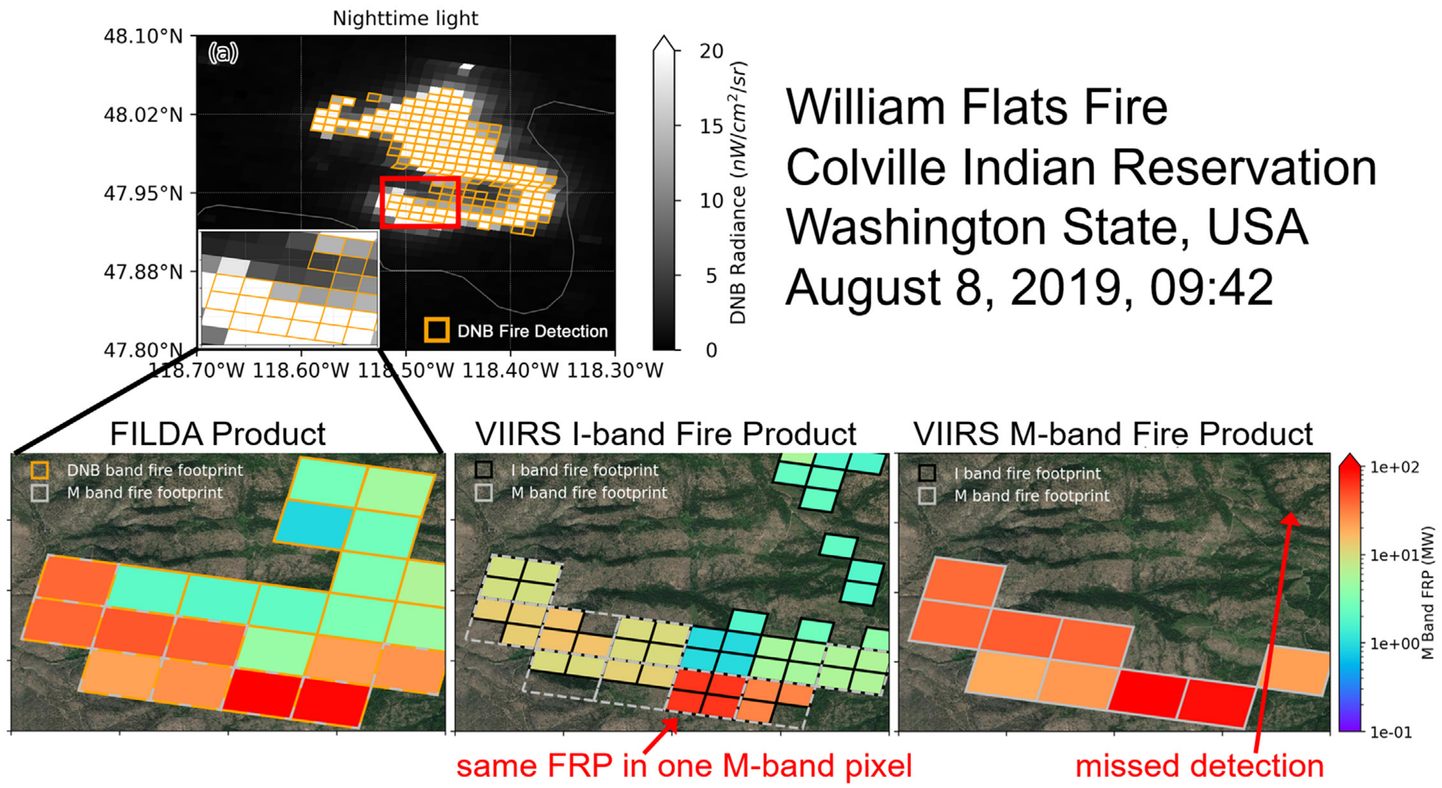


The Meteorological Impact on Combustion

"Historically, fire emission factors are often treated as constants in fire emission estimates, not affected by wind speed and relative humidity, which influence fire dynamics, or the life cycle of the fire," says Wang. So, what is the relation of wind and humidity to VEF, FRP, and MCE? To answer this, Wang's team compared these factors across the early days of California's Camp Fire that occurred in November 2018. Retrievals (above, top left) show that VEF and MCE were highest on day 3 of the fire (November 11), but FRP was highest on day 1 (November 9). "It turns out this peak of MCE reflects the results of high wind speed up to 7 meters per second and low relative humidity down to 25% on the third day, as compared to low wind speed of 3 to 4 meters per second and high relative humidity of 30 to 50% on the first two days," points out Wang. What happened was that a phenomenon called the Diablo wind—hot, dry wind from the mountains—came through on day 3 and influenced combustion (above, top and bottom right). The obvious link between this dramatic weather shift and the spike in VEF and MCE values shows the promise in using VEF and MCE for forecasting fire direction.

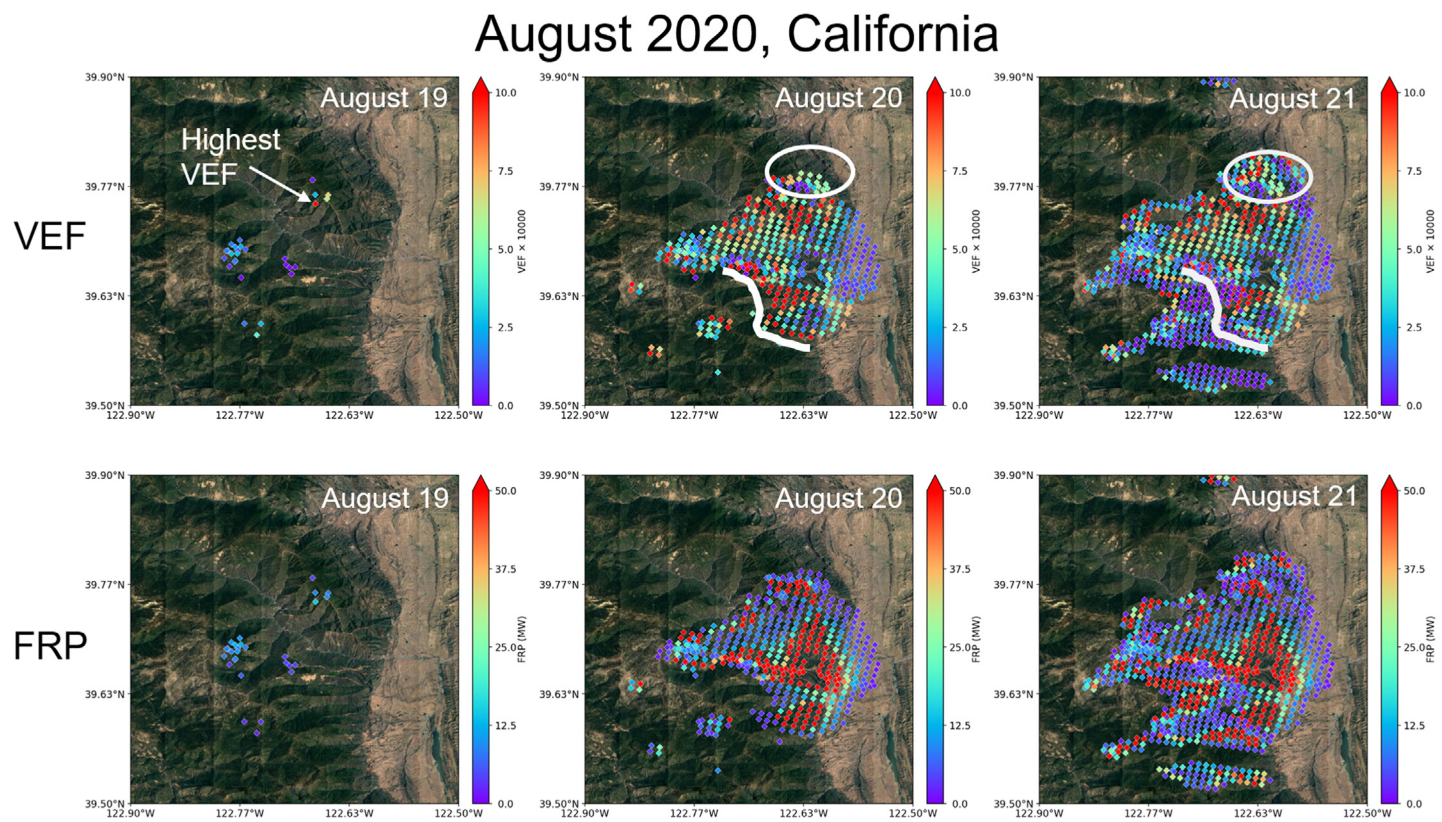
ESTIMATING FIRE GROWTH WITH FILDA

Besides computing combustion efficiency, the FILDA product with its combined VIIRS Day/Night Band and M-band detection does well at finding smaller and cooler fires that are missed by other products. To show this, Wang compared the performance of FILDA, VIIRS M-band, and VIIRS I-band fire detection products for the William Flats Fire in August 2019. For awareness, the standard VIIRS fire detection product relies on M-band to compute FRP. I-band is not used because of a saturation problem, but it detects smaller fires with relatively high accuracy making it a good comparison tool. In his analysis, Wang found that several fires detected by VIIRS I-band were not detected by VIIRS M-band (shown below). "But," he says, "with our algorithm using Day/Night Band together with M-band, we can detect the fires at a similar level of accuracy that is found using the I-band."



CLICK IMAGE TO ENLARGE.

In addition, FILDA has the potential to better predict fire movement. For example, looking at a 2020 California fire (below), the starting location on August 19 was confirmed by the highest VEF value (in red). The next day, August 20, the fire had grown and VEF along the southern edge (white line) was very high (red), but the FRP was low (blue-purple). So, where will the fire spread next? Fire growth is driven by the flaming phase and, if high VEF is a hint, then the fire should grow past its southern edge. This is indeed what happened on August 21—the fire expanded far past where VEF values were the highest the previous day. FRP tells a different story and little about where the fire might spread. Land cover affects growth, too, which is noticeable along the northern edge (circled) where fire growth was limited by the lack of vegetation to the north and east.



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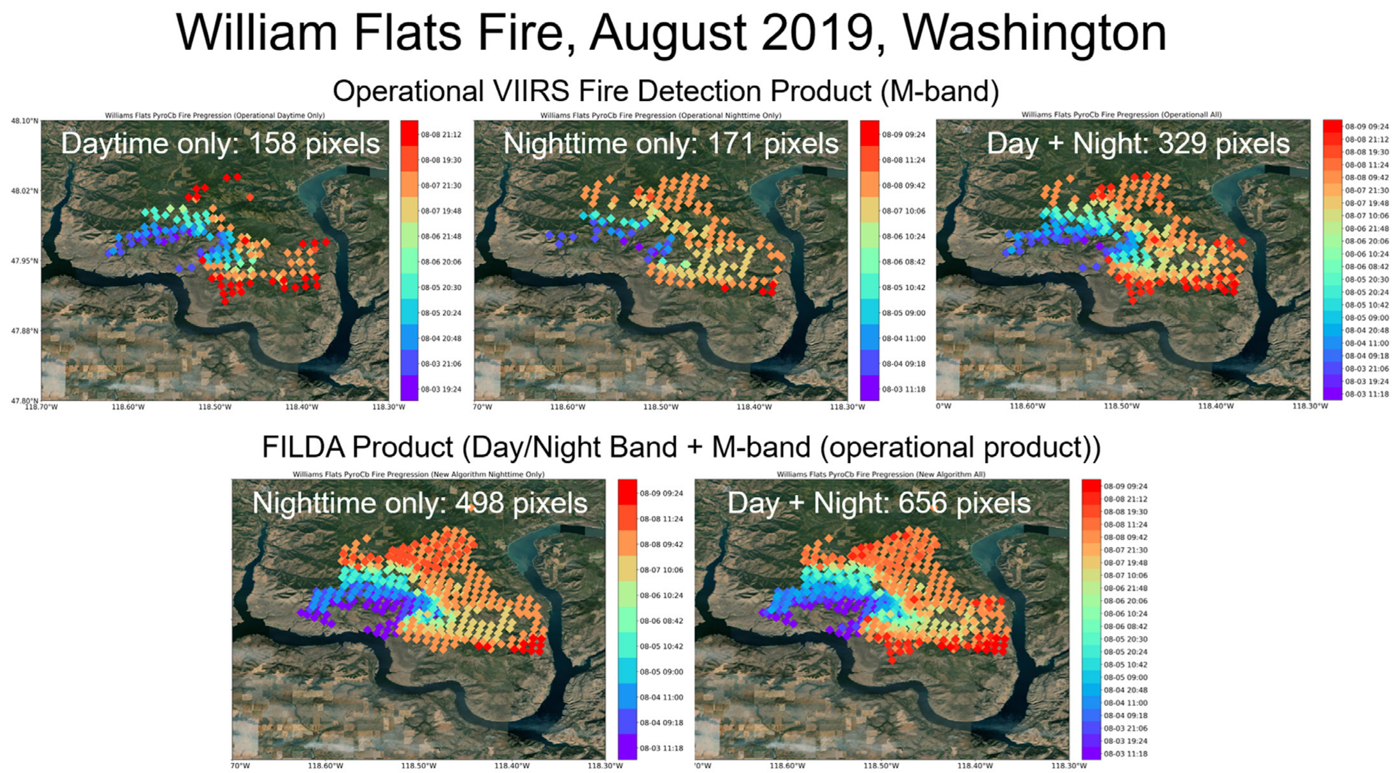
The FILDA product gives responders a more complete description of fire. The increase in fire pixels detected is shown below—more than double when Day/Night Band is added! Wang emphasizes the importance of this additional data: "We can see more clearly where the fires started and what direction they went with more fire pixels—critical information for firefighters."



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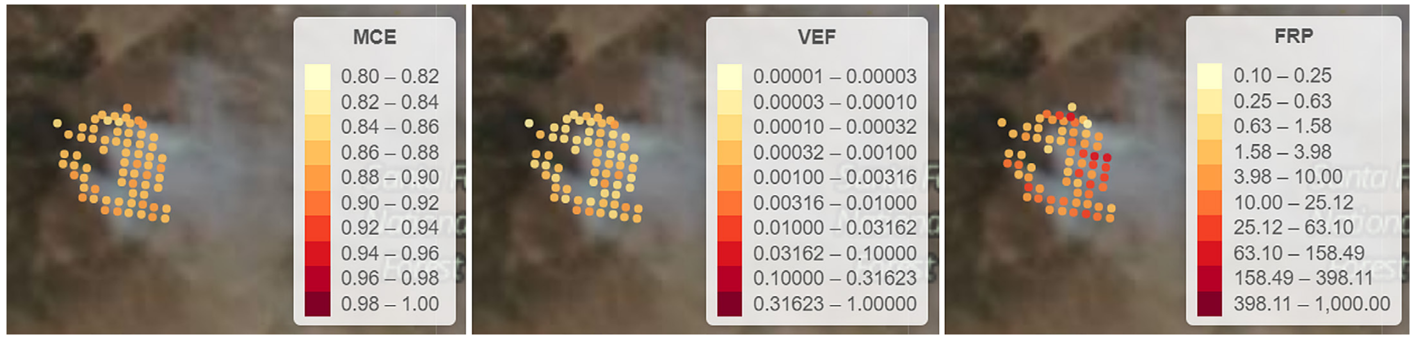
A near real-time version of FILDA over the continental U.S. is available at http://esmc.uiowa.edu:3838/fires_detection/ for use by the research and response communities. The product is maintained by the University of Iowa Atmospheric and Environmental Research Lab (UIOWA-AER Lab) research group led by Wang. Below is an example of FILDA output showing the MCE, VEF, and FRP for the Cerro Pelado Fire that ignited in April 2022 near Santa Fe, New Mexico.



CLICK IMAGE TO ENLARGE. MCE (left), VEF (middle), and FRP (right) from FILDA for day 9 (April 30, 2022) of the Cerro Pelado Fire located about 35 miles west-northwest of Santa Fe, NM. The FILDA values overlay a VIIRS S-NPP True Color Image.

RELATED RESEARCH

Wang and his colleagues are also working on using VIIRS Day/Night Band to retrieve global smoke aerosol optical depth at night, a measurement currently only available in daytime. Doing so will improve model forecasting and the understanding of the role of aerosols in atmospheric chemistry. Wang also wants to know how high wildfire smoke can rise, which impacts how far it is carried by the wind. "Aerosol layer height is needed by air quality managers who want to know if the smoke layer is high or low so they can make accurate air quality advisories for the community," explains Wang. More can be found about this ongoing research in several recent publications:

- Wang, J., Zhou, M., Xu, X., et al. (2020). Development of a nighttime shortwave radiative transfer model for remote sensing of nocturnal aerosols and fires from VIIRS. Remote Sensing of Environment, 241:111727. https://doi.org/10.1016/j.rse.2020.111727
- Zhou, M., Wang, J., Chen, X., et al. (2021). Nighttime smoke aerosol optical depth over U.S. rural areas, first retrieval from VIIRS moonlight observations. Remote Sensing of Environment, 267:112717. https://doi.org/10.1016/j.rse.2021.112717
- Chen, X., Wang, J., Xu, X., et al. (2021). First retrieval of absorbing aerosol height over dark target using TROPOMI oxygen B band: Algorithm development and application for surface particulate matter estimates. Remote Sensing of Environment, 265:112674. https://doi.org/10.1016/j.rse.2021.112674

PERSPECTIVE

This research shows that VEF is better at describing the fire combustion phase than fire radiative power, which is valuable for fire response and emergency management. Earlier response is critical for reducing loss of life, health impacts, and property damage. Using FILDA to identify fires that have a higher threat of spreading will enable responders to focus their resources, which are often limited, especially when battling multiple fires in a region. The relationship between VEF and MCE is robust and appropriate for estimating emission factors at the satellite pixel level, which could have important implications on atmospheric modeling and the timeliness of air quality alerts. Wang and his colleagues continue to conduct nighttime field and lab work to further evaluate VEF and the FILDA product, which, under the support of NOAA and NASA, continues to improve and evolve. ✦

STORY SOURCE

The information in this article is based, in part, on the October 18, 2021, JPSS Science Seminar "Lighting the Dark: Insights of Fire Combustion Efficiency and Smoke Transport at Night From VIIRS" presented by Dr. Jun Wang, a James E. Ashton Professor in the College of Engineering at the University of Iowa, Assistant Director of the University of Iowa Technology Institute, and Director of the Atmospheric and Environmental Research Lab.

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Wang, Jun. (2020, October 21). Remote Sensing of Fire Combustion Efficiency & Smoke Plume Height [Video]. YouTube. https://youtu.be/oQTT2Te5Zuk

Engaging with National Centers for Environmental Information (NCEI) Data Users

Collage of climate and weather-related events that represent the range of data housed by the NOAA National Centers for Environmental Information (NCEI). Source: NOAA.

The evolution of NCEI. Clockwise from top left: File cabinets lining the walls of the Grove Arcade Federal Building in Asheville, NC, the location of NCEI in the 1950s (known at the time as the National Climatic Data Center); staff in 1950s using a key punch machine for data entry; the present day NCEI building in Asheville, NC; and staff in 1960 using the Film Optical Sensing Device for Input to Computers (FOSDIC) to convert data on microfilm to computer-readable magnetic tape. Source: National Climate Data Center Collection, University of North Carolina-Asheville Archives, http://toto.lib.unca.edu/findingaids/photo/national_climatic_data_center/default_national_climatic_data_center.htm.

The NOAA National Centers for Environmental Information (NCEI) is one of the world's largest archives of environmental data, containing oceanic, atmospheric, and geophysical information from the stone age to the near-present and across the globe. The type of data NCEI houses varies as much as its time span, including data from the surface of the sun and the depths of the oceans, million-year-old sediment records, weather observations taken by Thomas Jefferson, satellite remote sensing data, and much more, and all these data are free to the public. For more than 70 years, NCEI has been reaching end users with products and services ranging from custom reports to case studies to interactive online tools.

Housing mostly historical information, NCEI's data is important for looking back at the patterns of the past to understand the present and to help form a baseline for predictions and outlooks into the future. Serving as the "gold standard" of environmental information, NCEI's vast archives are invaluable for commercial applications, policy development, and decision-making about goods and services across all sectors of the U.S. economy. NCEI is far reaching, and its data are applicable to any industry that is impacted by weather and climate, from agriculture to retail and beyond.

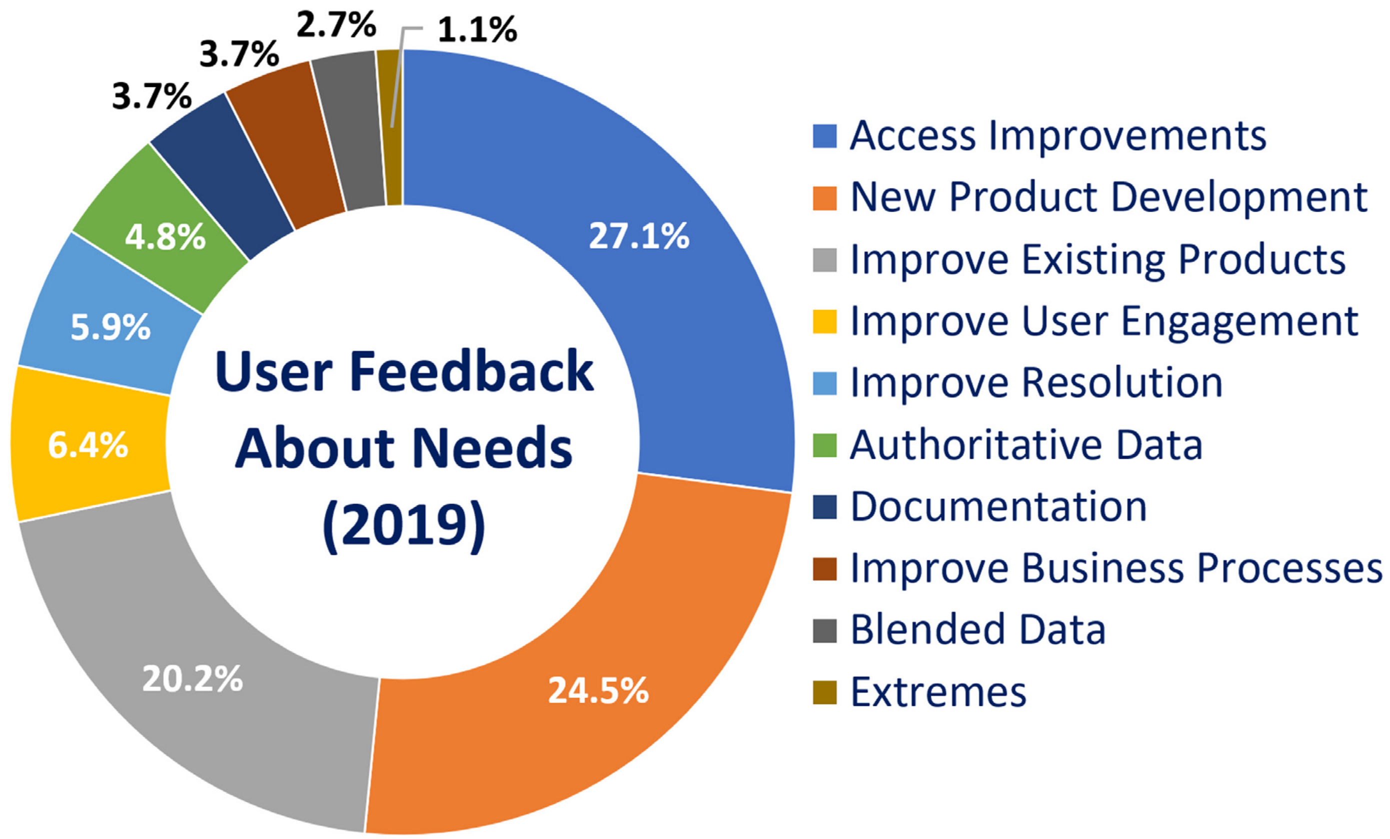
Getting the right data into the right hands can be tricky because of the staggering amount of information available—NCEI archives contain more than 37 petabytes of data, equivalent to about 400 million filing cabinets filled with documents. Imagine sorting through and interpreting even a fraction of that! This amount of data can be overwhelming for the most seasoned NCEI user and is even more so a barrier for the non-technical or casual user. NCEI is tackling this challenge by actively engaging stakeholders and developing user-friendly products tailored to meet sector-specific needs. At the July 2022 JPSS Science Seminar, Dr. Mike Brewer, Chief of Information Services in the Climatic Science and Services Division (CSSD) at NCEI, and Axel Graumann, a meteorologist at NCEI, provided an overview of NCEI user engagement activities and the NCEI user community with a focus on JPSS data and information.

LEARNING THROUGH USER ENGAGEMENT

Over the last decade, science has moved away from the "if you build it, they will come" attitude toward a more active approach of engaging users and incorporating their feedback into products and services. Not only does this help meet user needs but it also builds trust between the scientific and user communities. Simply put, user engagement can make stakeholders feel heard and understood, thereby generating greater product buy in. Customer insight also comes from web analytics that measure website activity—when, where, and how users are accessing a site. NCEI uses all these approaches to understand their users and the benefit they get from NCEI data. For NCEI, this information is important for understanding the role their data plays in decision making so they can develop actionable products that address societal and economic issues at local, regional, and national levels.

Interactions with users, whether direct (a one-on-one conversation) or indirect (a user downloading data), provide an opportunity to learn about a customer's needs and behaviors. Such data helps guide NCEI science and development to improve and expand their services and products. Since 2015, Brewer and his colleagues across NCEI and six Regional Climate Centers (RCCs) have documented users and user engagements as part of the broader NOAA National Environmental Satellite, Data, and Information Service (NESDIS) User Engagement strategy. But NCEI's mission is slightly different than most of NESDIS. Brewer explains:

> A lot of the satellite data coming in is used in real time to feed the National Weather Service and other partners that need that information for the protection of life and property and for making forecasts. Most of NCEI's business deals with retrospective information—helping people look backward into the past so that they can understand something that's happening now. Our job and products pick up where the real-time mission ends.



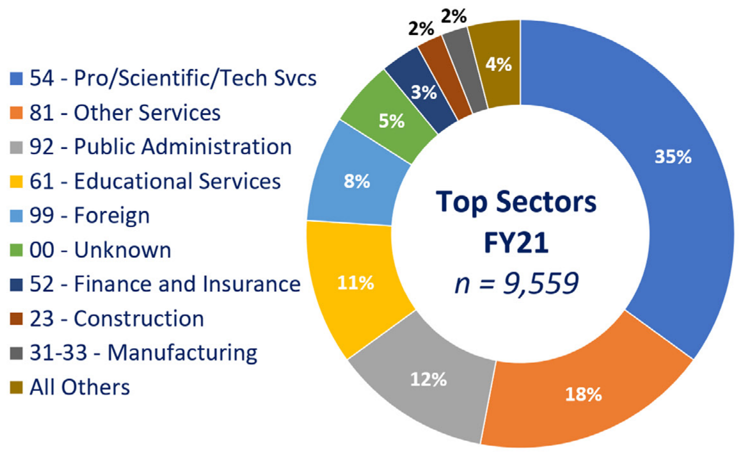
User needs and recommendations compiled during the 2019 NCEI Users' Conference. Source: Brewer et al. 2020.

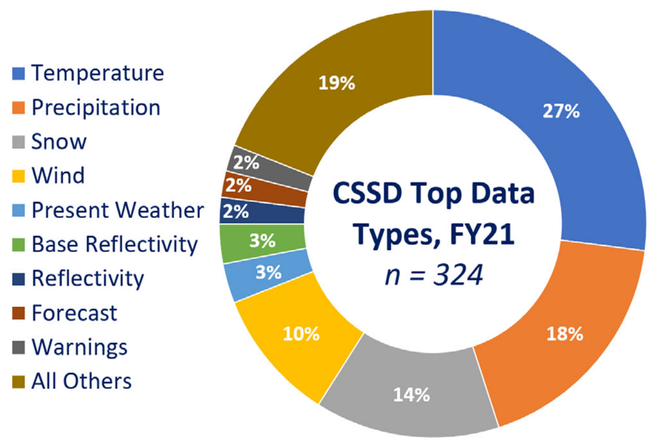
So far, more than 75,000[1] direct and indirect user interactions have been captured in a powerful Customer Relationship Management (CRM) tool that documents who users are, when they engaged or accessed data, how they use NCEI data, their unmet needs, and other feedback. Direct interaction with users comes from different engagement opportunities: NCEI customer service and order fulfillment, workshops, conferences, and other one-on-one or group conversations. One example is the 2019 NCEI Users' Conference that provided a forum for stakeholders to share their needs and recommendations for product innovation (outcomes are summarized in the graph). Events like this are an avenue for learning about customers so that NCEI can better serve them.

Indirect interactions complement direct engagement and are traced through website analytics that provide information about when, where, and how users download NCEI data from various access points, like the NOAA Comprehensive Large Array-Data Stewardship System (CLASS). Because of privacy rules and other network limitations, it is difficult to identify specific users. However, even at a high level, website analytics help Brewer get an idea of who is accessing data and how often they interact with NCEI.

WHO ARE NCEI USERS?

NCEI information touches every sector of the U.S. economy, which can be summarized by the 20 North American Industry Classification System (NAICS) industry codes covering public and private sectors. "It's not unusual for us to hit all 20 [sectors] in a month, and we certainly hit all 20 every quarter," remarks Brewer. User engagement data helps Brewer see how far into a sector NCEI is reaching. For example, in fiscal year 2021, NCEI interacted with nearly 10,000 users (below left) most of whom were from the Professional, Scientific, and Technical Services sector, "people like consulting meteorologists and lawyers," Brewer explains. About 70% of users requesting NCEI Climatic Science and Services Division data want temperature, precipitation (including snow), and wind data (below right), but, Brewer notes, "we also see interest in forecasts and warnings for looking back to see how well a model performed for an event."



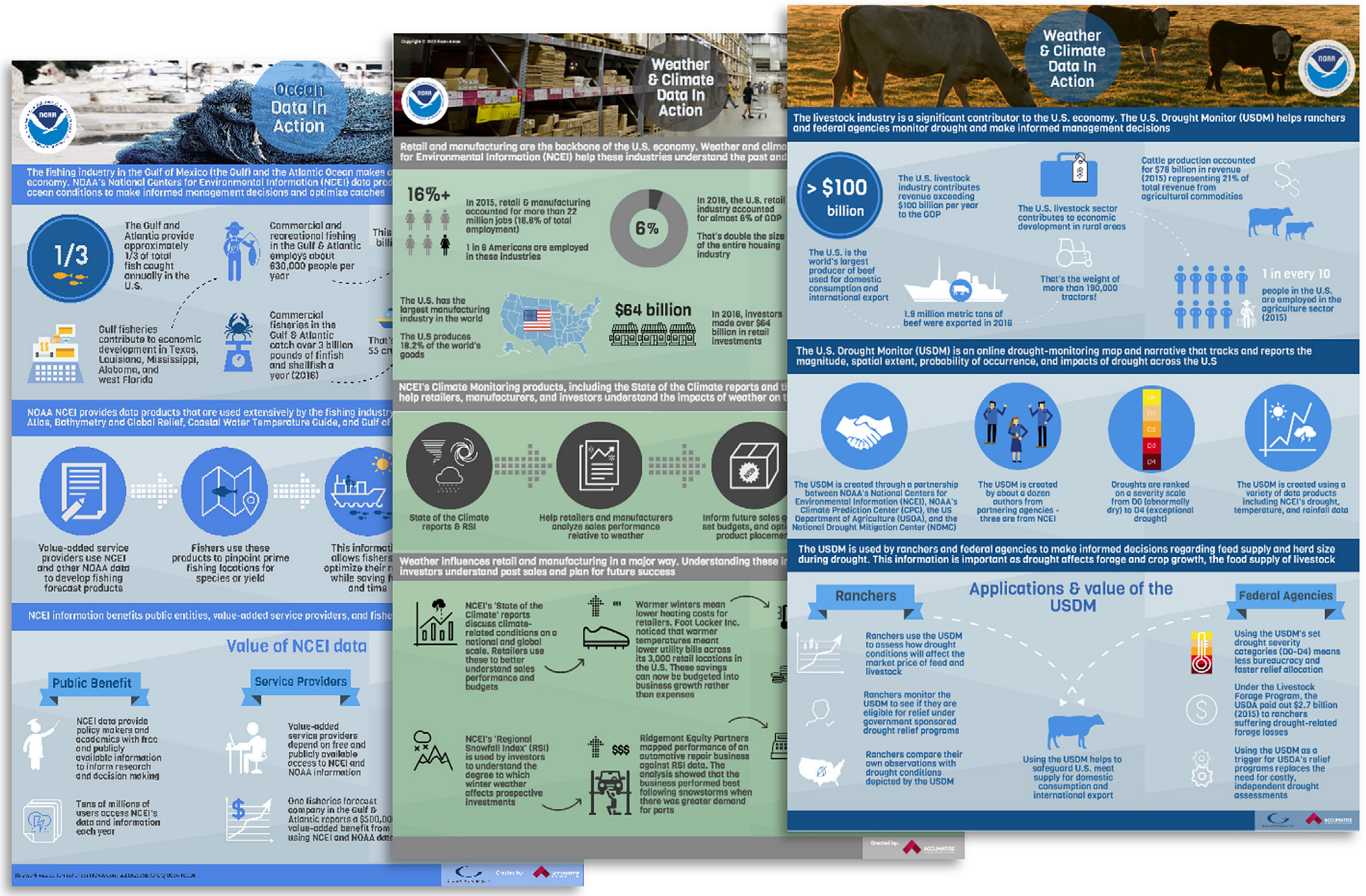


CLICK IMAGE TO ENLARGE. Left: Top NAICS sectors accessing NCEI data based on user engagements in fiscal year 2021. The category "All Others" represents sectors with less than 2% data use. Right: Top types of NCEI Climatic Science and Services Division (CSSD) data accessed. The category "All Others" represents sectors with less than 2% data use.

All in all, more than 10 terabytes of NCEI data are downloaded annually, and with the CRM tool Brewer can dig into the details, for example, the kind of data downloaded like local climatological data or global historical climate data. This information gives valuable insight into what is important to users and hints at how data are being used. But to really understand the user and the impact NCEI has on various sectors, one-on-one conversations are crucial.

Gaining an Understanding, Listening to Feedback, and Responding With Change

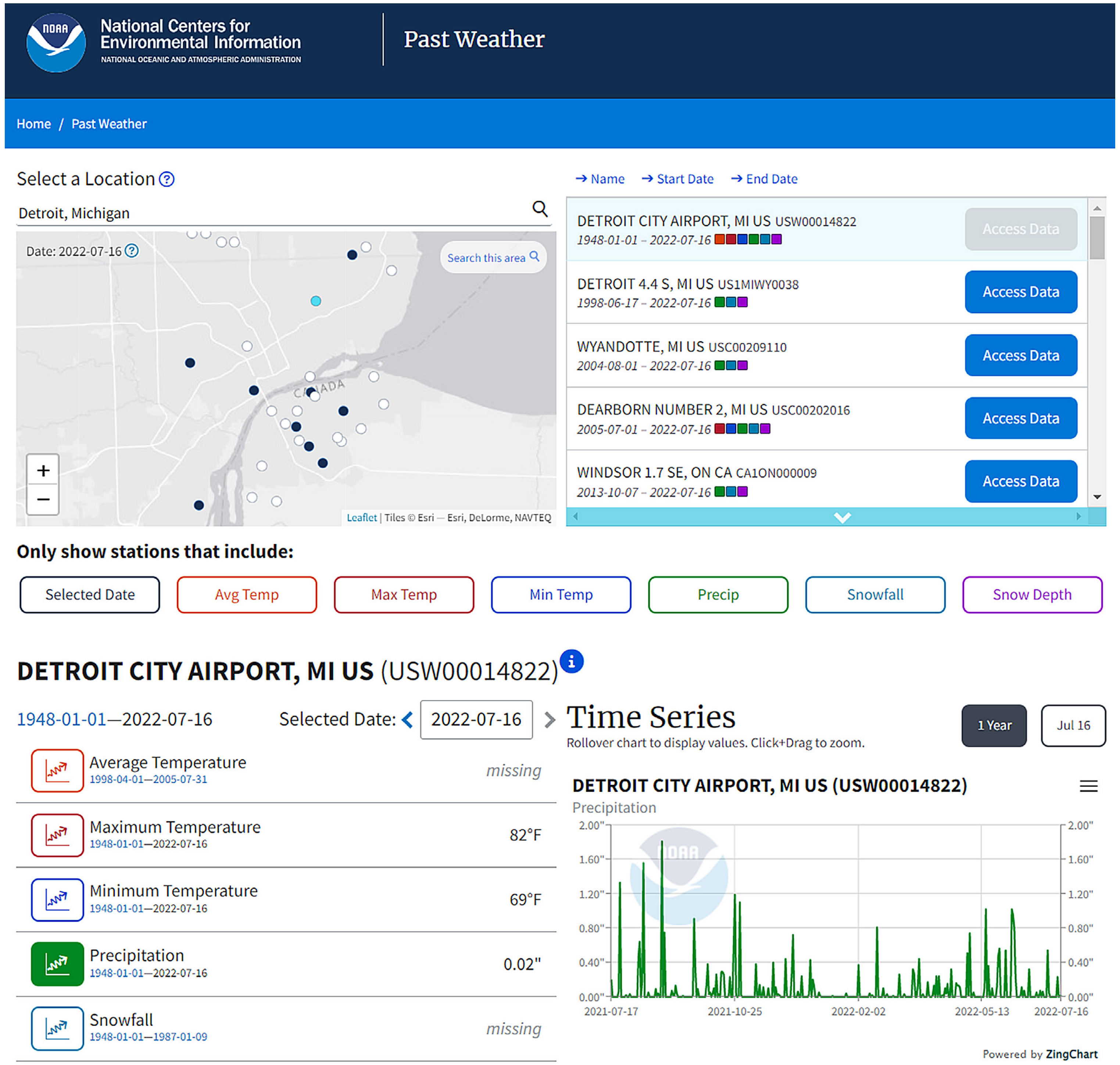
"Behind each of these numbers is a person," Brewer emphasizes. Through outreach and other avenues, Brewer and his colleagues engage with individuals, businesses, and organizations and use what they learn to develop user stories, case studies, and other tools and resources for different sectors. For many, they go a step further and create outreach materials like posters and infographics that display the benefits and uses of NCEI data to the U.S economy. These activities are opportunities for users to share their perspectives and give Brewer and his team a clearer picture of the value of NCEI data.



Case studies and other information about NCEI's impact are available on their website: www.ncei.noaa.gov/about/our-impact.

Besides learning about NCEI's impact, Brewer uses customer interactions to identify and address the most common questions and data requests that NCEI receives. Brewer elaborates, "Addressing questions improves customer response and NOAA relevance, and gives users what they're asking for, especially for users who just want a quick look at the information." One example of turning user feedback into an actionable product is the NCEI Past Weather Tool, a web interface that answers the most common climate-related questions from users without requiring specialized knowledge about the data or system. This tool arose from customer requests for user-friendly historical weather data and is an example of how NCEI delivers change (as new products) based on user feedback.

User interactions such as these, along with website analytics, help Brewer and his team better understand the resources, datasets, products, and services that are needed to support all sectors of the U.S. economy. But with the vast amount and diverse data that NCEI archives, how does JPSS fit into this?



The NCEI Past Weather Tool allows users to search for historical temperature, precipitation, snowfall, and snow depth data for individual weather stations across the United States, as well as many international locations. The tool is available at https://www.ncei.noaa.gov/access/past-weather.

Fishing Forecast Services: A Case Study

How do fishers find fish? One way is with a fishing forecast report. Third-party fishing forecast service providers use NCEI data to create inexpensive custom reports that provide information about where fish are likely to gather based on temperature, ocean color, and other variables that can be measured with NCEI data and products. In one example, a Florida tournament fisherman purchased a custom fishing forecast to get a leg up on the competition. Thanks in part to the report, he won $500,000 in prize money in one weekend. Commercial fishers also benefit, using forecast reports to decide where to go, and more importantly, where not to go. Brewer explains, "The amount of gas money savings alone will exceed the cost of a fishing report" making it a worthwhile investment. This is just one example of the unique insights uncovered through conversations with NCEI data users.

CLASS

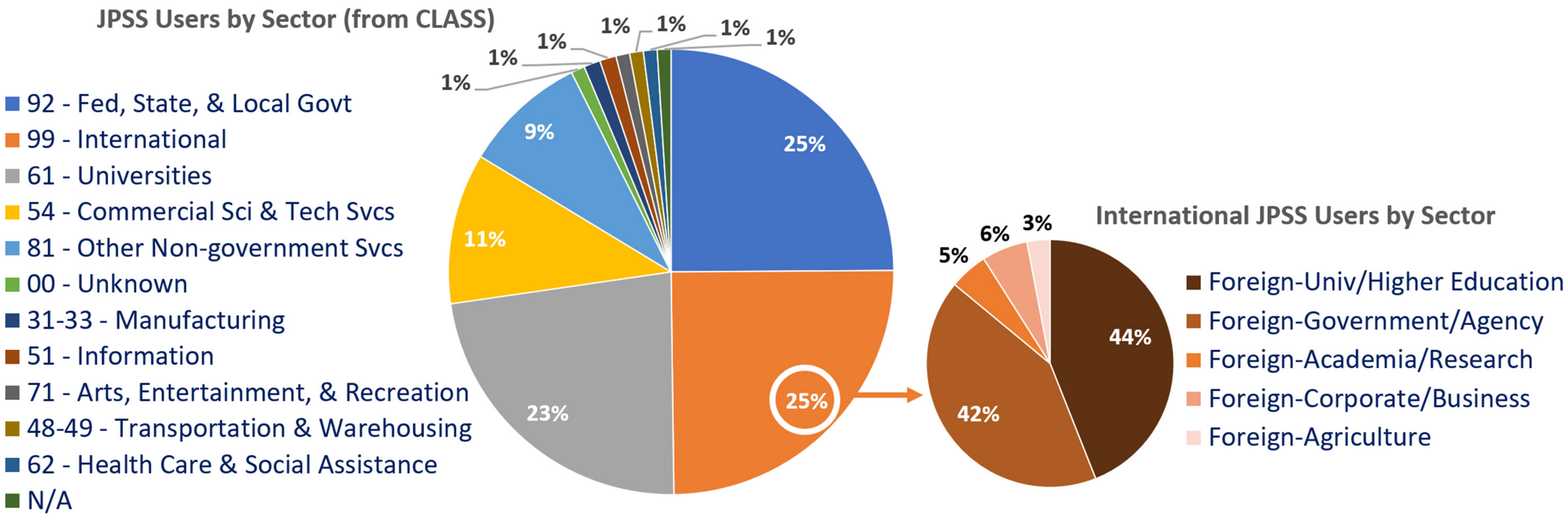
The Comprehensive Large Array-data Stewardship System (CLASS) is an electronic library of NOAA environmental data with more than 35,000 registered users. It is NOAA's primary online access point for distribution of NOAA and U.S. DoD satellite and derived data, including JPSS data, Geostationary Operational Environmental Satellite (GOES) data, among others.

Profiling JPSS Data Users

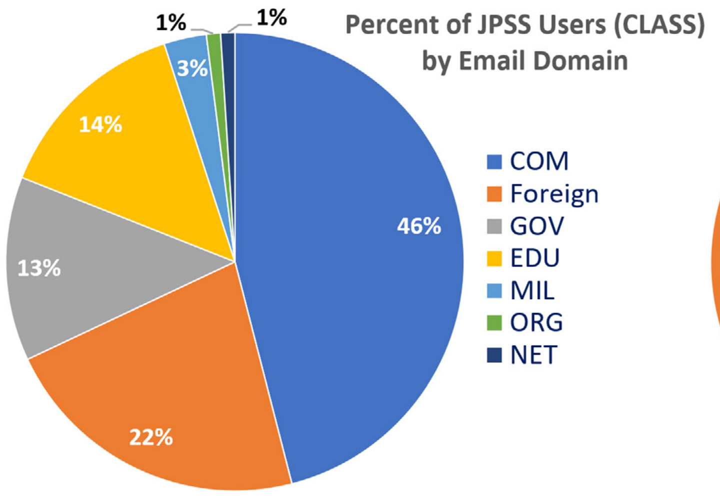
"Most satellite data users get their data through the CLASS system," says Axel Graumann, an NCEI meteorologist in CSSD's Information Services Branch. The same holds true for NCEI customers that access JPSS data. Website analytics, file counts (downloads), and direct user contact through NCEI and CLASS customer service provide enough information about access patterns for Brewer and Graumann to better understand customer needs. Graumann adds, "Because obtaining a CLASS account requires an email address, we can track the domains accessing the system," which provides a different view into what data is most important and to whom.

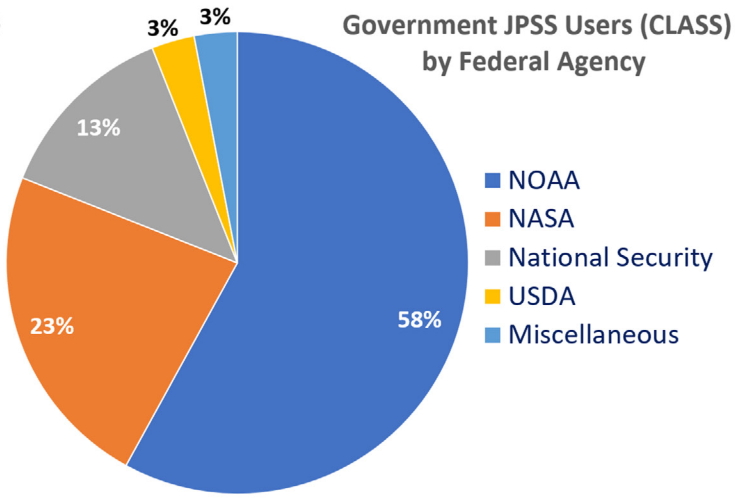
JPSS Data Users

Based on the collected information, the top sectors (by NAICS code) that use JPSS data are federal, state, and local governments; foreign entities; universities; and commercial scientific and technical service providers (below, left). Combined, these sectors make up nearly 85% of the users retrieving JPSS data through CLASS. Separating out international users (below, right) reveals that most foreign users represent universities/higher education (likely research centers) and foreign governments/agencies, which could include various sectors within the community, such as agriculture, forestry, climate, and so on. Taken together, academia and government make up the overwhelming majority of JPSS CLASS data users, suggesting that research and policy or decision-making may be primary applications of JPSS data from this source.



When breaking down users by email domain, something to note is that while most JPSS users are associated with a ".com" address, these may not be commercial entities as the domain indicates. "In fact," notes Graumann, "through user engagement we found that many of the '.com' users are from research centers or government agencies from abroad and within the U.S." Also, about 10% of ".com" users are foreign but are not counted in the "foreign" category because of complexities with geo-referencing some registered CLASS users. Not surprisingly, most of the U.S. Federal Government users are from NOAA or NASA, followed by National Security agencies that may use JPSS data to assess natural disasters, climate change, and other environmental hazards that challenge the stability of the U.S. economy and the health and well-being of its citizens.



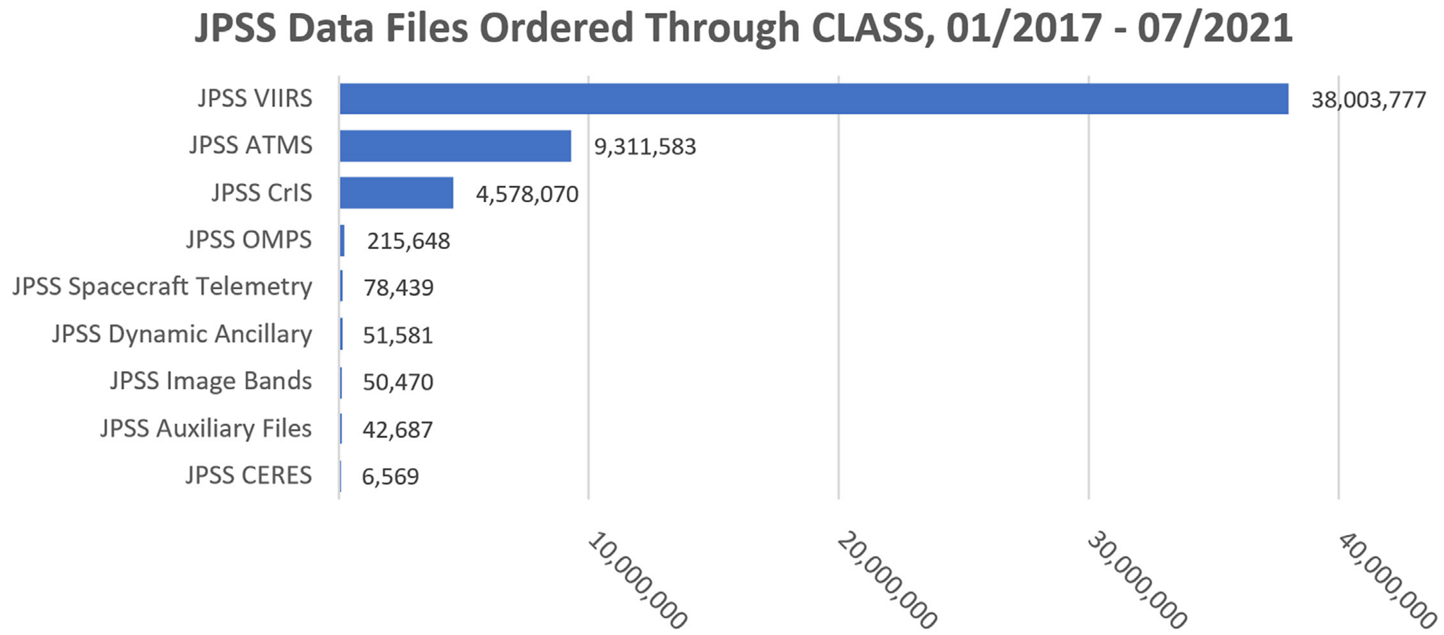


CLICK IMAGE TO ENLARGE.

Popular JPSS Data Products

With a general idea of who JPSS data users are, the question remains: what data are they accessing? Based on CLASS information, the answer is undoubtedly Visible Infrared Imaging Radiometer Suite (VIIRS) datasets and products with more than 38 million files ordered since 2017! A not close but still impressive second is Advanced Technology Microwave Sounder (ATMS) data with more than 9 million downloads in the past four and a half years. This information offers clues about the issues JPSS data users—largely from academia and government—are most concerned about.

What might the overwhelming popularity of VIIRS mean? The VIIRS instrument, flying on Suomi NPP and NOAA-20 satellites, generates high resolution global data that are critical to understanding and investigating changes and properties



in vegetation, land cover/land use, the hydrologic cycle, and the Earth's energy budget. Its data are used for monitoring active fires and smoke plumes, assessing air quality, estimating water resource availability, detecting power outages, identifying harmful algal blooms, tracking hurricanes, and much more. VIIRS' popularity is no surprise given its broad range of measurements, daily imaging capabilities that span visible and infrared wavelengths, and its sensitive Day/Night Band that allows for viewing of the Earth in low light conditions on cloud-free nights. The full scale of VIIRS applications is listed in the table, providing an idea as to what the more than 38 million data files ordered may have been used for. What is certain is that JPSS data products are getting into the hands of a great number of researchers and decision makers around the globe.

VIIRS Applications

Atmosphere	**Ocean**
Aerosol Optical Thickness	Sea Surface Temperature
Aerosol Particle Size	Ocean Color/Chlorophyll
Suspended Matter	
Cloud Optical Thickness	**Land**
Cloud Effective Particle Size	Active Fires
Cloud Top Pressure	Land Surface Albedo
Cloud Top Height	Land Surface Temperature
Cloud Top Temperature	Ice Surface Temperature
Cloud Base Height	Snow Ice Characterization
Cloud Cover/Layers	Snow Cover
Cloud Mask	Vegetation Health Index
Polar Winds	Green Vegetation Fraction
	Surface Type
Day Night Band	Net Heat Flux
Nighttime Lights data products	NIR bands for nightfire detection

Source: ncc.nesdis.noaa.gov/VIIRS/VIIRSNovelApplication.php

PERSPECTIVE

Brewer and Graumann have learned that different user groups want different things from the NCEI archive and CLASS system. "The majority of satellite data users we never hear from, they just download data on their own, but those users that do come to NCEI are seeking help—they know what data they want but they are looking for help with accessing the data," explains Brewer. For occasional users it is not always easy to get information out of the CLASS system, which is where NCEI and CLASS customer service can assist. Given that, it is not surprising that the most expressed words in customer service requests include "CLASS," "request," "access," and "assistance," illustrated by the word cloud derived from engagement data.

Looking ahead, NCEI will continue to patch new data together with archived data to keep lengthening the climate data record, which goes back to the first NOAA weather satellite, the Television Infrared Observation Satellite (TIROS-1) launched in 1960. Brewer notes that NCEI is working with the JPSS program to make sure that new JPSS data is included as it becomes available. "Most of NCEI's business

Word cloud developed from customer service requests documented with a CRM tool since 2017. The largest words are the most expressed across all requests.

is retrospective, which makes partnerships with JPSS, GOES, and other NOAA programs absolutely essential," he emphasizes. As NOAA and others move forward with new technology and satellites, and the climate data record stretches, new context and perspective about the climate will emerge. Now more than ever, such knowledge is critical for protecting life and property and enhancing the U.S. economy. ✦

STORY SOURCE

The information in this article is based, in part, on the June 23, 2022, JPSS Science Seminar "NCEI User Engagement" presented by Dr. Mike Brewer, Chief, Climatic Information Services Branch in NOAA's National Centers for Environmental Information (NCEI), Climatic Science and Services Division (CSSD) and Axel Graumann, Meteorologist in NCEI CSSD.

FOOTNOTES

1 Excludes Regional Climate Centers engagement data, which are not currently merged with NCEI engagement data.

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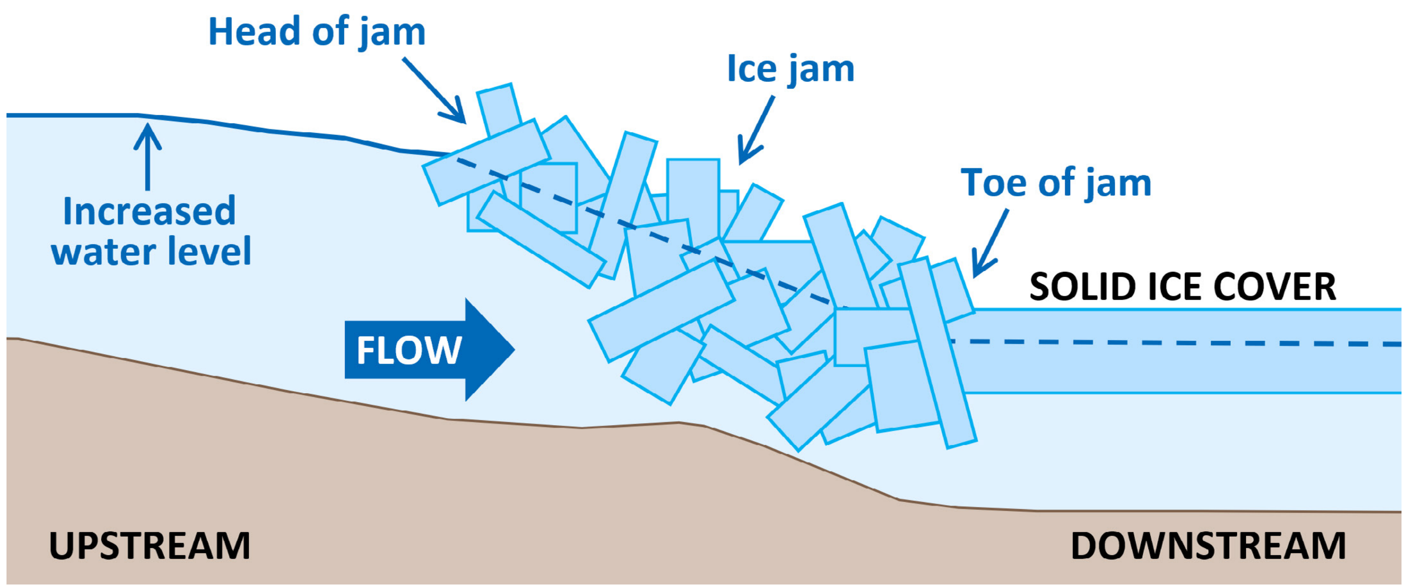
Connecticut River ice jam at the East Haddam Swing Bridge, January 19, 2018.
Source: Civil Air Patrol via National Weather Service.

FEATURE 9

Mapping and Monitoring River Ice With a Visible Infrared Imaging Radiometer Suite (VIIRS) Product Tool

Each winter, temperatures dip and rivers freeze across cold regions of North America. Spring brings rain and warmer temperatures that cause river ice to melt and trigger ice to break up into chunks. These ice chunks flow downstream and can get stuck in narrow river bends or under bridges, blocking river flow and causing flooding. Ice jam flooding happens very rapidly and can take a community by surprise, emphasizing the need for accurate, near-real time information on river ice conditions.



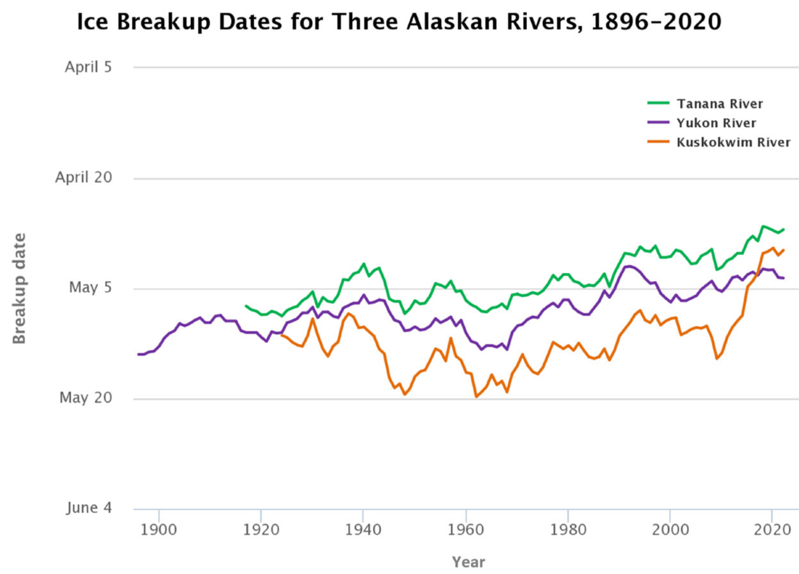
How an ice jam blocks the flow of water and causes flooding in surrounding areas. Source: Ice Jam Information Guide, Credit Valley Conservation, https://cvc.ca/document/ice-jam-information-guide/.

ROLLOVER IMAGE. The development of an ice jam in Northern Vermont on January 12, 2018 where an ice jam developed in less than 30 minutes. Source: NOAA NWS, Au Sable Forks, NY.

More than 22,600 ice jams have been reported in the U.S. since records began in 1780, mostly affecting northern U.S. states from the Northeast to the Northwest and Alaska, though major ice jams have occurred in more temperate regions like the Mid-Atlantic. Ice jams can interrupt shipping and hydroelectric power, affect drinking water quality, and destroy bridges, trees, and homes. Ice-related hydrology events cause an estimated $120 million per year in damages in the U.S.

Left: Ice jam and flood in Galena, AK in May 2013 that required the evacuation of the entire village. Source: U.S. Army. Right: Ice jam on the Delaware River in Trenton, NJ on January 15, 2018.

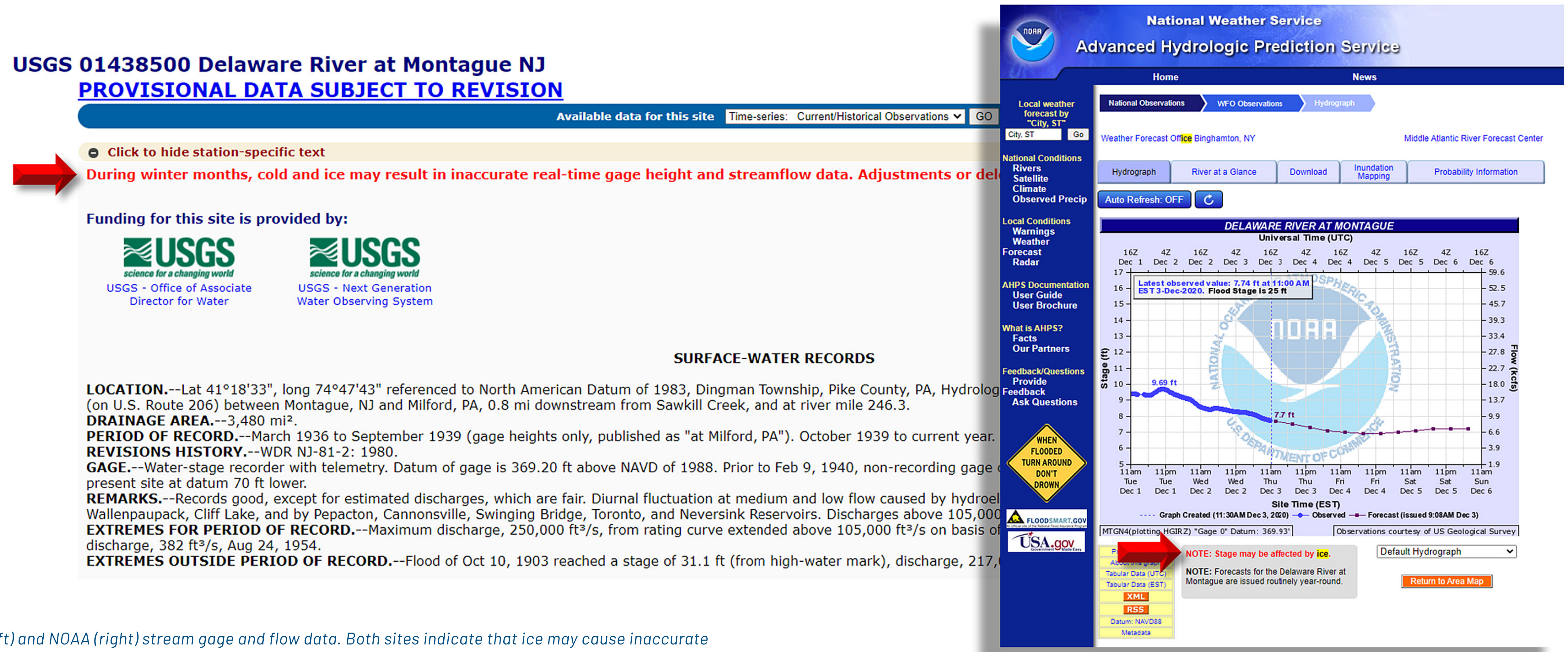
Ice breakups are rapid events and can be difficult to predict, especially since they are influenced by a number of factors, like the warming climate, natural annual variations, and land development. In northern regions ice breakups are happening earlier in the year in large part because of climate change. In fact, Alaska is warming faster than the rest of the U.S. and ice breakup dates for three major Alaskan rivers—the Tanana, Yukon, and Kuskokwim—have shifted earlier by up to nine days over the past century or so, as shown in the chart. Changes like these make it challenging to accurately forecast when ice breakups will happen. Using satellites to monitor changing river ice conditions is critical for evaluating flood risk and for providing timely warning to protect lives and property.



CLICK IMAGE TO ENLARGE. Source: U.S. EPA Climate Indicators Explorer, https://www.epa.gov/climate-indicators/alaskan-rivers

Traditionally, river ice observations rely on cameras and local observation. But these methods are limited in how much ground they can cover, and cameras can fall prey to spring storms or other hazardous winter weather conditions. While the U.S. Geological Survey (USGS) monitors U.S. rivers via ground stations, "the problem is when ice jams up a river and water flow stops, USGS stations stop reporting streamflow," says Dr. Marouane Temimi, Associate Professor at Stevens Institute of Technology. While a stop in monitoring indicates the presence of river ice, it also means no more streamflow and water height data until the ice melts, leaving little local information available about potential flood conditions. "Other methods are needed to infer river ice properties so that flow can be simulated in hydrology models to better predict ice jam flood risk during winter and spring months," Temimi asserts.

Satellite imagery has been used to monitor river ice breakups since at least the 1970s. These days, forecasters and researchers use data from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard JPSS satellites. With its 3,000 km swath, VIIRS provides wide, high resolution views of the Earth every 12 hours. The instrument rides on the Suomi NPP and NOAA 20 satellites that travel the same path about 50 minutes apart making VIIRS especially good at detecting river ice and ice jam floods, which can develop and evolve rapidly with little warning. With this knowledge, Temimi and his team developed an automated system that continuously maps ice on rivers and lakes throughout the U.S. and Canada. The River Ice Mapping System uses VIIRS data to monitor changes in river ice conditions, helping emergency managers and flood forecasters to see how river ice is progressing and identify areas at highest risk for flooding. The system portal is available to the public at https://web.stevens.edu/ismart/land_products/rivericemapping.html. Temimi shared the system's capabilities at the July 12, 2022, JPSS Science Seminar.



Example of USGS (left) and NOAA (right) stream gage and flow data. Both sites indicate that ice may cause inaccurate measurements during winter months (red arrows).

THE CAPABILITIES OF THE RIVER ICE MAPPING SYSTEM

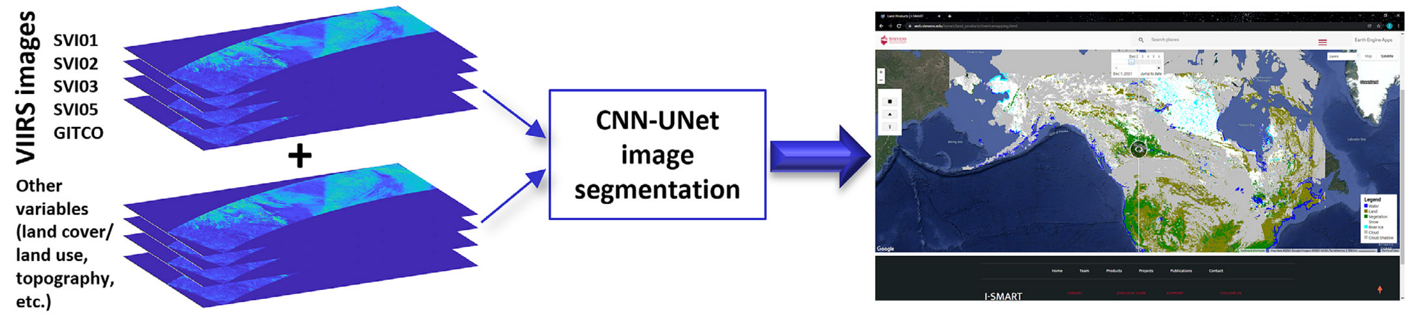
The River Ice Mapping System applies a branch of machine learning called deep learning to VIIRS I-band images and other data for monitoring ice, snowmelt, and other factors associated with river ice breakups. It does so with an image segmentation algorithm called U-Net, a type of convolutional neural network (CNN), that divides visual input into segments to make images easier to analyze. U-Net allows for fast and accurate detection of seven classes from VIIRS I-band images: water, land, vegetation, snow, river ice, cloud, and cloud shadow. Using VIIRS I-band has advantages over other VIIRS bands. The I-band channels have higher resolution (375 m) making them useful for cloud detection, and "they are sensitive to the presence of water and ice and the contrast between them when both are present on rivers," says Temimi.

CNNs & U-Net

Convolutional neural networks (CNNs) are deep learning algorithms that take an input image and assign importance to various aspects or objects in the image to tell them apart from one another. CNNs help computers see an image, classify it, see patterns, and learn from it. U-Net is a modified type of CNN used for fast and precise image segmentation. U-Net can locate objects and boundaries in images making it valuable for tracking river ice movement.

River Ice Mapping System VIIRS I-band Inputs

Channel	Spectral Range	Bands	Wavelength
I1	0.60-0.68 µm	Reflective	Visible (Vis)
I2	0.85-0.89 µm	Reflective	Near infrared (NIR)
I3	1.58-1.64 µm	Reflective	Shortwave infrared (SWIR)
I5	10.50-12.40 µm	Emissive	Longwave infrared (LWIR)



CLICK IMAGE TO ENLARGE. Diagram illustrating the River Ice Mapping System workflow: inputs, segmentation, and distribution of outputs to an interactive interface hosted by Google Earth Engine.

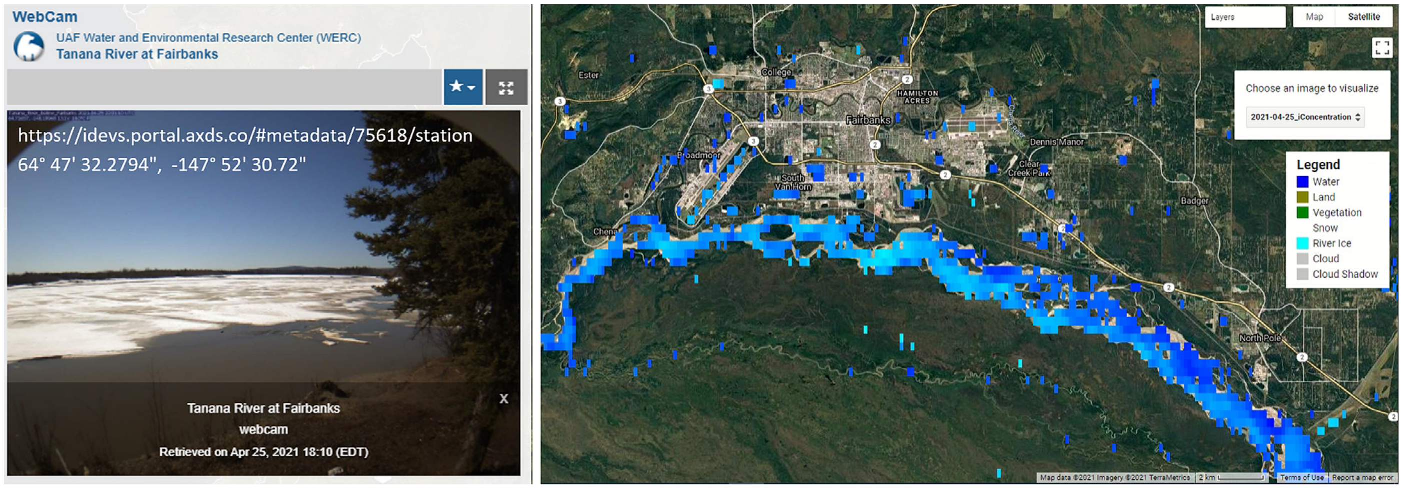
Melting snow triggers the mechanical breakup of ice, so Temimi added snow, water, land, and cloud classes to the system rather than limiting the tool to ice. This way, the user can see the relationship between melting snow and ice breakup on a local level to better estimate potential outcomes. Other inputs to the River Ice Mapping System include geography data and descriptive variables, such as land cover/land use and topography.

The system runs automatically and continuously generates maps of all seven classes, as well as estimating ice concentration and ice thickness and evaluating ice motion. Additional sensors (Sentinel-2 and Sentinel-3) were added so that users can compare and validate the River Ice Mapping System's output against true color (RGB) images, which show what the eye sees such as the presence of and change in snow and ice cover. All this valuable information is packaged in a Google Earth Engine interface, a platform for analyzing geospatial information, that offers user-friendly features like a split-screen slider for comparing side-by-side images. The user can also produce and download multi-day composites as GIF animations and time series graphs that show snow, ice, and water area for user-selected regions.

With so many capabilities, the River Ice Mapping System helps forecasters and researchers better understand both near-real time conditions and historical trends that provide insight into future ice breakup patterns. The following sections explore the system's output, functionality, and effectiveness in monitoring river ice conditions and associated factors.

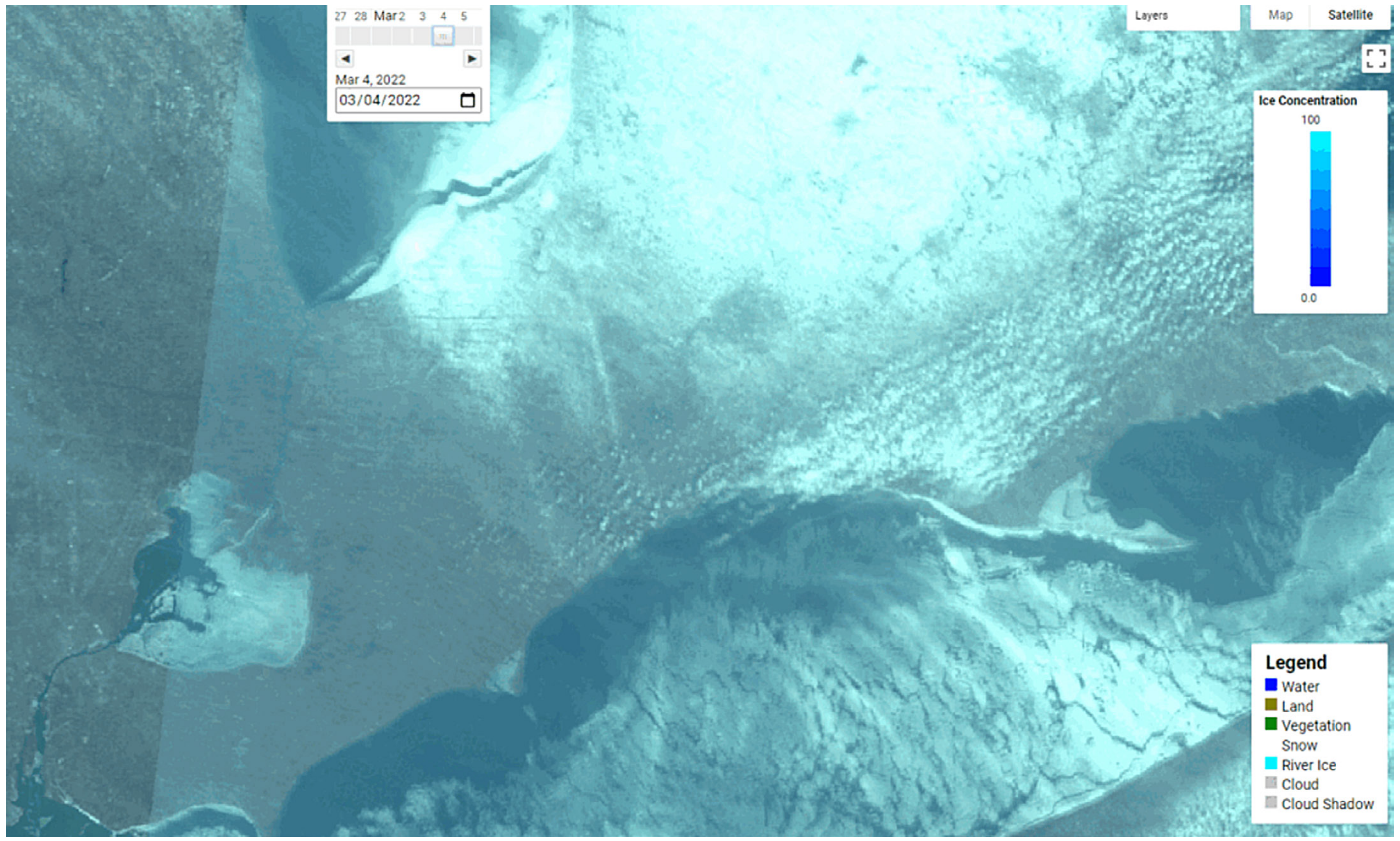
Estimating Ice Concentration

Ice concentration—the fraction of ice covered river (or other water body)—is very important information for the shipping industry and navigation in northern climates. Changes in ice concentration can mean ice cover is fractured and fractured ice is more sensitive to melt, which has implications for ice breakup dates. The River Ice Mapping System estimates ice concentration with the integration of the VIIRS ice concentration product, enabling the user to see changes over time. Monitoring ice concentration variability helps to explain how ice forms, grows, and moves on rivers. The screenshot below shows varying ice concentrations along the Tanana River in Alaska during the spring of 2021 from the River Ice Mapping System. Temimi explains, "The north bank of the river shows lower ice concentrations because of a higher velocity of water, which does not favor the formation and accumulation of ice compared to the southern bank."



Varying ice concentrations on the Tanana River in Alaska on April 25, 2021, as shown by a ground-based webcam (left) and the River Ice Mapping System (right). The webcam confirms the mapping system's output. Note the varying ice concentration along the river that follows the river curvature. In situ webcam data was provided by Fresh Eyes on Ice, a program of the University of Alaska Fairbanks: https://idevs.portal.axds.co/#metadata/75618/station/data.

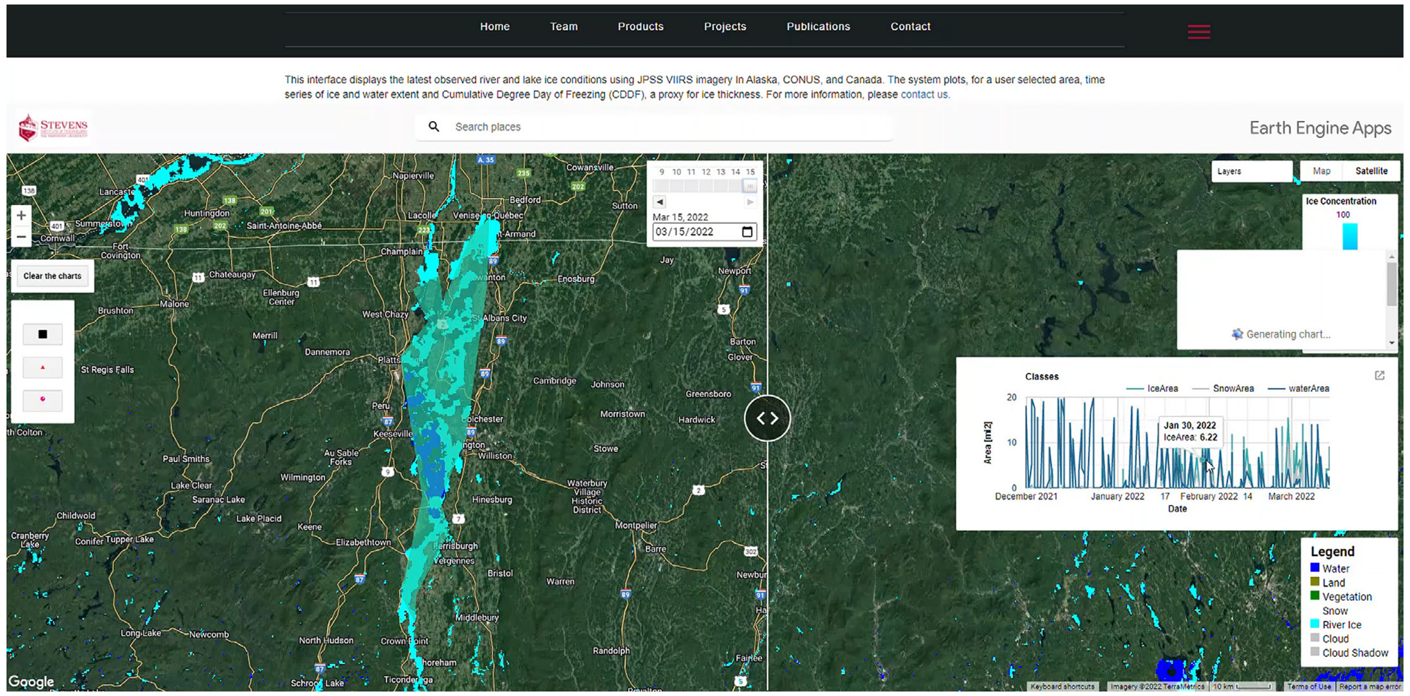
"The portal also allows the user to overlay the VIIRS ice concentration product with images from other sensors like Sentinel-2 or -3," says Temimi. While he has not yet classified Sentinel images—this is work in progress—comparing these observations with VIIRS images helps to show how ice moves and changes throughout the day since Sentinel and VIIRS sensors have different orbit times.



ROLLOVER IMAGE. Screenshots from the River Ice Mapping System show an estimate of ice concentration for St. Clair River, Detroit, MI, on March 4, 2022, from the VIIRS ice concentration product (blue) compared to a Sentinel-3 image (gray-green) from the same day. The comparison shows good agreement. Note that the change in ice motion is due to the gap in overpass time between VIIRS and Sentinel-3.

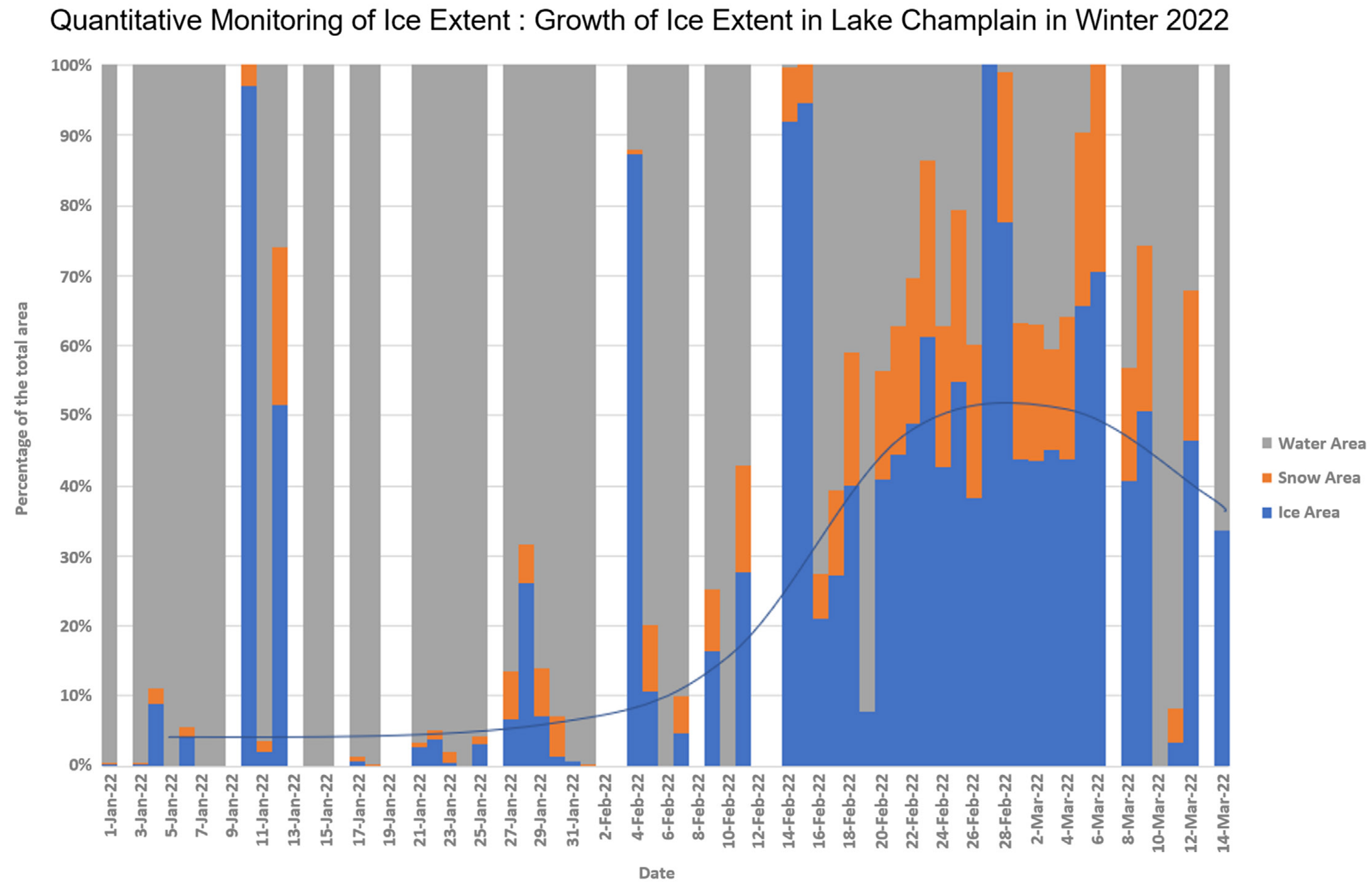
Time Series Graphs of Ice, Snow, and Water Areas

The River Ice Mapping System interface provides a point-and-select geometry tool for defining an area of interest and building a time series graph. The time series graph compares the extent of ice, snow, and water for the selected area, which can be downloaded as a CSV file for numerical analysis in Excel. Time series graphs are valuable tools where each point corresponds to both a time and a quantity that is being measured. In this example, a time series was built for Lake Champlain for the winter of 2022.



CLICK IMAGE TO ENLARGE. The River Ice Mapping System offers geometry tools that can be used to select an area of interest and build a time series graph of ice extent, snow extent, and water extent for the selected area. The screenshot here shows data for Lake Champlain on March 15, 2022.

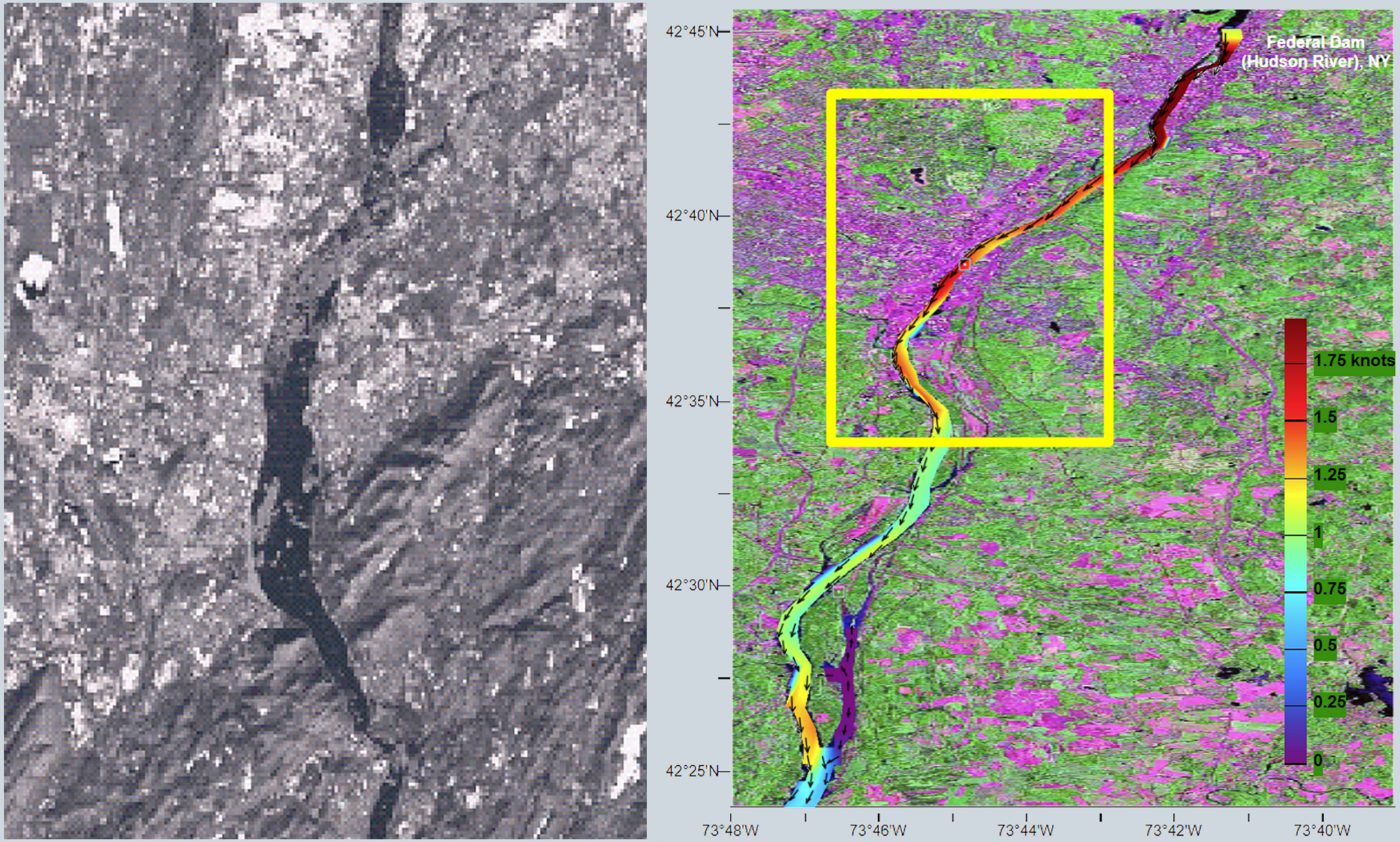
Looking at exported time series data in Excel makes it easy to see the growth in ice area—how ice developed throughout the winter—in this case for Lake Champlain, which reached 50% or more of the entire lake in early 2022. This feature of the River Ice Mapping System allows the user to study the ice conditions of a specified area over days or months, revealing patterns in ice cover formation.



CLICK IMAGE TO ENLARGE.

Inferring Ice Motion and Velocity

As ice moves, it carries with it information about its surface velocity, the speed at which it moves in a particular direction. Atrapid speeds, larger ice chunks and loose ice sheets can knock down trees and damage bridges, boats, and other features in or along a river. Ice velocity also influences the amount of destruction that occurs when a river ice jam breaks—it is not uncommon for a sudden surge of ice to produce rapidly rising waters, leaving people scrambling for safety. By comparing images of the same area on the same day from different sensors onboard different satellites, it is possible to infer ice velocity, which is essential for modeling river ice dynamics and assessing flood hazards during spring break-up. "It is a very important river hydraulic variable that is very difficult to measure," Temimi explains.



ROLLOVER IMAGE ON LEFT: Comparison of VIIRS ice concentration product data (blue) and Sentinel-2 imagery (gray) from the River Ice Mapping System that illustrates ice motion for a downstream portion of the Hudson River in New York on February 26, 2022. Right: Velocity values in the Hudson River on February 26, 2022, from the Stevens Flood Advisory System (https://hudson.dl.stevens-tech.edu/sfas/).

In this example, drifting ice called ice floe was tracked in the Hudson River on February 26, 2022, by comparing VIIRS ice concentration product data with Sentinel-2 imagery in the River Ice Mapping System. Sentinel-2 passed over the area at 10:30 AM EST while VIIRS onboard the NOAA-20 satellite passed over at 2:20 PM EST. This nearly four hour difference gave Temimi an opportunity to measure how far ice moved and calculate its velocity—in this case 3 km, which is equivalent to a surface velocity of 0.2 meters per second (m/s). Temimi confirms, "This is in line with values reported in the literature in other studies and with the NYHOPS[1] system that simulates and forecasts river and coastal hydrodynamics in the area." Ice velocity data is essential for tracking the movement of ice sheets that could cause an ice jam down river.

Mapping Ice Thickness

Ice thickness is another one of the many factors that control the timing of mechanical ice breakups. Thicker ice helps strengthen ice jams when they develop making them potentially more destructive. At the edges of very cold climates, ice thickness can vary from season to season making ice jams difficult to predict. Having an estimation of thickness is important for locating areas at highest risk.

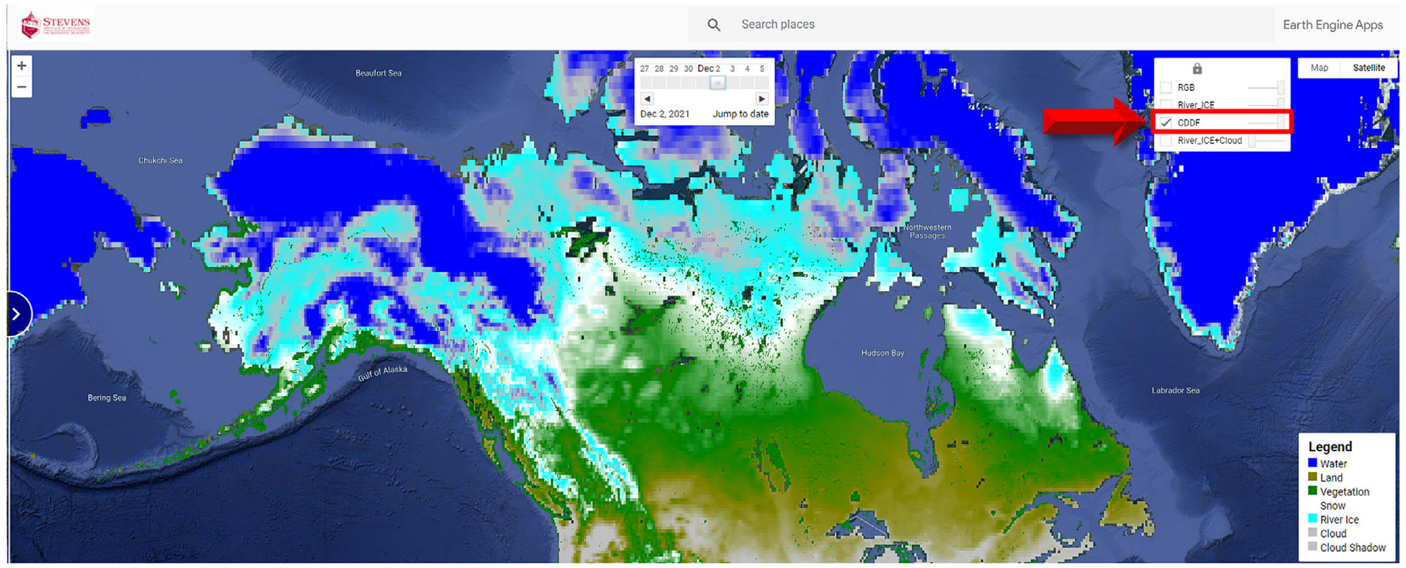
CDDF: What's a "degree day?"

Cumulative Degree Days of Freezing (CDDF) is an indicator of ice growth. It refers to the cumulative number of sub-zero average daily air temperatures—in other words, how much below freezing the average air temperature is on each day, added up over a period of freezing weather.

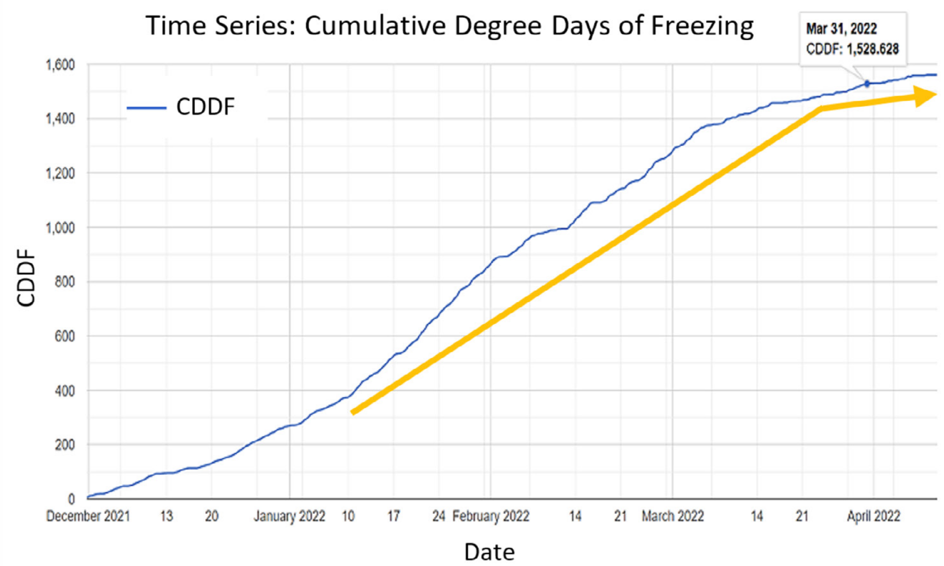
*A "**degree day**" is the difference in average daily temperature from an arbitrary base temperature, in this case, 32°F (freezing). For example, when the average daily temperature is 0°F, the freezing degree days are 32 for the day:* ***32°F – 0°F = 32 degree days**.*

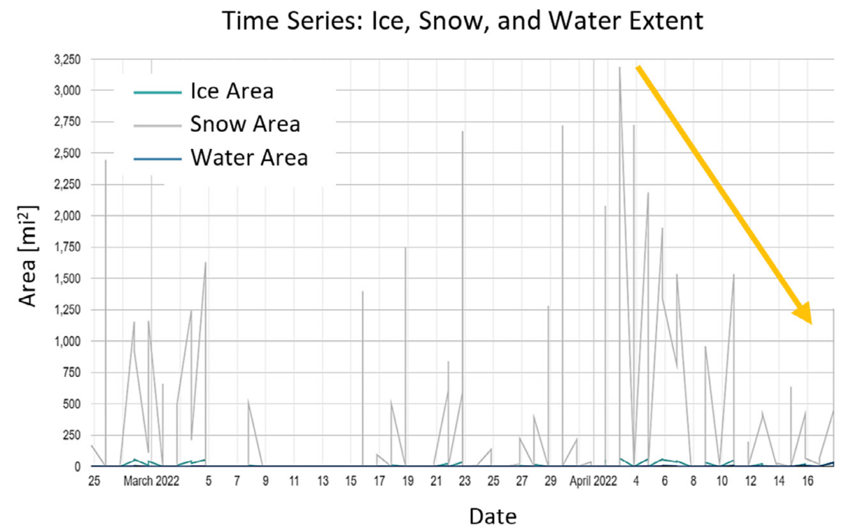
Because direct measurements are not always obtainable, Cumulative Degree Days of Freezing (CDDF) is commonly used to estimate the thickness of ice cover as an indicator of ice growth. In the River Ice Mapping System, users can map CDDF and generate a CDDF time series alongside a time series of ice/snow/water extent for a user-defined area. Time series data is useful in evaluating the relationship between ice thickness and ice extent, especially for local conditions.

Ice extent and CDDF are positively correlated, meaning that as ice extent increases over time, so does CDDF—ice is growing thicker. Conversely, as ice extent decreases, CDDF also decreases, indicating a warming trend that is tied to a decline in ice thickness. A plateau in CDDF generally signals the start of snowmelt (decrease in snow extent) and ice breakup. Example time series data from the River Ice Mapping System (bottom of next page) shows a flattening of the CDDF curve (left graph) followed by a rapid decline in snow extent (right graph) in the same region. This example is discussed in detail in a case study presented later.



CLICK IMAGE TO ENLARGE. Example of CDDF mapping from the River Ice Mapping System portal (screenshot) showing CDDF across Alaska and Canada in December 2021. CDDF is retrieved from the NASA North American Land Data Assimilation System (NLDAS) reanalysis (https://ldas.gsfc.nasa.gov/nldas).



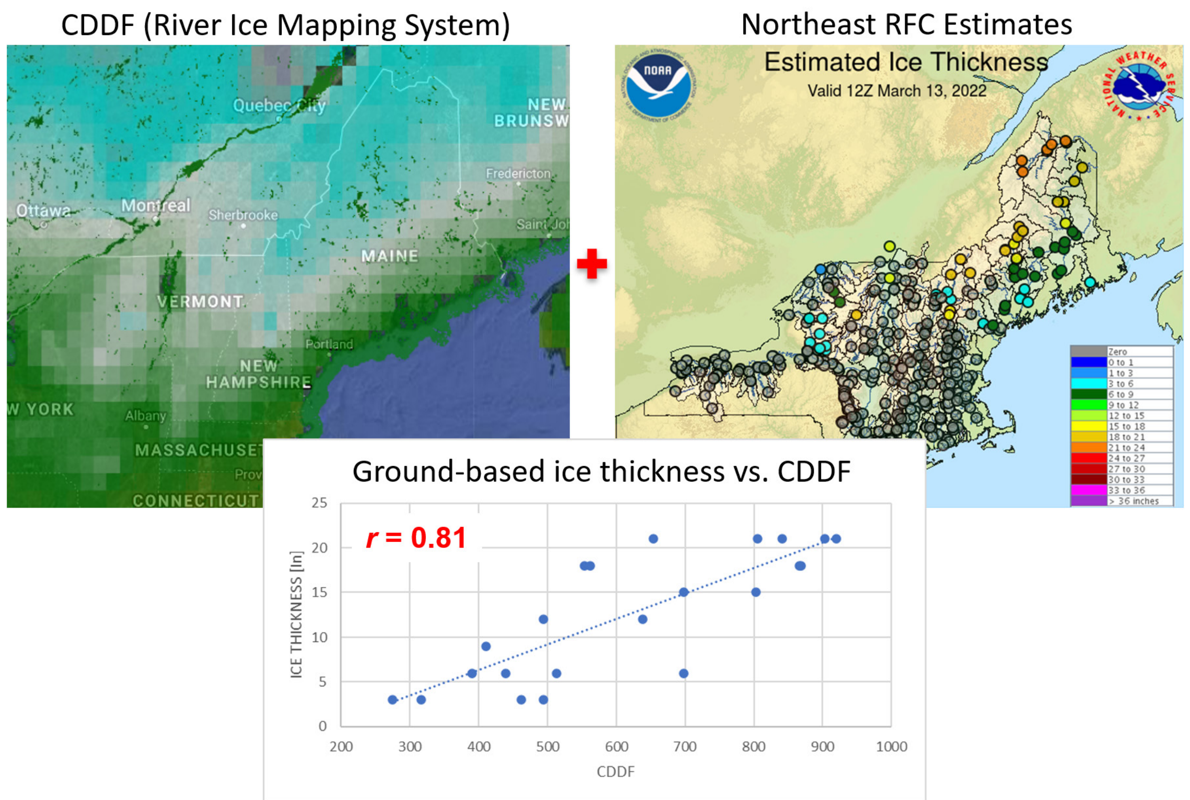


CLICK IMAGE TO ENLARGE. Time series data from the River Ice Mapping System of CDDF (above) showing CDDF plateauing in late March 2022, just before snow extent (right) begins to rapidly decline in early April in the Upper St. John River subwatershed.

r Value

In statistics, the correlation coefficient r measures how closely two variables relate to one another and always ranges between +1 and -1. An r value of +1 means that there is a perfect uphill (positive) linear relationship between the two variables. In other words, the closer the r value is to +1, the better the correlation. The opposite is true for an r value of -1: a perfect downhill (negative) linear relationship, indicating poor correlation.

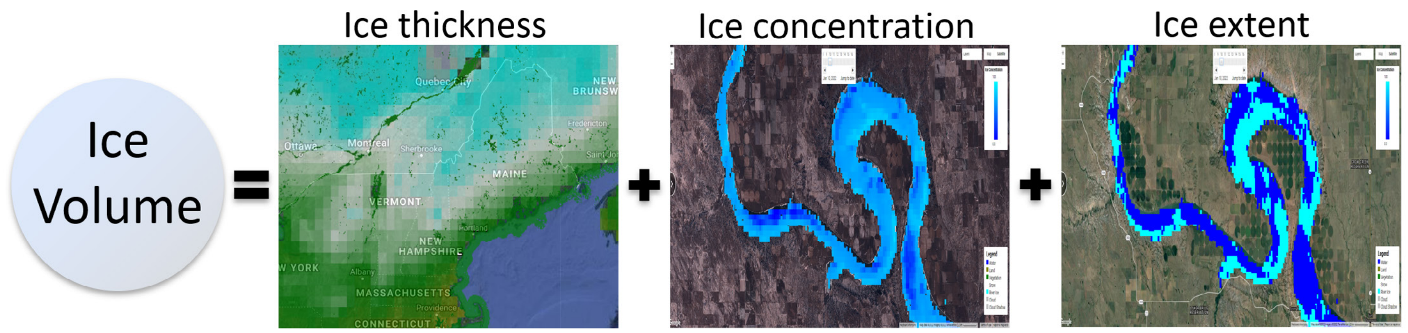
Temimi's team is continuously improving the River Ice Mapping System by adding ground-based data to supplement satellite-derived measurements. "We added ice thickness values reported by the Northeast RFC [River Forecast Center] and improved the correlation between CDDF and ice thickness," remarks Temimi. In fact, an *r* value of 0.81 was calculated when comparing CDDF values (with added Northeast RFC data) from the River Ice Mapping System to ground truth data from the Fresh Eyes on Ice program (below), meaning there is good correlation between the two. "The idea is to eventually replace CDDF using a relationship like this one, which could be region-specific because correlation depends in part on the climatology of the region," says Temimi.



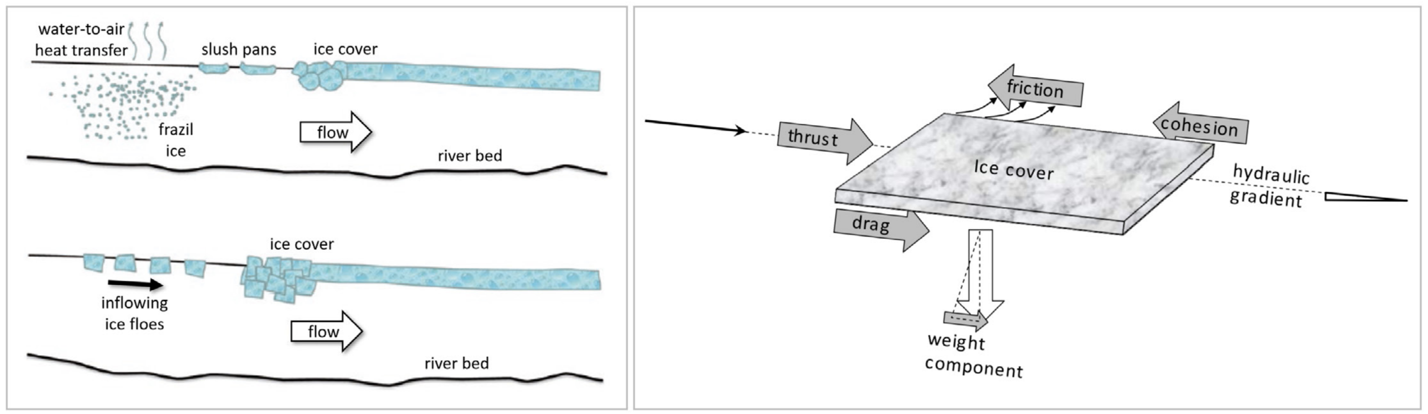
CLICK IMAGE TO ENLARGE. Ground-based ice monitoring data from the Northeast River Forecasting Center (top right) was added to the CDDF product in the River Ice Mapping System (top left), which improved correlation between ground-based ice thickness observations from the Fresh Eyes on Ice program and CDDF output from the River Ice Mapping System (bottom).

Determining Ice Volume

While important variables on their own, ice thickness, ice concentration, and ice extent information combined are helpful in calculating ice volume, which can be challenging to obtain otherwise. Ice volume is a key input for streamflow forecasting and for modeling the impact of ice on the movement of water in northern watersheds—without it, events are difficult to model.



As Temimi explains, these and other variables are used in hydraulic modeling "to simulate the interaction of different forces of friction and river hydraulic movement on the ice floe [drifting ice] and the equilibrium of ice floe." The interaction of these different forces influences ice breakup and ice jam formation. With the River Ice Mapping System, forecasters can estimate many of the key inputs needed for thorough river ice modeling.

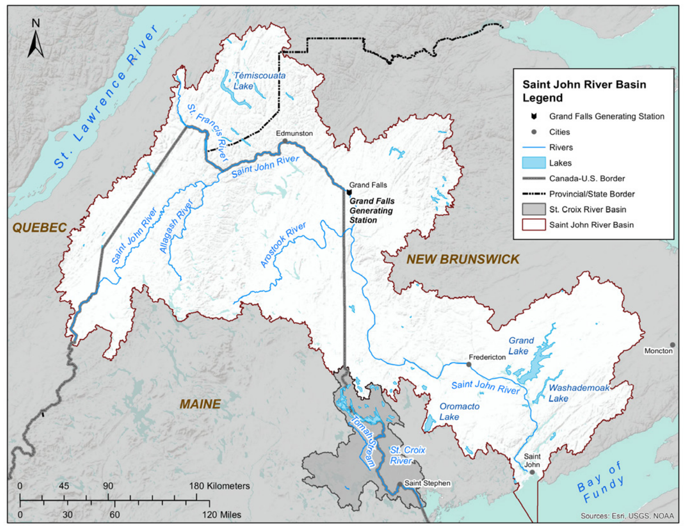


CLICK IMAGE TO ENLARGE. Left: Example of the type of dynamics in ice-covered rivers that must be accounted for in hydraulic modeling. Source: Lindenschmidt 2020. Right: Forces applied on an ice cover. Source: Lindenschmidt 2012.

EXAMPLES OF USING THE RIVER ICE MAPPING SYSTEM FOR RIVER ICE FORECASTING

The Link Between Snowmelt and Ice Breakup: A Case Study in the Upper St. John River Subwatershed

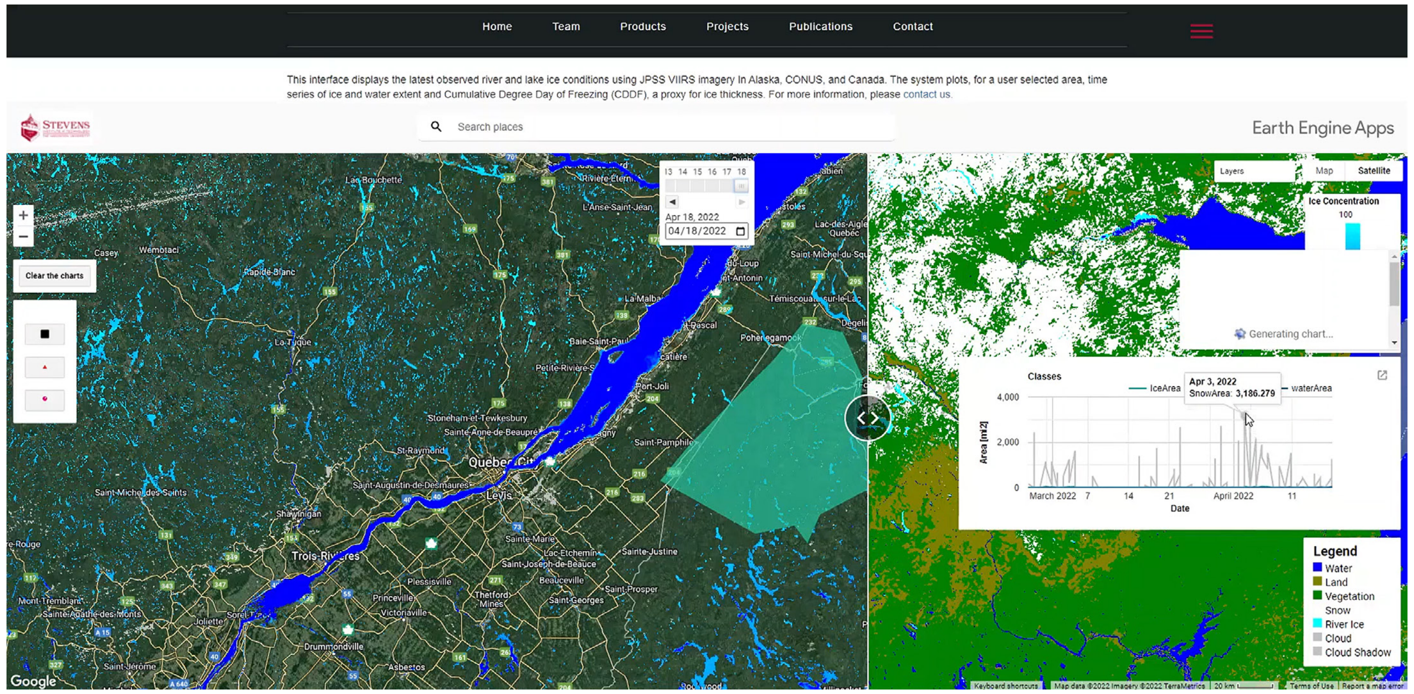
Straddling the border between northern Maine and Canada is the Upper St. John River subwatershed, part of one of the largest river basins on the U.S. East Coast (St. John River Basin) draining more than 21,000 square miles (mi2) of land. Spring ice breakup here causes frequent flooding, and as the climate continues to warm it is thought that flooding will become more severe and frequent in the region. Snow and ice extent information from the River Ice Mapping System can be used to monitor



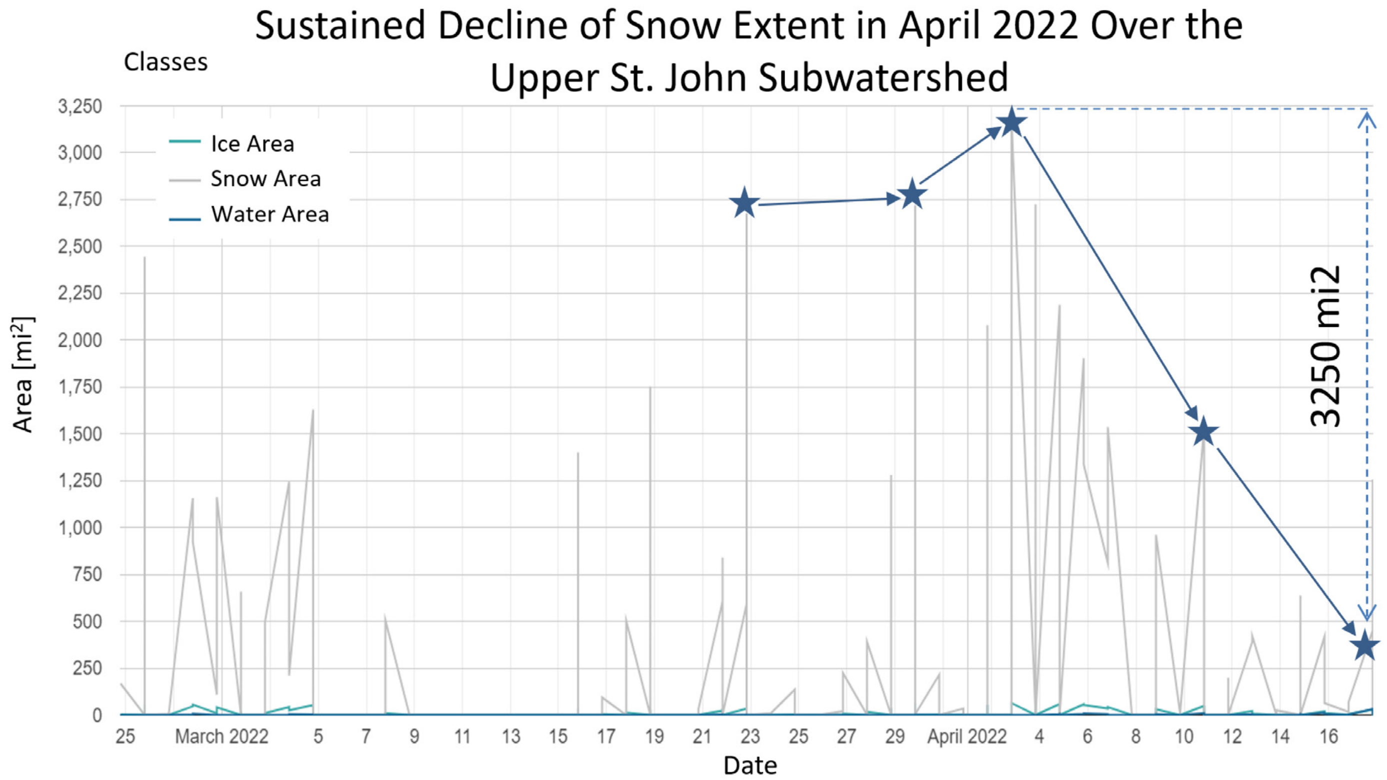
CLICK IMAGE TO ENLARGE. The St. John River Basin. Source: https://ijc.org/en/saint-john-river

snowmelt—runoff produced by melting snow—so that communities can plan for potential hazardous events like flash flooding.

Understanding the interaction between ice, snow, and water can also help decipher how snowmelt triggers



CLICK IMAGE TO ENLARGE. A screenshot of the River Ice Mapping System used to monitor the decline in snow coverage in the Upper St. John River subwatershed in April 2022. The region was selected using the point-and-select geometry tool, which prompted the automatic generation of the snow area extent graph seen on the right.

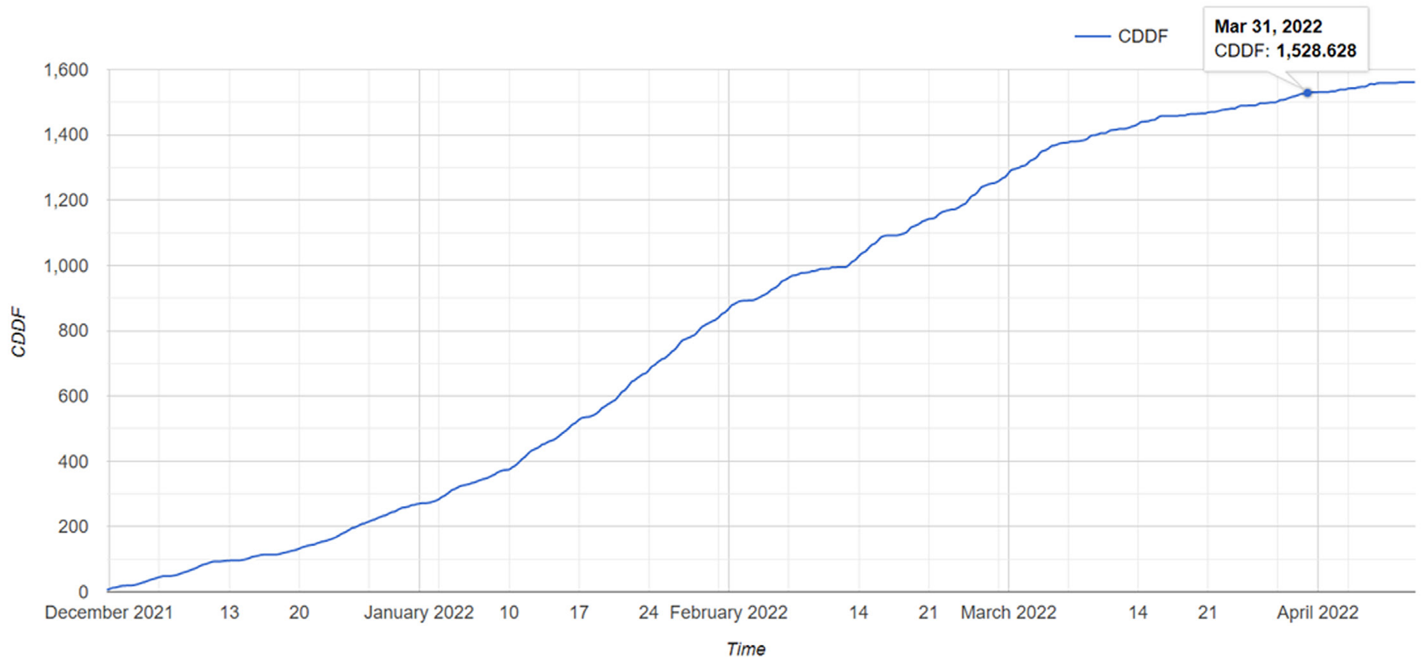


CLICK IMAGE TO ENLARGE. Time series graph of ice, snow, and water area generated by the River Ice Mapping System for the Fort Kent, ME area of the Upper St. John River subwatershed. Blue stars (added after download) indicate cloud-free scenes that were used to calculate the volume of snowmelt in April 2022.

ice breakups. "The endpoint is the breakup itself, but we'd like to know the precursors, what leads up to the breakup, which is useful in monitoring and forecasting breakups," says Temimi. Knowing how early in terms of days and volume that snow starts to melt before ice begins to break is key information for river ice forecasting.

In the case of the Upper St. John River, the River Ice Mapping System showed a sustained and rapid decline of snow coverage (snow class from VIIRS) in the first half of April 2022 over an area upstream of Fort Kent, Maine. Using cloud-free scenes from the automatically generated time series graph (indicated by blue stars on the plot above), Temimi's team estimated about 3,250 mi^2 of snowmelt in an 18 day period.

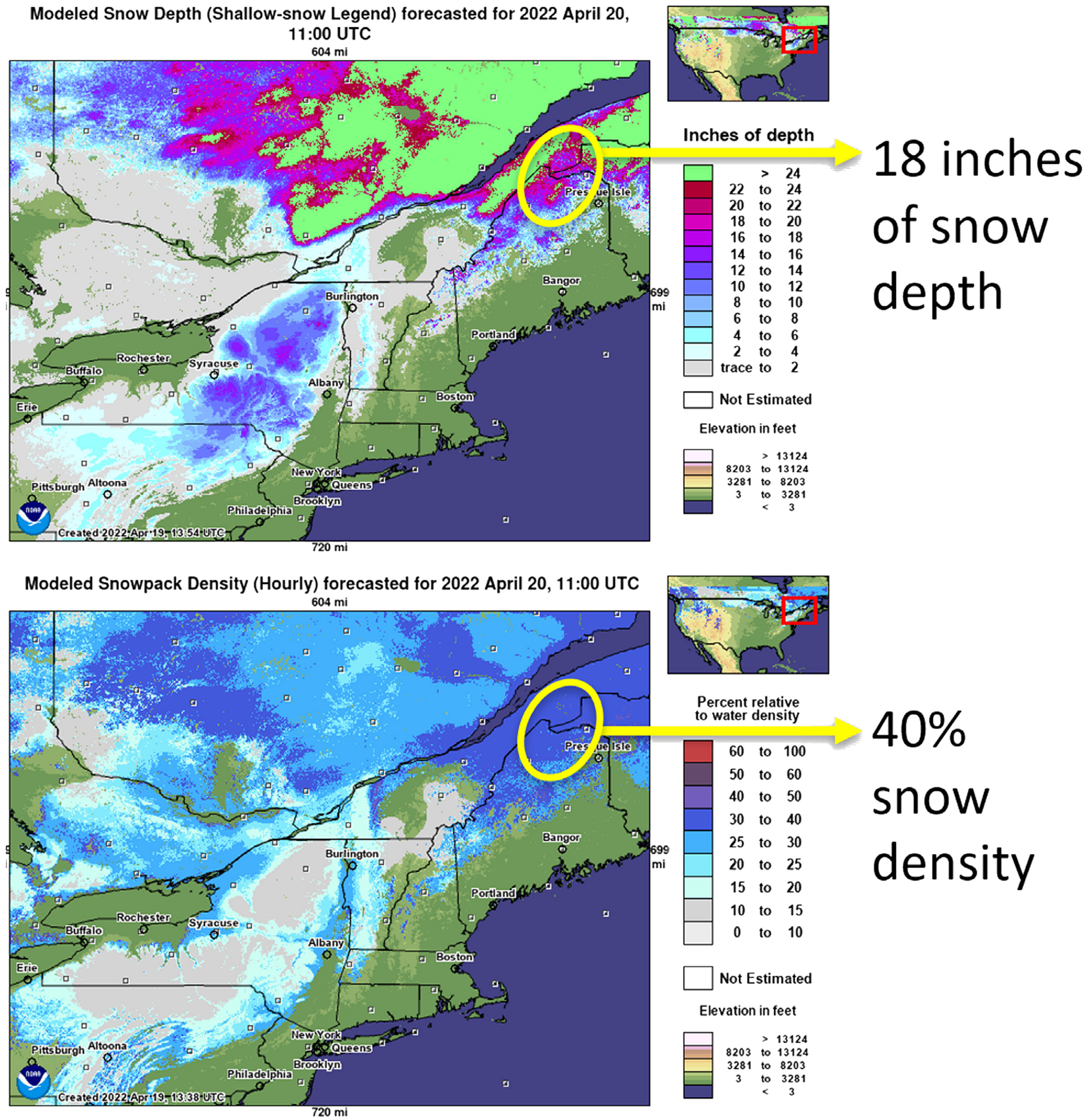
The start of snowmelt prior to ice breakup was further confirmed when the team looked at CDDF from the River Ice Mapping System, which flattened at the start of April (plot on next page). The plateau means that temperatures were consistently above freezing around the same time that steady snowmelt began, as shown in the ice, snow, and water extent time series, above.



CLICK IMAGE TO ENLARGE. Cumulative Degree Days of Freezing (CDDF) over time for the Fort Kent, ME area of the Upper St. John River subwatershed.

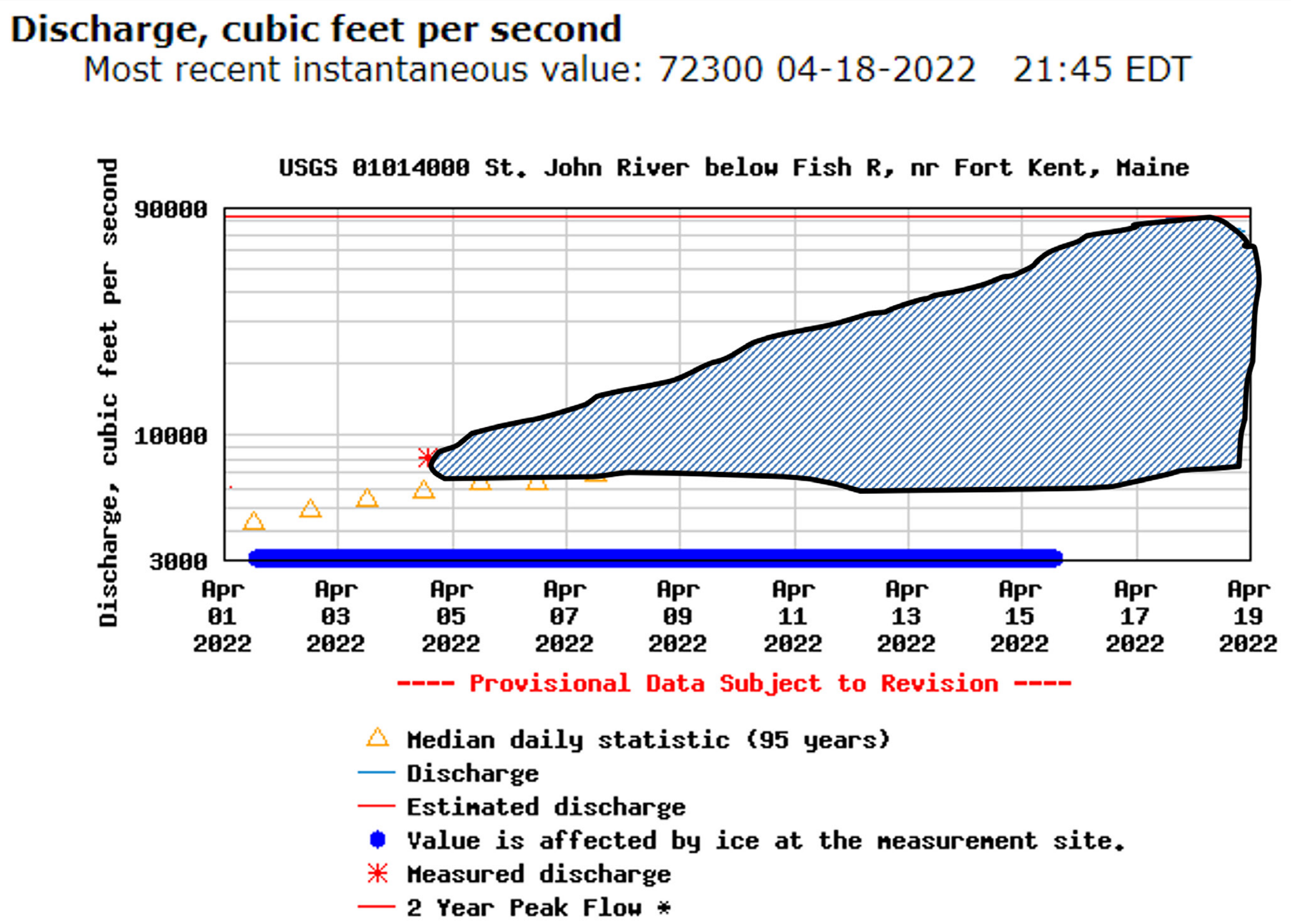
With these data confirmed, Temimi wondered how much runoff had been generated by the 3,250 mi^2 of snowmelt, an indicator of flood risk. "We looked at NOAA snowpack density and snow depth data for the region," says Temimi, which showed 18 inches of snow depth and 40% snowpack density (relative to water density) on April 20, 2022, in the Fort Kent area. Altogether, this translates to about 51 billion cubic feet (ft^3) of runoff from snowmelt.

This information is important because runoff is a major factor in the timing and severity of river ice breakup and likelihood of ice jam flooding. When temperatures warm in the spring, runoff from snowmelt can push a significant amount of water into a river. The force from a surge of water can cause river ice to float and move (mechanical breakup), giving rise to ice jams in river bends and narrow channels downriver and triggering water upstream to rise very rapidly. Sometimes flow is so constricted along the main river that water backs up and causes flooding in tributaries miles away from the ice jam. Knowing the potential for runoff is essential for management and monitoring.



Modeled snow depth and snowpack density for April 20, 2022, from the NOAA Northeast River Forecast Center. www.weather.gov/nerfc/Snow

To verify their calculation from River Ice Mapping System data, Temimi's team checked ground-based discharge data from the USGS Fort Kent gaging station. The USGS discharge curve estimated about 61 billion ft^3 of added runoff from snowmelt, which is close in magnitude to the volume inferred by VIIRS data from the River Ice Mapping System (51 billion ft^3). Temimi notes, "There are major uncertainties here, but the purpose of comparing these was to find out if at least we were talking about the same order of magnitude." And yes, they were. This similarity in output helps validate the River Ice Mapping System and its use in understanding the dynamics between snow and ice for forecasting.



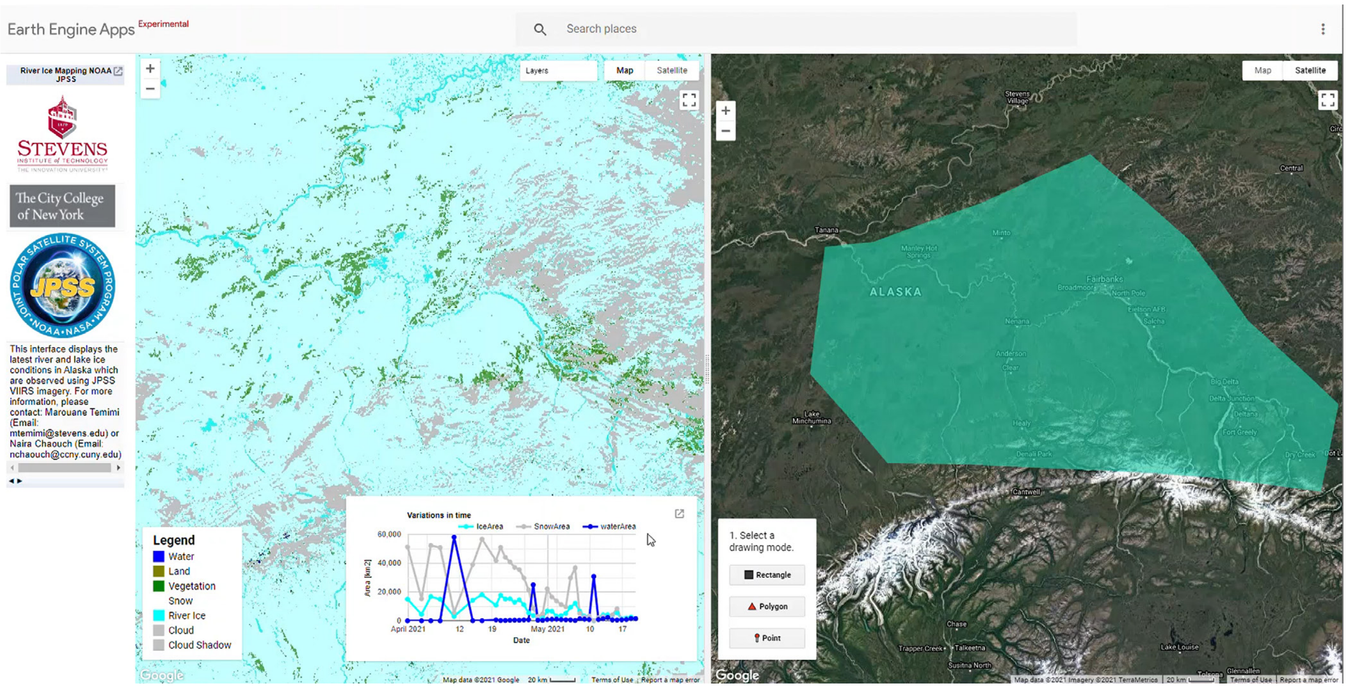
Discharge data (cubic feet per second) from the USGS Fort Kent, Maine stream gage station in the Upper St. John River subwatershed. The shaded area indicates the estimated volume of added runoff from snowmelt.

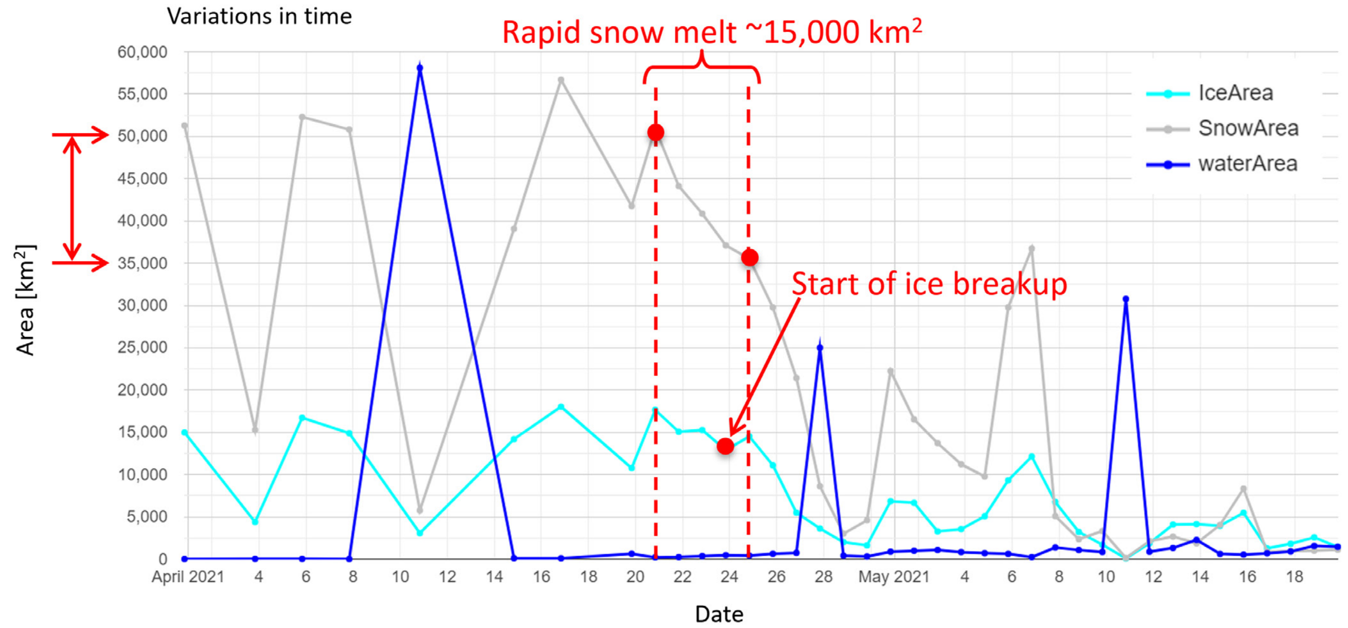
Remotely Sensing the Precursors of Ice Breakup: An Alaskan Example

The Tanana River is a 584-mile tributary of the Yukon River that flows in a northwest direction across Alaska. Ice breakup dates are occurring earlier in the region and are difficult to predict, and ice jam flooding is affecting Tanana River communities more frequently. In just one example, about half the residents of Manley Hot Springs, Alaska, were displaced in May 2022 because of major flooding from an ice jam on the Tanana about 12 miles downriver. It was the worst flooding in 45 years according to the National Weather Service and was brought on by rapid snowmelt and the breakup of ice from rapidly warming temperatures. "The detection of snowmelt and its progress could be an important precursor that indicates locations where mechanical breakup could be triggered in rivers," explains Temimi. The River Ice Mapping System is just the tool for the job.

CLICK IMAGE TO ENLARGE. Tanana River, Alaska. Map derived from https://commons.wikimedia.org/wiki/File:AK_map_Tanana_river.svg.

To demonstrate, Temimi and his team selected the Tanana River watershed in the system interface to generate a time series of ice, snow, and water extent. Like in the Upper St. John River, they saw a swift decline of snow cover that produced a large volume of melt water in a short period. Here, snow began to rapidly melt on April 21, 2022, melting about 9,300 mi^2 (15,000 km^2) of snow cover within four days, which led to a mechanical ice breakup in the Tanana River around day three.

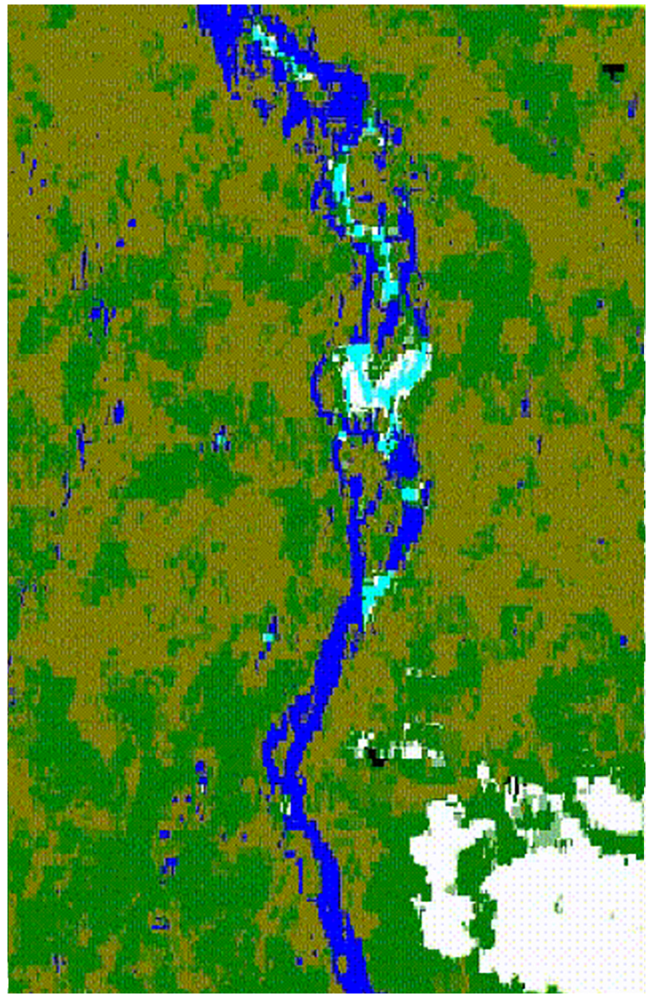




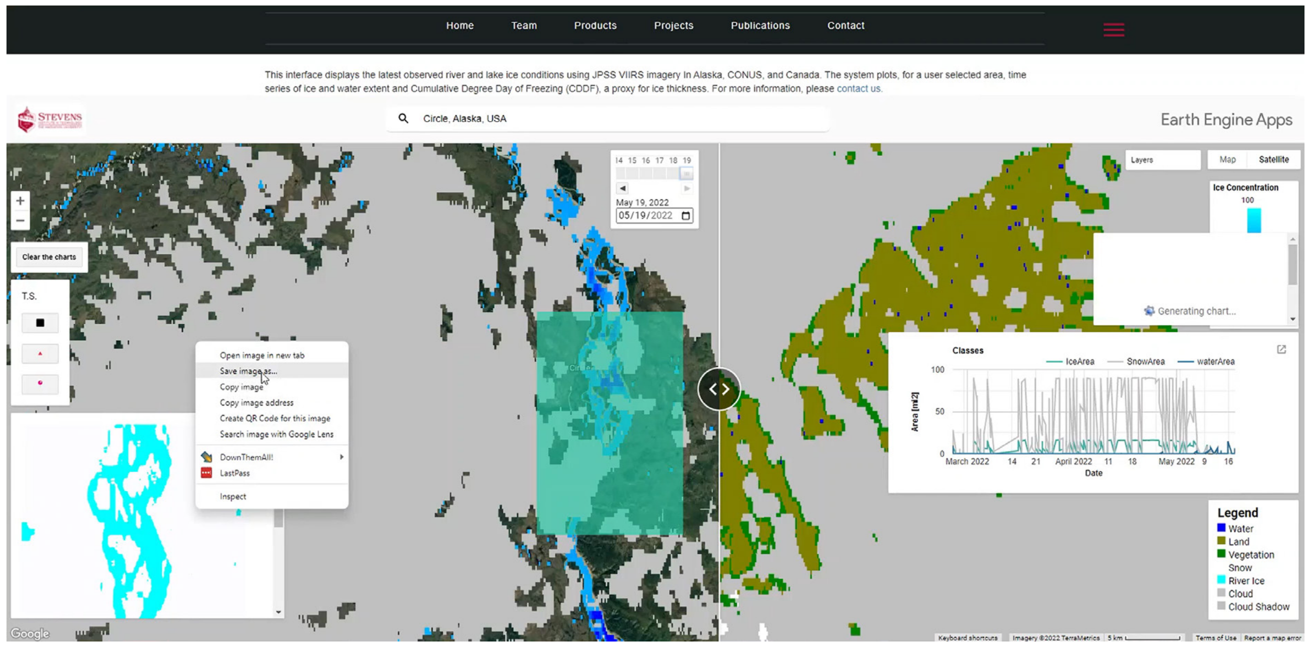
CLICK IMAGES TO ENLARGE. Top: Screenshot showing the Tanana River watershed. Bottom: The time series graph that was automatically generated for the selected area in the system. Explanatory text (red) was added to the graph after download.

The purpose of this example is to highlight how the River Ice Mapping System can be used to infer a relationship between ice extent and snow melting—here, the link is obvious on both the interactive map and the time series graph. But these relationships are unique to a location because snow and ice properties and topography vary by region, which impact melting and the timing of ice breakup. “That’s why the capabilities that we have with the system for the user to generate this relationship locally with retrospective data is very useful for forecasting ice breakups,” says Temimi. With more validation underway, the River Ice Mapping System so far has shown to be a reliable source of both near-real time and historical conditions that provide information about the timing of future events.

Using Animations To Understand Ice Breakup Dynamics

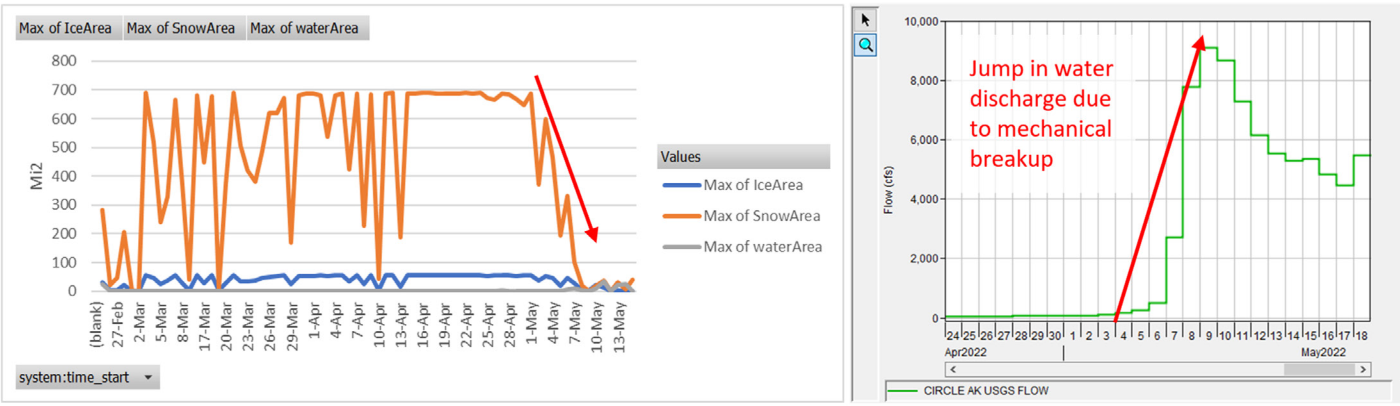


Animations of sequential satellite images can help explain the dynamics of river ice breakup, highlight change over time, and provide valuable context to better understand the impact of environmental events like ice jam flooding. When an area of interest is selected in the River Ice Mapping System, a downloadable animation (GIF) is automatically created in the interface. The rollover image on the right is the type of imagery that can be saved as an animation. This example shows the evolution of an ice breakup event over an area selected around Circle, Alaska (below). Temimi explains, in the animation “we start to see melt and how the melt occurs downstream and upstream as the temperature starts to rise, then ice disappears on the river.”



CLICK IMAGE TO ENLARGE. The screenshot (above) demonstrates the capability of the River Ice Mapping System to automatically create animations of a selected area (screenshots shown in rollover image top right), which can be downloaded and saved. Here, the rollover image shows the development of snowmelt and ice breakup around Circle, AK in the spring of 2022. Light blue indicates ice, dark blue indicates water, white indicates snow cover, and green/brown indicates vegetation. Flooding was reported by the Alaska Pacific RFC on May 10, 2022, which corresponds to peak water extent as indicated by the product.

Looking at the time series of ice and snow extent for the same region (also automatically generated when an area is selected), the ice breakup can be linked to rapid snowmelt in the first week of May (below left, indicated by the red arrow). Following the breakup was a dramatic increase in runoff that caused area flooding, confirmed with streamflow measurements from the Circle, AK USGS gaging station (below right). "The important thing here is to point out that the user can visually determine the causality between snowmelt and ice breakup and in which part of the subwatershed this happens," Temimi says. If the behavior repeats itself season after season and a pattern is established, ice jams or breakups could be predicted more accurately.



The snow area time series for Circle, AK in spring 2022 from the River Ice Mapping System (left) shows a sharp decrease in snow extent starting on May 1, 2022, which corresponded to a rapid increase in water discharge due to the mechanical breakup of ice as reported by the USGS Circle, AK station (right) and resulted in flooding around May 10, 2022.

LOOKING AHEAD

With help from NOAA and other end users, Temimi's team continues to validate the performance of the River Ice Mapping System. The system has proven reliable in enhancing the understanding of snow and ice dynamics. The team plans to add more observations to the system because, as Temimi points out, "the more information we collect, the better the monitoring." One idea is to integrate observations from the Canadian Space Agency RADARSAT Constellation Mission (RCM) to fill data gaps from cloud interference. Unlike VIIRS, the RCM can see through clouds so images of the Earth's surface can be obtained no matter the weather conditions. Another idea is to use reflectance data from the VIIRS Day/Night Band to support nighttime monitoring of river ice. More sensors also mean more observations at different overpass times for tracking ice movement. With these and other expanded capabilities, like automated alerts and daily reports, Temimi hopes to increase the effectiveness of the River Ice Mapping System assisting in the response to river ice jams and the flooding that often accompanies it. ✦

STORY SOURCE

The information in this article is based, in part, on the July 12, 2022, JPSS Science Seminar "Satellite River Ice Product" presented by Dr. Marouane Temimi, Associate Professor, Stevens Institute of Technology, Hoboken, NJ.

FOOTNOTES

1 NYHOPS is the New York Harbor Observing and Prediction System available at https://hudson.dl.stevens-tech.edu/maritimeforecast/index.shtml.

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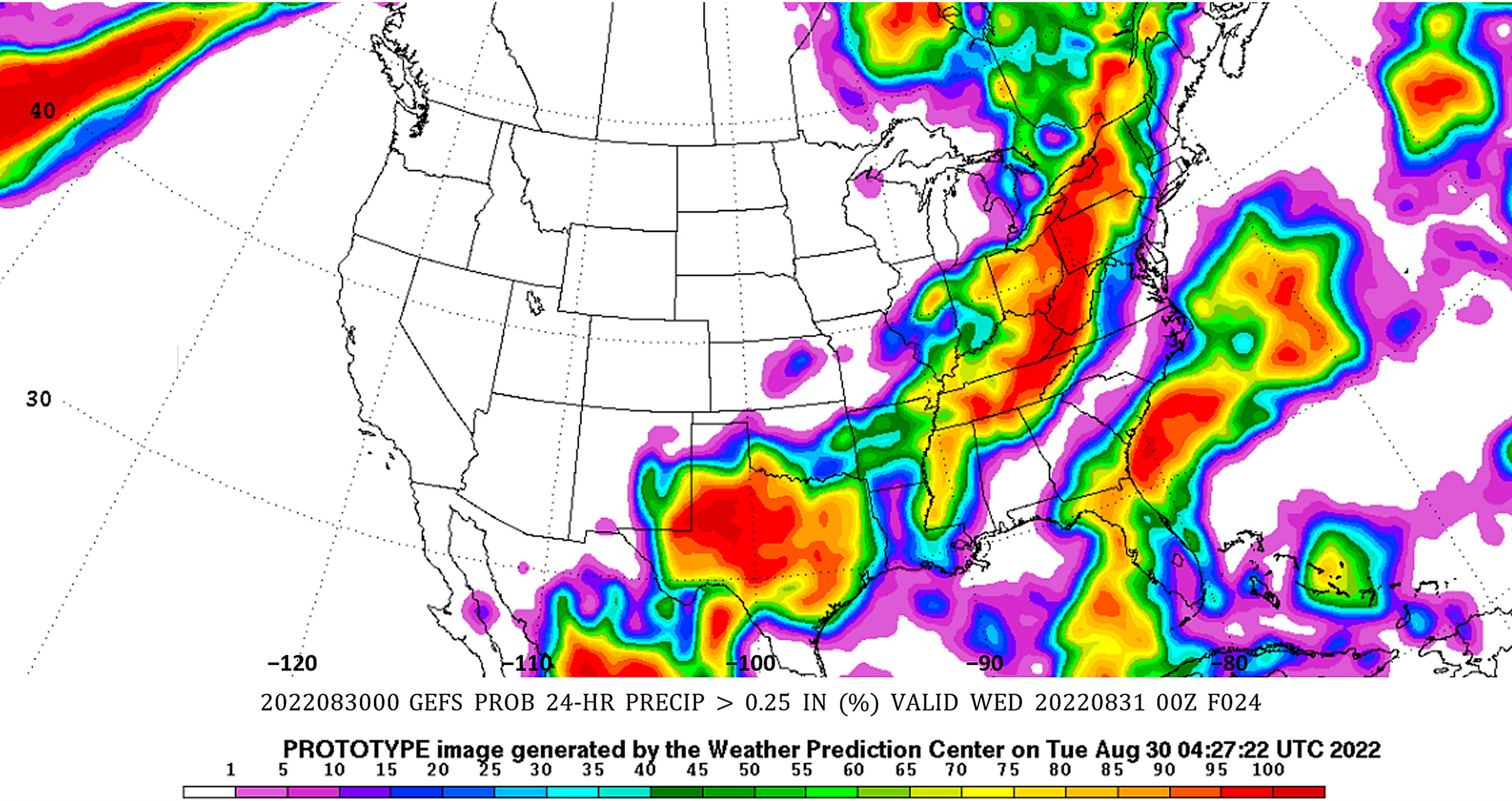
FEATURE 10

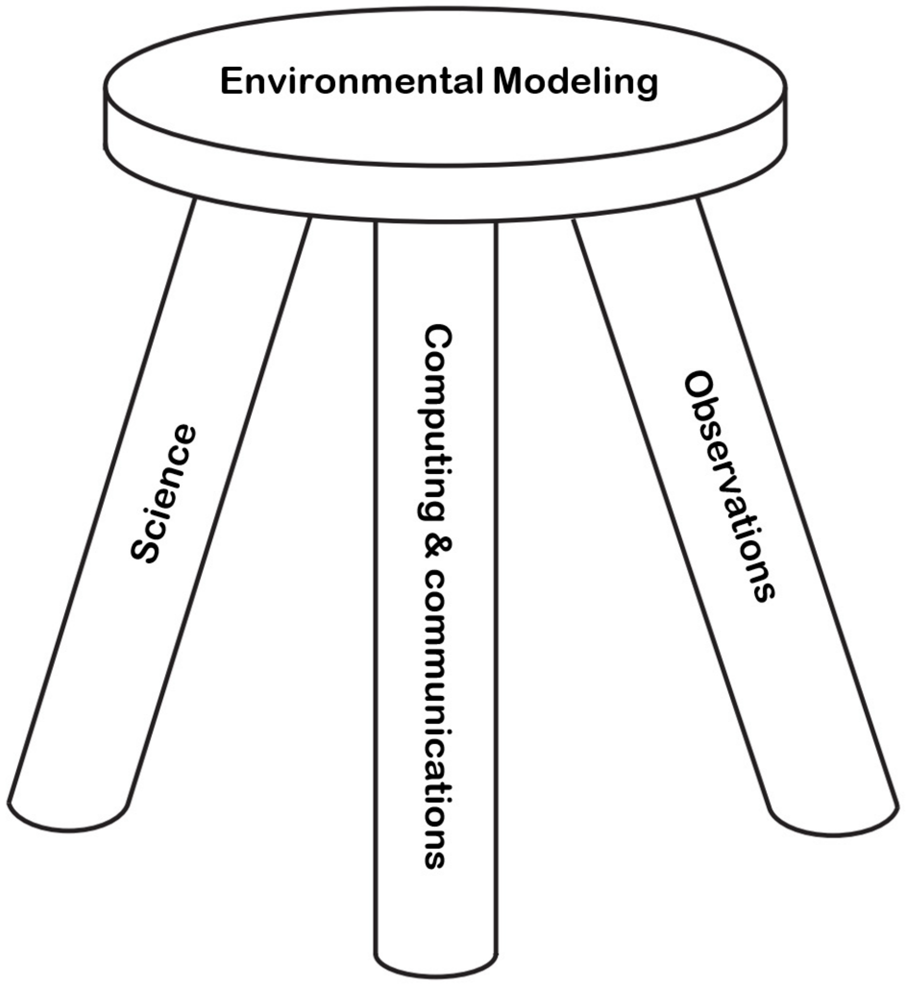
The Role of the Joint Center for Satellite Data Assimilation in Data Assimilation for Better Weather and Climate Prediction

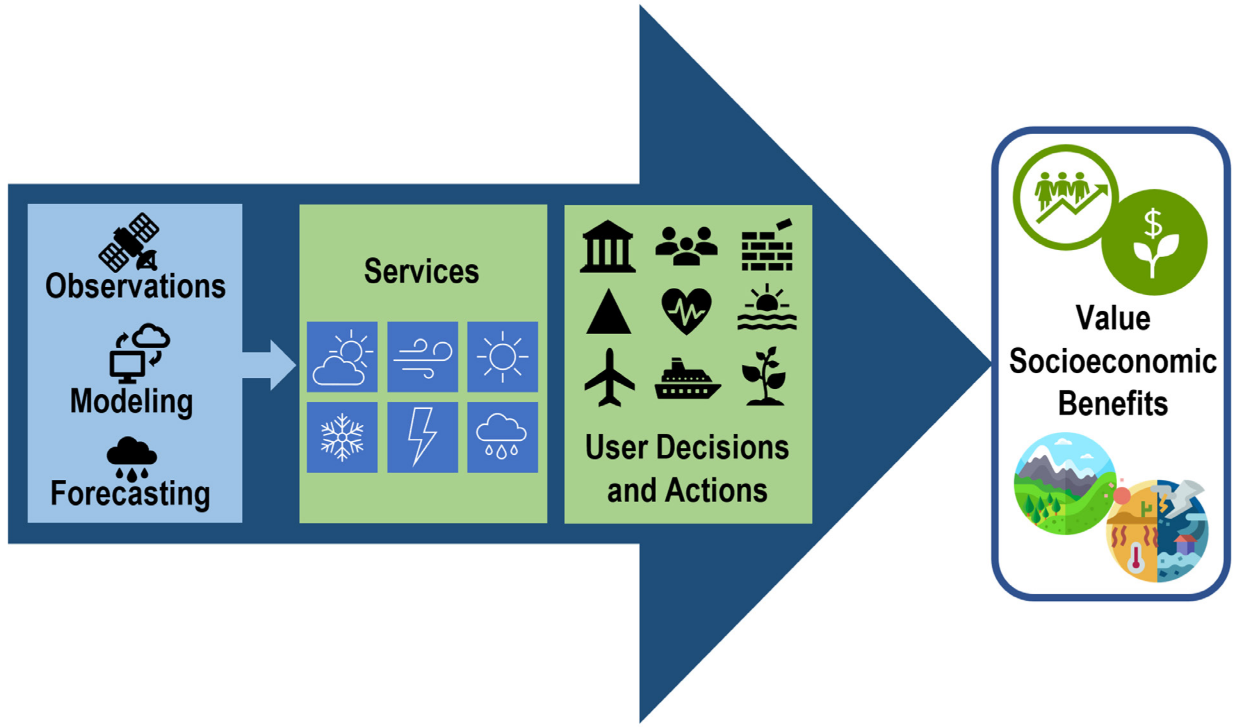


A prototype product showing probabilistic forecasting for precipitation greater than 0.25 inches for the lower 48 states from the Global Ensemble Forecast System (GEFS) generated by the Weather Prediction Center (experimental web page). The GEFS is a weather forecast model made up of 21 separate forecasts, or ensemble members. Source: https://www.wpc.ncep.noaa.gov/exper/toolsbody.html.

Environmental models are mathematical representations of complex environment processes that occur in the real world. They are used to predict the weather, study the climate, investigate coastal conditions, and much more. Environmental models improve the understanding of how natural systems react to changing conditions. They help inform decisions and policy and are invaluable tools in predicting outcomes and future events. Numerical Weather Prediction (NWP), a method of weather forecasting, is one of the most common examples of environmental modeling.

Dr. Louis W. Uccellini, retired director of the U.S. National Weather Service (NWS), has likened environmental modeling to a three-legged stool where the "legs" are observations, computing and communications, and science. Observations establish the initial state of the system being predicted, computing and communications involve moving and processing data and performing predictions, and science includes developing modeling, data assimilation systems, and subject matter expertise to interpret the results. "The three-legged stool is not a static picture—there are always evolutionary considerations," explains Dr. James G. (Jim) Yoe, Chief Administrative Officer for the Joint Center for Satellite Data Assimilation (JCSDA), continuing, "All the elements of the three-legged stool change over time as computing resources increase, scientific understanding gets better, and we get new and improved observations, which provide a better understanding of the environment."





Left: The socioeconomic benefits of weather forecasting through the hydrometeorological value chain. Figure adapted from Kull et al. 2021 using design elements from Freepik/Flaticon. Right: Minimum global socioeconomic valuation of the benefits of weather prediction. Source: Kull et al. 2021.

In the case of operational NWP models, assimilation of satellite observations considerably reduces model forecast error. This is important because the value of accurate weather prediction is immense, going far beyond the protection of people and property during extreme weather events. The World Bank recently valued the global socioeconomic benefits of weather prediction at $162 billion U.S. dollars, at minimum, with the greatest benefits seen in the disaster management, agriculture, energy, and transportation sectors. With such an impact, forecast accuracy is paramount.

Keeping with the three-legged stool concept, a reliable forecast needs a good NWP model and data assimilation system (science), good data to assimilate (observations), and computing capabilities to process it all and perform complex calculations at high speeds (computing and communications). The JCSDA has the expertise to develop data assimilation infrastructure for environmental models and share their research with operational and research communities around the globe. At the January 29, 2022, JPSS Science Seminar, Dr. Yoe provided an overview of satellite data assimilation in weather forecasting, insight into the collaborative nature and capabilities of the JCSDA, and a look into future pursuits.

THE IMPORTANCE OF ACCURATE WEATHER FORECASTING

Private individuals, all levels of government, and organizations across all economic sectors use weather forecasts to support decisions ranging from whether an event should be postponed due to rain to issuing severe weather warnings to protect life and property. The impact of weather is far-reaching and accurate forecasting is critical to support effective decision-making.

Weather forecasts range from hours in advance (nowcasting and short-range forecasting) to days and weeks ahead (medium- and long-range forecasting) to several months in advance (sub-seasonal to seasonal forecasting). Each has its own applications—nowcasting, for example, is used in aviation for predicting very short-term phenomena such as lightning. Medium- and long-range forecasts that look days to weeks ahead are important for planning a wide variety of activities like when to plant crops, snow removal pre-positioning, holiday events, when to deploy personnel and equipment to help restore power, hurricane evacuation orders, mosquito management, commercial aircraft rerouting, water resource management, and so on.

Improvements in forecast skill and communication benefit society by allowing federal, state, and local officials, businesses, and individuals to make decisions and to take timely action in response to weather conditions. A key component in precise forecasting is data assimilation, which is used to make sure that forecasts closely match current observations.

Weather forecasts

Short-range forecast: 0-48 hours ahead

The NWS issues short-range forecasts by part of the day, for example, today, tonight, etc. Nowcasting is a short-term forecast made for less than 6 hours ahead and is very accurate.

Medium-range forecast: 3-7 days ahead

A seven-day forecast can accurately predict the weather about 80% of the time and a five-day forecast can accurately predict the weather about 90% percent of the time.

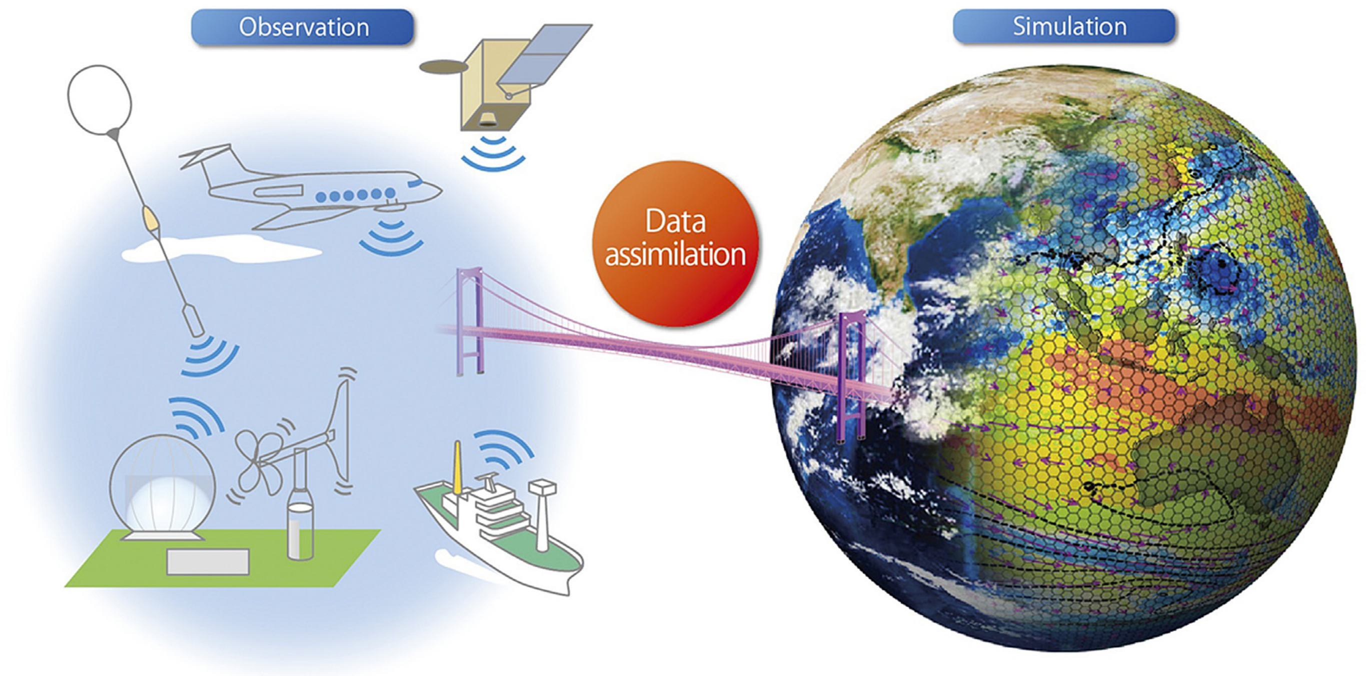
Long-range forecast: >7 days ahead

These include 8-14-day outlooks, monthly outlooks, and seasonal outlooks.

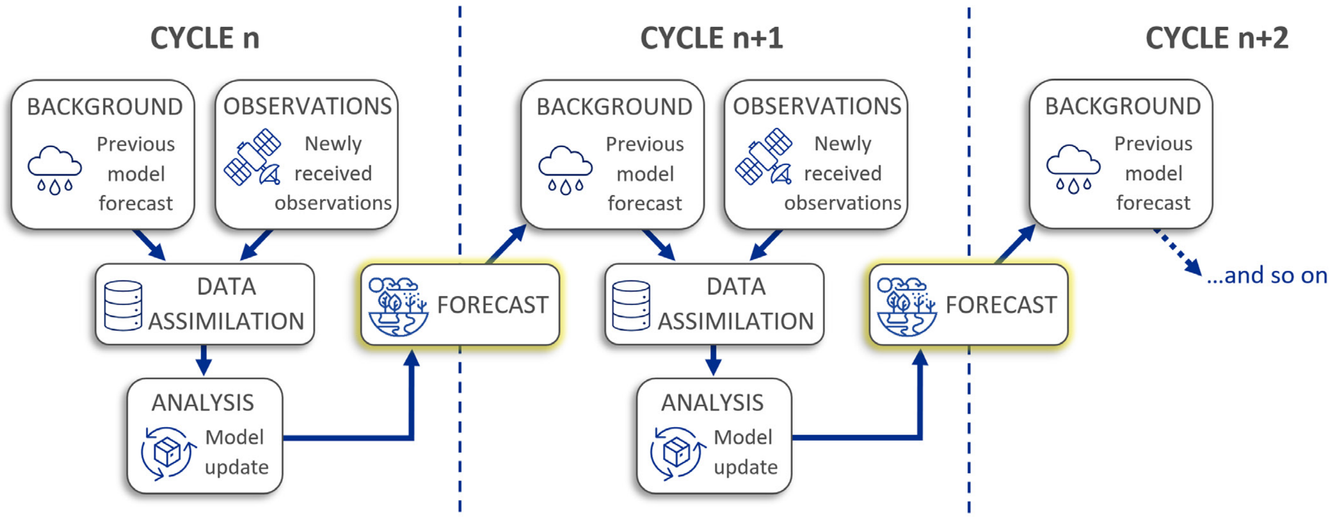
Data Assimilation: What Is It and Why Is It Needed?

Data assimilation involves the fitting of a prediction model to observed data providing a reality check to guide the model. In weather prediction, data assimilation often involves combining Earth observations with short-range forecast model data to create an updated forecast. The goal is to best predict atmospheric conditions for a location, to quantify the uncertainty associated with the prediction, and to do so quickly. Yoe explains, “In data assimilation, you’re trying to get to the best analysis as quickly as you reasonably can in order to get the most accurate result from whatever environmental model you’re running.”

About 80% of observations assimilated in global NWP models come from satellite sensors with the remaining 20% from other sources, like radiosondes onboard weather balloons, surface-level instruments, sensors on drones or airplanes, radar, ocean buoys, and weather ships. While satellites provide a great deal more information than surface-based instruments, the latter are generally more accurate due to lower signal strength and other issues sometimes associated with space-based observations. Using surface measurements alongside satellite data delivers a good balance between data quantity and data quality and helps fill data gaps.

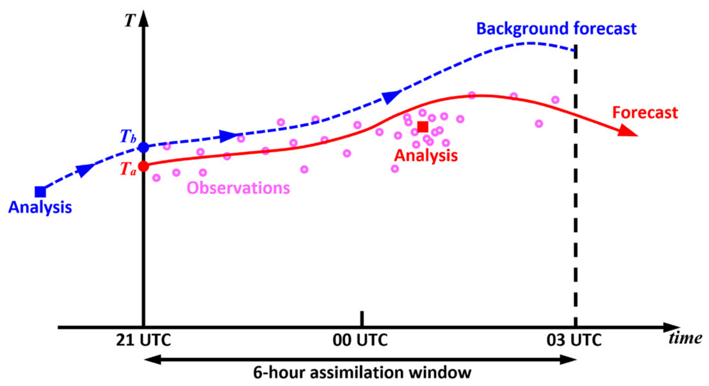


Data assimilation is the bridge between real-world observations and computer simulations. Observations from many sources increase the accuracy of weather forecasting through numerical weather prediction models. Source: RIKEN AICS.



Satellite observations are the main data source for NWP models in large part because satellites provide continuous spatial and temporal coverage of the globe, including remote areas like oceans and deserts where surface observations are sparse. Before forecasters use data from instruments like the JPSS Advanced Technology Microwave Sounder (ATMS) and Cross-track Infrared Sounder (CrIS), the data must first be assimilated into environmental models. In weather prediction, this is a cyclical process in which a previous estimate of the state of the atmosphere called the "background" (that is, the previous model forecast that includes prior observations) is compared with new observations to produce an "analysis" where the model is updated to align with the new observations. This analysis—the update step—is the estimate on which numerical weather forecasts are based.

Data assimilation is fundamental to successful NWP. It adds value to observations by filling data gaps in space and time and to models by correcting them to fit new observations. Data assimilation techniques have been successfully applied to NWP for several decades, but are also used to study the Earth's climate, evaluate air quality, assess renewable energy resources, and analyze the value of global observations. In support of these and other applications, the JCSDA plays a central role in the development of operational assimilation of satellite data thanks to their collaborative approach and unified systems.

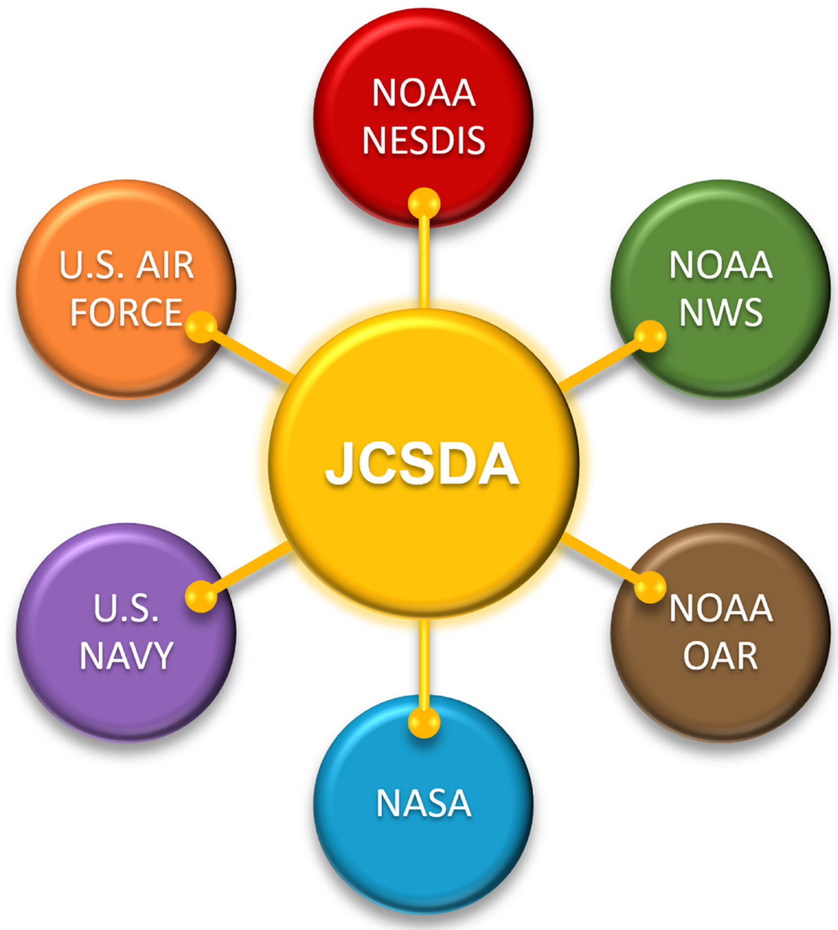


CLICK IMAGE TO ENLARGE. An example of a 4-dimensional variational (4D-Var) data assimilation system, which determines a correction to the background initial condition (blue line) that leads to an analysis that is somewhere between background and observations. In simplest terms, the analysis is a weighted mean of the background and observations. Source: Owens and Hewson 2018.

THE JOINT CENTER FOR SATELLITE DATA ASSIMILATION

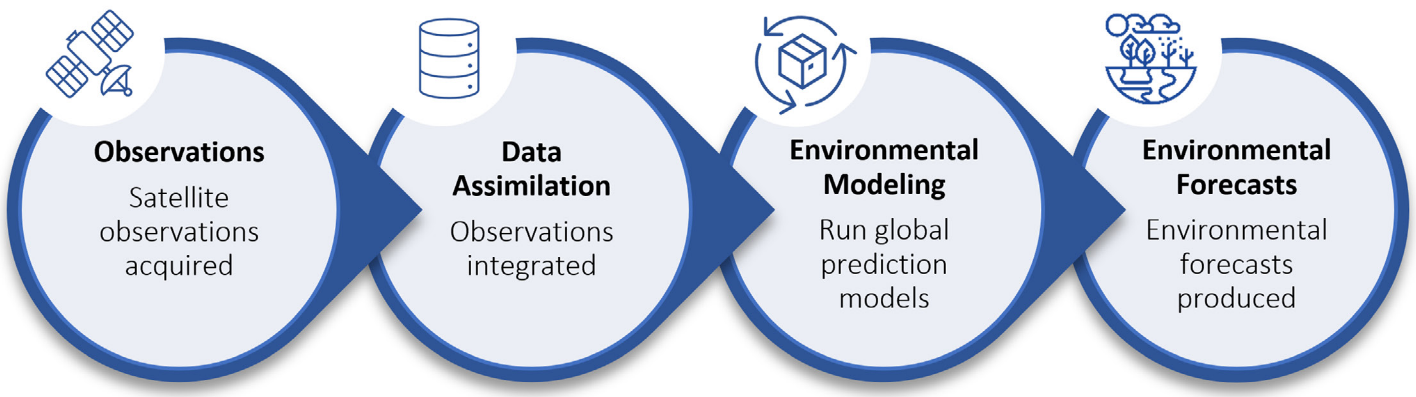
The Joint Center for Satellite Data Assimilation (JCSDA) is a multi-agency research center focused on a common goal: to maximize the benefit of satellite observations in weather, ocean, climate, and environmental analysis and prediction systems to improve forecasts and the accuracy of climate datasets. Since 2001, the JCSDA has approached their mission by bringing together partners that have common technical and logistical challenges. Partner agencies and organizations including NOAA (NESDIS, National Weather Service, and Office of Atmospheric Research), NASA (Earth Science Division), U.S. Navy (Naval Research Laboratory and Oceanographers of the Navy), and U.S. Air Force (557th Weather Wing) work together through the JCSDA by combining their expertise to solve shared problems.

"The JCSDA has been around for 20 years but there's been an evolution recently," Yoe explains. Today, the JCSDA is structured like a hub-and-spoke where the JCSDA is a centralized hub with dedicated researchers that organize the partners to focus on a common goal where everyone benefits. "We have a truly distributed center rather than a union of randomly overlapping activities like we had in the past—now, it is designed for integration, unlike before when we had a lot of activities going on, but it was hard to define what was truly a joint effort," emphasizes Yoe. The hub-and-spoke model reduces duplication of effort and helps the partners make progress with their own problems, that is, to assimilate satellite data better and more quickly and to improve their own systems.



The JCSDA's Approach to Data Assimilation Development

The volume of satellite data is rapidly growing as new, more powerful instruments are developed. In fact, JPSS satellites alone deliver more than seven terabytes of data to end users each day! To put this into perspective, one terabyte of storage is roughly equal to 1,500 audio CDs—after all, the prefix tera comes from the Greek word for monster. All this data means a greater need for big data processing and assimilation capabilities. With their satellite data assimilation expertise, the JCSDA is well situated to meet the challenges that arise as more satellites are launched and new models are developed. Yoe notes, "Every challenge is an opportunity and agencies take advantage of these opportunities through the JCSDA." But how do they do it? The answer, in part, is through the Joint Effort for Data assimilation Integration (JEDI), their adaptable systems for data assimilation development that is designed to support collaboration and inclusion of new Earth observation systems and models.



A high level overview of the process of producing environmental forecasts.

High-level objectives

Observations

- *Build the largest suite of observation operators*
- *Artificial intelligence for observation processing*

Algorithms

- *Test various JEDI algorithms with global NWP*
- *Build and evaluate coupled assimilation systems*

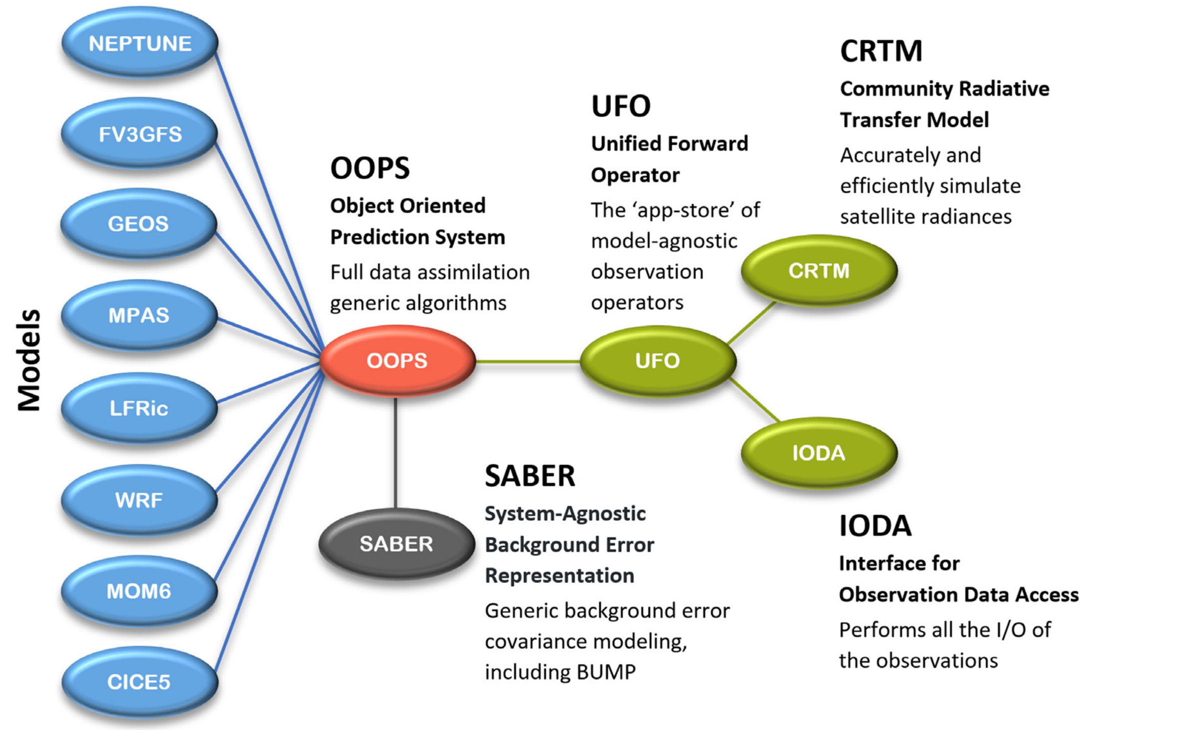
Applications

- *Build and test JEDI-based applications that are transferable to multiple systems and end uses*
- *Operate real-time development in the cloud*

The Joint Effort for Data Assimilation Integration (JEDI) Framework

JEDI is a community resource to enhance, develop, and test tools, components, and methodologies for satellite data assimilation across multiple data assimilation and modeling systems. Its purpose is to reduce duplication of work across communities, increase research efficiency, and simplify the transition from research to operations. JEDI supports all aspects of data assimilation including teaching the fundamentals to those new to assimilation, developing and validating advanced algorithms, cutting edge research, and operational weather forecasting. JEDI involves many people, many organizations, and many models making fast progress possible.

The JEDI framework is based on the notion that today's data assimilation systems are too complex for any one person to fully grasp—breaking a system apart into manageable pieces allows for better collaboration, understanding, flexibility, and scalability. "The whole point is we want to be results oriented and agile enough to be both innovative and effective for operations," Yoe explains, continuing, "Through JEDI we achieve what we call 'separation of concerns' and can take advantage of flexible infrastructure." With the JEDI framework (below) each module addresses a separate issue where the roles of each are independent of one another, enabling software and algorithms to be efficiently adjusted and scaled as new science and functionality are obtained.



CLICK IMAGE TO ENLARGE. Components of the JEDI framework, which leverages the separation of concerns principle for breaking down an application into modules where the roles of each are independent of one another.

Satellite Versus Conventional Data Assimilation

Given its name, vision, and mission, it should be no surprise that the JCSDA primarily carries out satellite data assimilation activities. Yoe clarifies, "Satellite data assimilation and conventional data assimilation are not really separate things—they are based on the same basic theory, which is any system you put together you're trying to take advantage of all of the information available from your observations." But there are some differences.

Satellite observations are not made at synoptic times (regular intervals) like conventional meteorological observations, such as radiosondes and surface weather stations where different locations are observed at the same time. Instead, satellites observe different locations at different times as they orbit around the Earth. Satellites provide global coverage so there are considerably more satellite data than there are conventional data, which means fewer data gaps. Also, satellite sensors can measure horizontally and/or vertically (columns of information), whereas conventional observations may only measure a single point. Biases and other non-random errors are common with satellite data, but this is not the biggest problem. "Calibration/validation teams tackle this challenge to beat down these biases and errors," Yoe points out.

In many cases, satellite data forward models—models that simulate an outcome—are more complex that those for conventional data. There are also a greater number of situations where satellite data cannot be used because of inadequate forward models. Yoe explains, "More often you have these situations where satellite data can't be used because of cloud interference, poorly characterized land surface emissivity, or human-induced interference that contaminates a scene." Despite—or perhaps because of—their differences, satellite data and conventional data complement each other and are typically used together in weather prediction systems.

DISSECTING A DATA ASSIMILATION EQUATION

Different data assimilation methods exist and the one that is used depends on the particular purpose. In NWP, the central role in data assimilation is to minimize the cost function J—the distance between a model trajectory and the available information. In other words, one must find the best fit between the model solution and the observations that the model is trying to predict within the assimilation interval. Below is an example equation used to accomplish this. "This equation," says Yoe, "emphasizes the importance of minimizing the cost function J to ensure that when you start running a prediction model that you're starting with the best possible analysis." Remember, in NWP the previous model forecast (the "background") carries information from past observations into the current analysis. That is to say, previous information impacts future forecasts, so determining the most accurate picture of the present is crucial to produce good future analyses.

$$J(x') = \frac{1}{2}(x')^T B^{-1}(x') + \frac{1}{2}(y_o' - H(x'))^T R^{-1}(y_o' - H(x')) + J_c$$

J : Penalty (Fit to background + Fit to observations + Constraints)

x' : Analysis increment $(x_a - x_b)$; where x_b is a background

B : Background error covariance

H : Observations (forward) operator

R : Observation error covariance (instrument + representativeness)

y_o' : Observation innovations

J_c : Constraints (physical quantities, balance/noise, etc.)

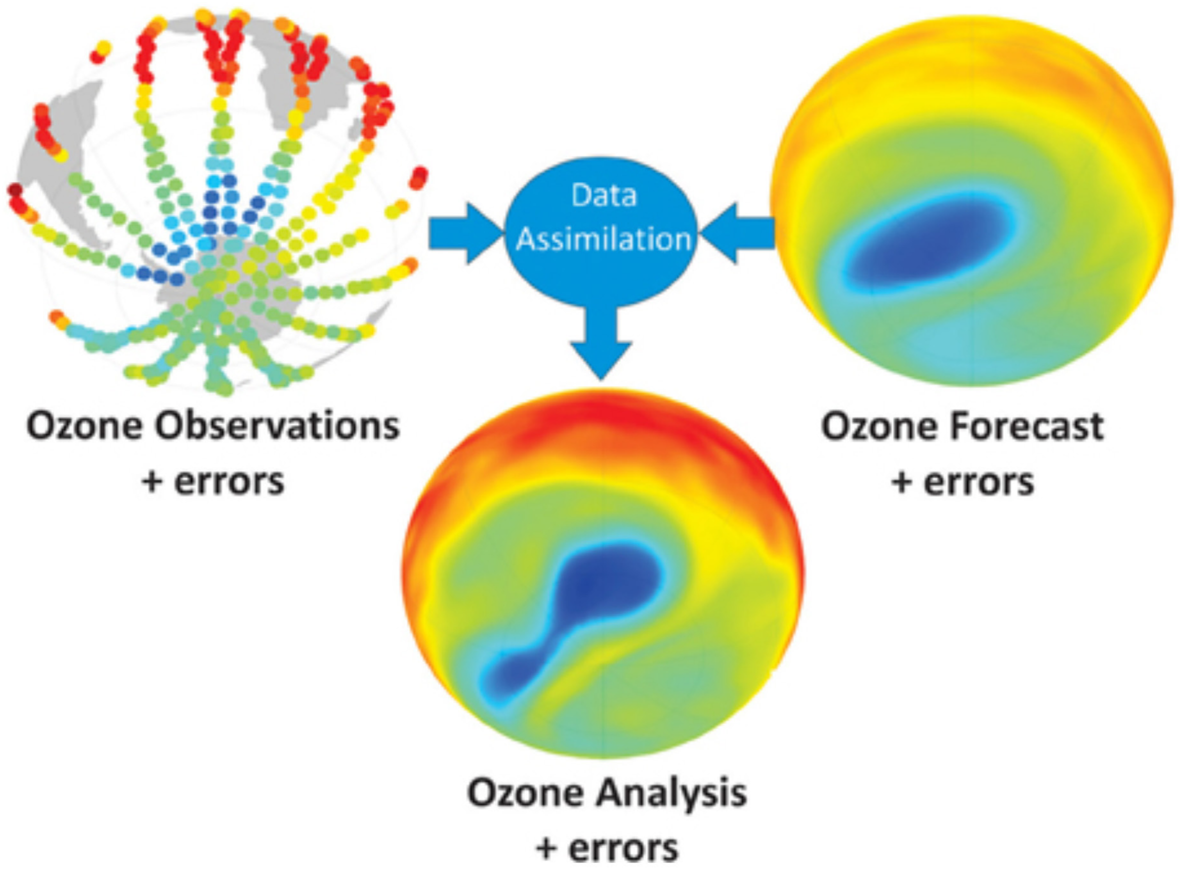
Example equation used in data assimilation for numerical weather prediction.

The cost function is the limiting factor in getting good model results and a better estimate of truth. "Generally speaking," Yoe says, "if you get a bad result, it's not because of your solution technique but because you've done a poor job in defining and tuning the cost function." The most important aspect of data assimilation is to make sure that a good initial state is brought into the model with a good convergence to come to a solution faster. Yoe clarifies, "In order for a model to run on time you have to have a convergence of this cost function to get your analysis done quickly."

Challenges and Constraints

For observations in a model to impact the analysis, the observations must be simulated from the analysis variables. "In other words," Yoe says, "we need to be able to forward-model the environmental fields to predict what we think we might expect to measure with satellite sensors in order to use those observations to nudge or increment our analysis." In some cases, this is simple. For instance, the satellite radiances seen at certain bands are modeled based on atmospheric temperature, moisture, and pressure.

"But in some cases, we don't have enough information on the analysis variables to do a proper simulation and that can limit the use of those particular observations," Yoe asserts. For example, in cloudy situations the forward model values may not match up with what is observed because the model assumes a clear atmosphere. Inadequacies like this often result in correlated errors. With data assimilation, all observations are used together, which is both a benefit and a challenge. Yoe explains, "Sometimes you can't use certain observations, so you hope that other observations you have in your set will compensate for the observations you don't have."



In data assimilation, the observations, models, and analyses have errors, which will never be known precisely, and which must be estimated. This concept is illustrated here with information from observations, models and their errors, input into the data assimilation algorithm, and producing an analysis, which also has errors. Source: Lahoz and Schneider 2014.

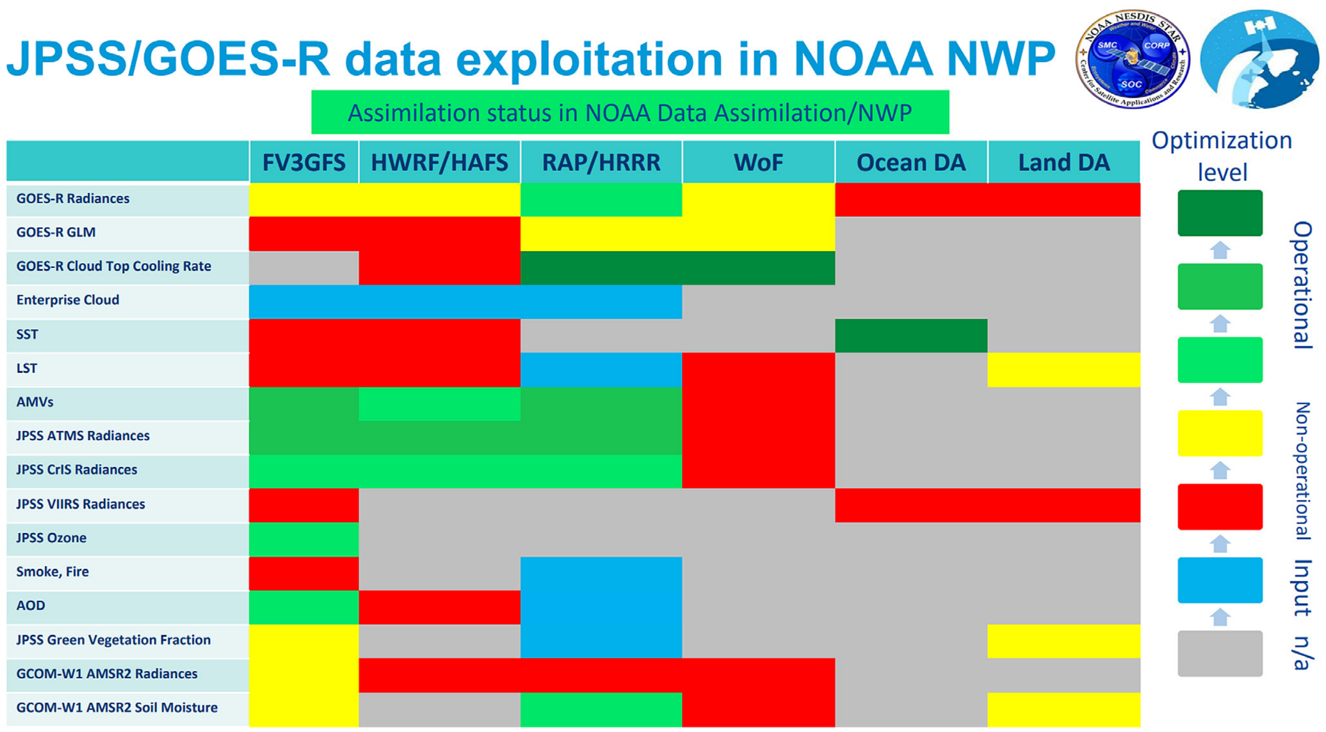
Observation errors are also a challenge. In NWP, two types of errors may occur: instrument error and representativeness error and either can dominate. Instrument error refers to the measurement precision of an instrument. Representativeness error is how well the model simulates an observation. "Even when you have inherent precision of the instrument, you still have error that is going to come from the representative side," says Yoe. Instrument and representative errors are often correlated, which reduces the usefulness of observations. Yoe explains, "You can have correlated errors between different observations in different locations from different instruments or you can be in the same location with the same instrument and get correlated errors." The latter is why only a subset of channels from sounders like CrIS are used for data assimilation—correlated noise becomes an issue when all channels are used.

There are also physical and statistical constraints to the analysis. Physical constraints follow the laws of physics. Moisture cannot be negative—moisture either exists (greater than zero) or it does not (zero)—this is a physical constraint. Sometimes statistical constraints point to things that are never expected to occur. Discovery of the ozone hole in polar regions was missed for years because of statistical constraints. Even though satellites had detected the hole, the algorithm assumed that such a phenomenon would never happen. For years, satellite measurements were discarded as incorrect, when in fact, they were true. In this way, statistical constraints can be especially dangerous because statistically unlikely events can happen. All of this is a tricky part of the problem of minimizing the cost function.

NOAA OPERATIONAL MODELS

The NOAA Center for Satellite Applications and Research (STAR) is the science arm of the NOAA National Environmental Satellite, Data, and Information Service (NESDIS). As a partner in collaboration with the JCSDA and other organizations, STAR contributes to numerical weather prediction through satellite radiance assimilation development, forward modeling advancements, optimization, next generation architecture studies, and other activities. Their priorities are based on potential impact and value and are focused on satisfying unmet needs for NWP users, particularly for JPSS and GOES-R data. Working closely with partners in the JCSDA on almost all aspects of data assimilation, STAR aims to maximize observation impacts on NWP analysis and forecasts.

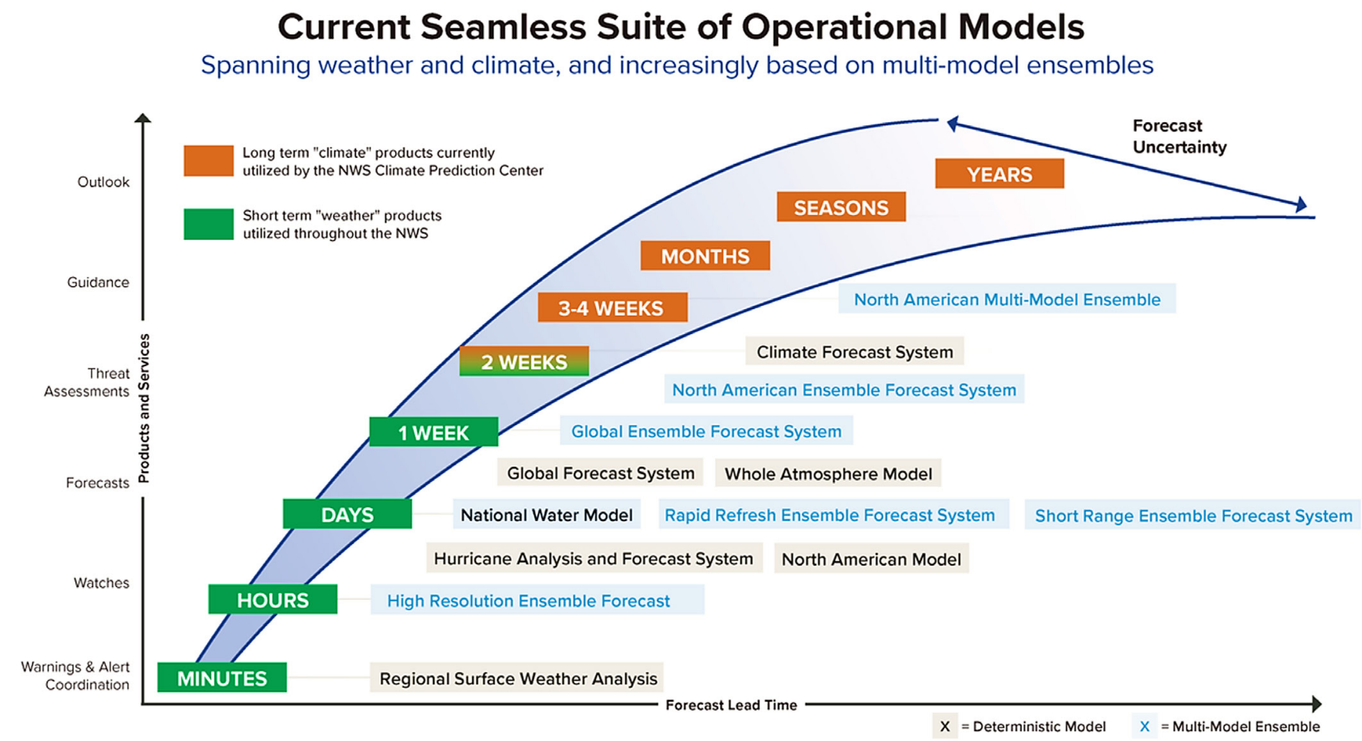
The assimilation status of JPSS and GOES-R data in NOAA NWP, as of 2020, is summarized below. Green indicates operational status, for example, radiances from JPSS CrIS, ATMS, VIIRS, and OMPS (ozone) sensors, Atmospheric Motion Vectors (AMVs), and Aerosol Optical Detection (AOD) products are assimilated and operationally available in the FV3GFS atmospheric model. Red and yellow colors mean those data are assimilated but non-operational in the respective models or data assimilation systems. Blue indicates input status, for example, Enterprise Cloud data for the FV3GFS atmospheric model,



CLICK IMAGE TO ENLARGE. Assimilation status of JPSS/GOES-R Data in NOAA NWP. Source: Garrett 2020.

HWRF/HAFS hurricane models, and RAP/HRRR high-frequency weather forecast models.

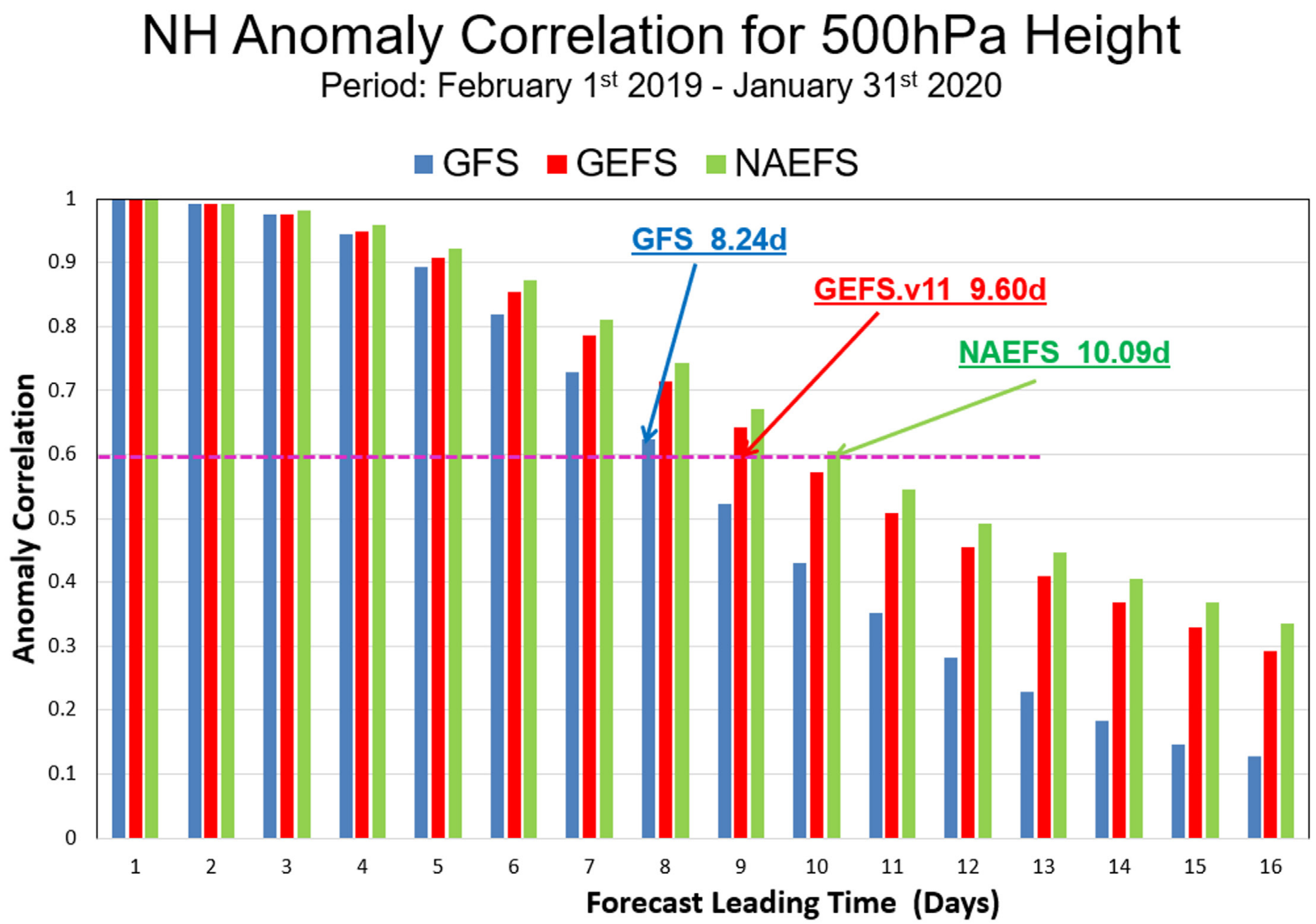
NOAA has a mission to forecast weather over time scales that increase from minutes—needed for issuing warnings to protect lives and property—to forward-looking outlooks that are interannual and beyond, such as detecting and predicting the strength of interannual events like El Niño. Achieving this requires a great number of models across different time and spatial domains, known as the National Centers for Environmental Protection (NCEP) Production Suite, a seamless suite of operational models (below). These include the Global Forecast System (GFS), the Global Ensemble Forecast System (GEFS), and the North American Ensemble Forecast System (NAEFS), a joint project involving the Meteorological Service of Canada (MSC), the NOAA National Weather Service (NWS), and the National Meteorological Service of Mexico (NMSM). Most, if not all, of the models in the NCEP Production Suite include data from instruments that were assimilated through collaboration with the JCSDA. For example, ATMS and CrIS have been operationally assimilated in GFS since 2012 and 2013, respectively.



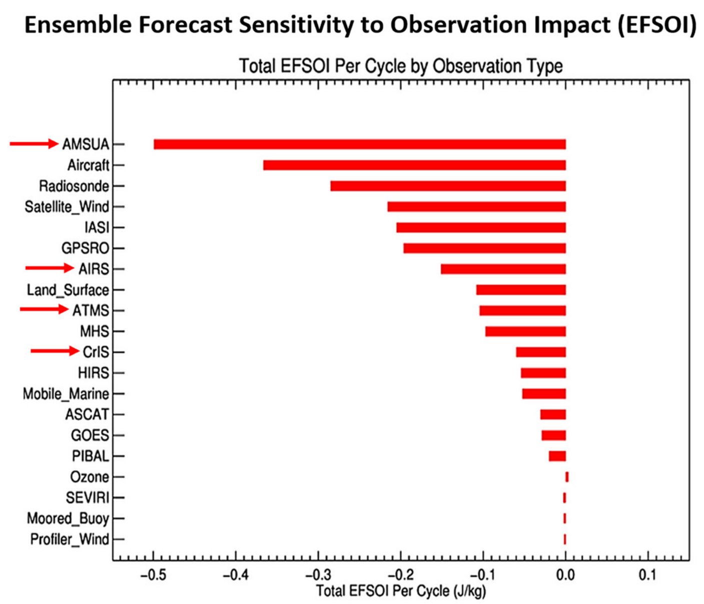
CLICK IMAGE TO ENLARGE. Select members of the NCEP Production Suite, the "seamless suite" of operational models used at NCEP including deterministic (black) and ensemble (blue), extending from very short out to seasonal time scales, and covering a range of phenomena. Source: Uccellini et al 2022.

A Look Into Prediction Skill

Evaluating a model's prediction skill is critically important for identifying model errors, improving forecast capabilities, and promoting the use of forecasts in decision making. It also provides essential feedback to model developers for identifying opportunities for improvement. Evaluation requires performance metrics, including the 500 hectopascal (hPa) anomaly correlation as a function of time that is shown in the graph below. The dashed horizontal line is the threshold of useful predictive skill. Scores at or above this line mean that the model has good predictive skill out the number of days indicated along the x-axis (forecast leading time). For instance, the GFS model is above the threshold on day 8 before dropping below the line, meaning that GFS can predict the weather about 8 days out with good predictive skill. The same is true for the GEFS and NAEFS models at about 9 and 10 days out, respectively. Performance differs because each model looks at different domains. As expected, scores for all models decline over time, becoming less reliable.



Breaking things down, the graph below shows the Ensemble Forecast Sensitivities to Operational Impact (EFSOI) set for the GFS model in 2016. EFSOI quantifies how much each observation type (e.g., AMSU-A sensor, aircraft, etc.) improves or degrades a subsequent forecast. The farther left from zero (that is, the more negative the number), the more influence an observation has on reducing model errors. Yoe explains, "The idea here is you're looking at a 24-hour energy metric with a goal of reducing the error, so going more to the left from zero means that you've done more to reduce the error in that system." Major contributors to error reduction are microwave and infrared sensors, including EUMETSAT AMSU-A, NASA AIRS, and to a lesser degree, JPSS ATMS and CrIS.



CLICK IMAGE TO ENLARGE. Total EFSOI impacts per cycle based on ensemble square root filter (EnSRF) products from a low resolution four-dimensional ensemble-variational (4DEnVar) data assimilation system configuration of the 2016 GSM GFS. Courtesy of David Groff via Jim Yoe.

Global Forecast System (GFS)

Dozens of atmospheric and land-soil variables are available through the GFS dataset, from temperature, wind, and precipitation to soil moisture and atmospheric ozone. The entire globe is covered by the GFS, which is used by operational forecasters to predict weather out to 16 days in the future.

Global Ensemble Forecast System (GEFS)

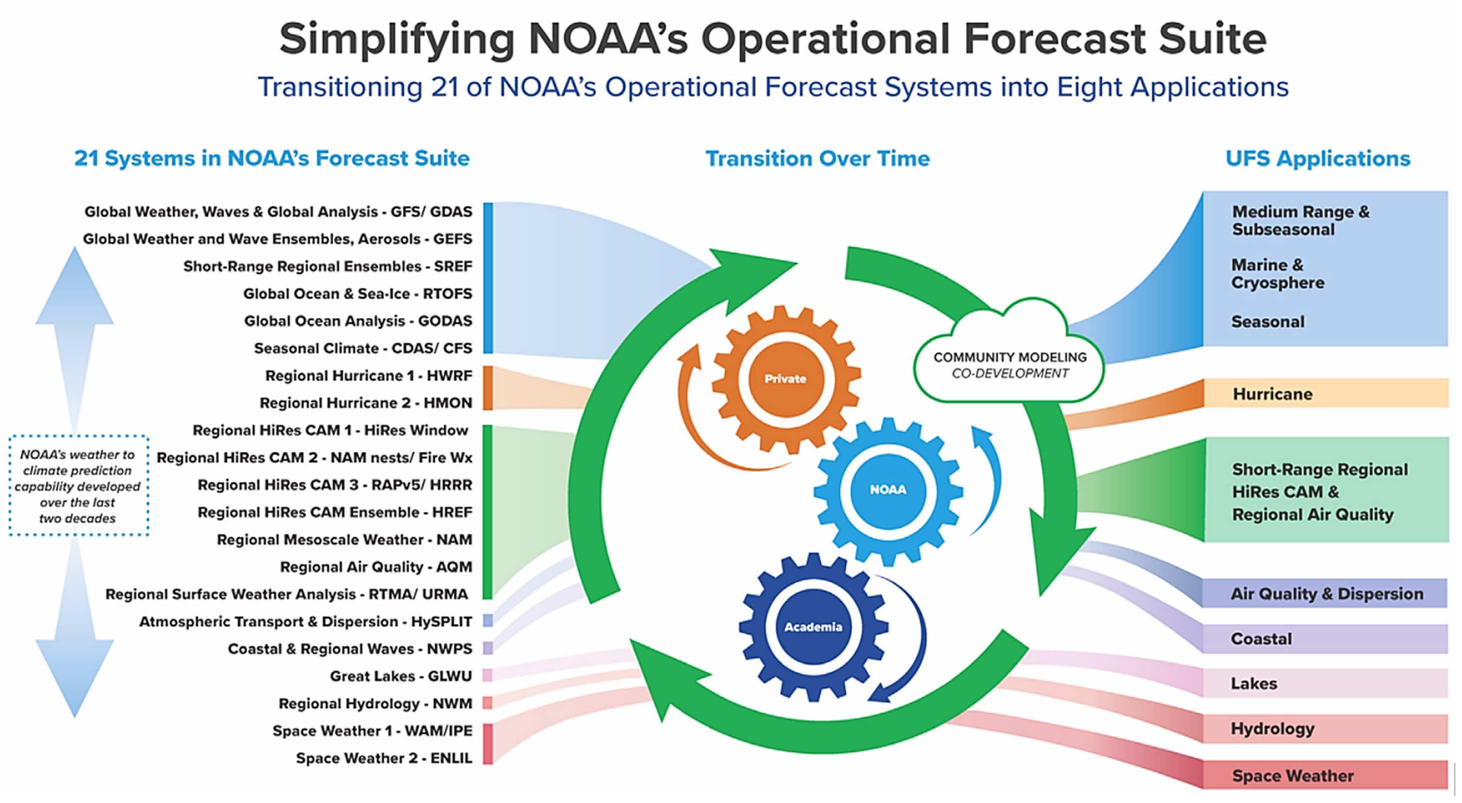
The GEFS is made up of 21 separate forecasts, or ensemble members. It addresses uncertainty by generating multiple forecasts that provide a range of potential outcomes. Each forecast compensates for a different set of uncertainties. With global coverage, the GEFS is produced four times a day with forecasts going out to 16 days.

North American Ensemble Forecast System (NAEFS)

The NAEFS combines ensemble forecasts from the MSC and the NWS, providing weather forecast guidance for the 1–14 day period that is seamless across the national boundaries between Canada, the U.S., and Mexico.

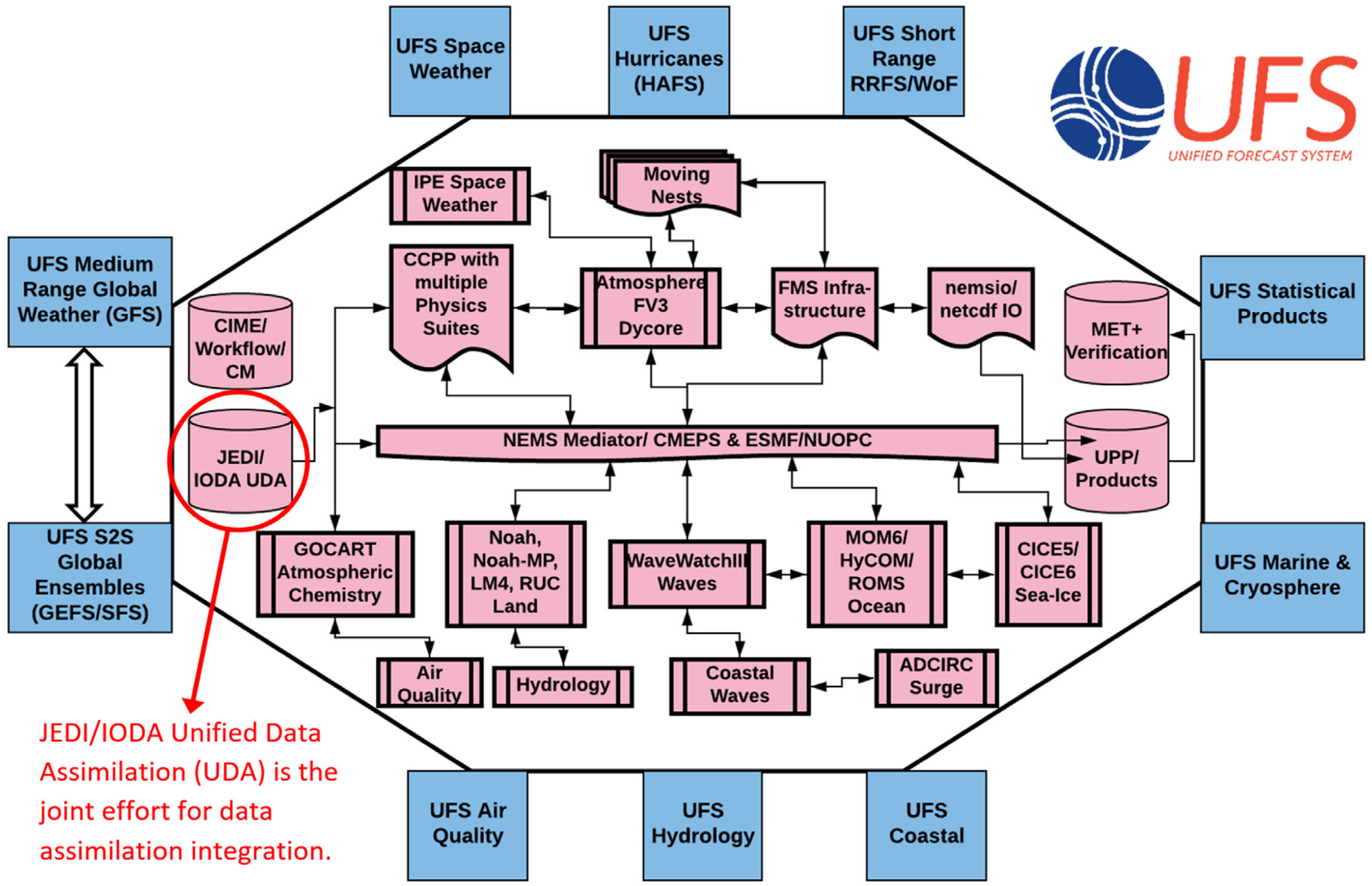
OPPORTUNITIES FOR EFFICIENCY AND COLLABORATION

For the NCEP Production Suite models to be improved, NOAA is transitioning to a simplified approach called the Unified Forecast System (UFS), a community-driven system that supports cooperative environmental modeling and data assimilation. The UFS will reduce NOAA's 21 stand-alone operational forecast models down to eight forecast systems (UFS applications) that share the same community modeling framework.



Unification of the NWS operational modeling suite through community-driven UFS. Source: Uccellini et al 2022.

The inherent flexibility of UFS allows for many applications that range from local to global with predictive time scales from minutes to more than a year for both research and operations. "The UFS will capture dependencies between models and provide a simplified structure that has as many common pieces as possible," Yoe affirms. This and other UFS features are expected to improve the efficiency and strength of NOAA's environmental modeling. The JCSDA plays a key role in the transition to UFS by providing a framework for data assimilation collaboration and integration, with open, agile development mirroring that of the UFS itself.



FUTURE TRENDS: MORE, MORE, MORE!

One of the biggest challenges for the advancement of data assimilation is the issue of "more." More observations from more varied sources that apply to more applications that are run on more modeling platforms by more community partners, and the list goes on. "Looking to the future we have to be prepared for the next generation satellite systems," concludes Yoe. Missions like JPSS follow-ons and NOAA's Geostationary Extended Observations (GeoXO) system may include hyperspectral infrared sounders, opening a new set of observational possibilities, and as NOAA expands their use of nanosatellites (SmallSats and CubeSats) and commercial satellite observations, more data than ever will be available for weather prediction.

Having "more" means that data assimilation systems must be scalable and able to handle the complexity and variability that comes with having a greater number of resources. This trend also has its benefits. With "more" comes greater opportunity to expand capabilities, improve the science, and solve previously unsolvable problems. The JCSDA and JEDI are critical to exploiting this trend, each having the necessary foundation to support bigger and better solutions for improving weather prediction. ✦

STORY SOURCE

The information in this article is based, in part, on the January 19, 2022, JPSS Science Seminar "Satellite Data Assimilation - A catholic (with a small c) Perspective" presented by Dr. James G. (Jim) Yoe, Chief Administrative Officer, the Joint Center for Satellite Data Assimilation (JCSDA) and with the NOAA National Centers for Environmental Protection (NCEP) Environmental Modeling Center (EMC). The presentation featured material provided by John Derber, retired data assimilation lead for NOAA/NWS/NCEP/EMC.

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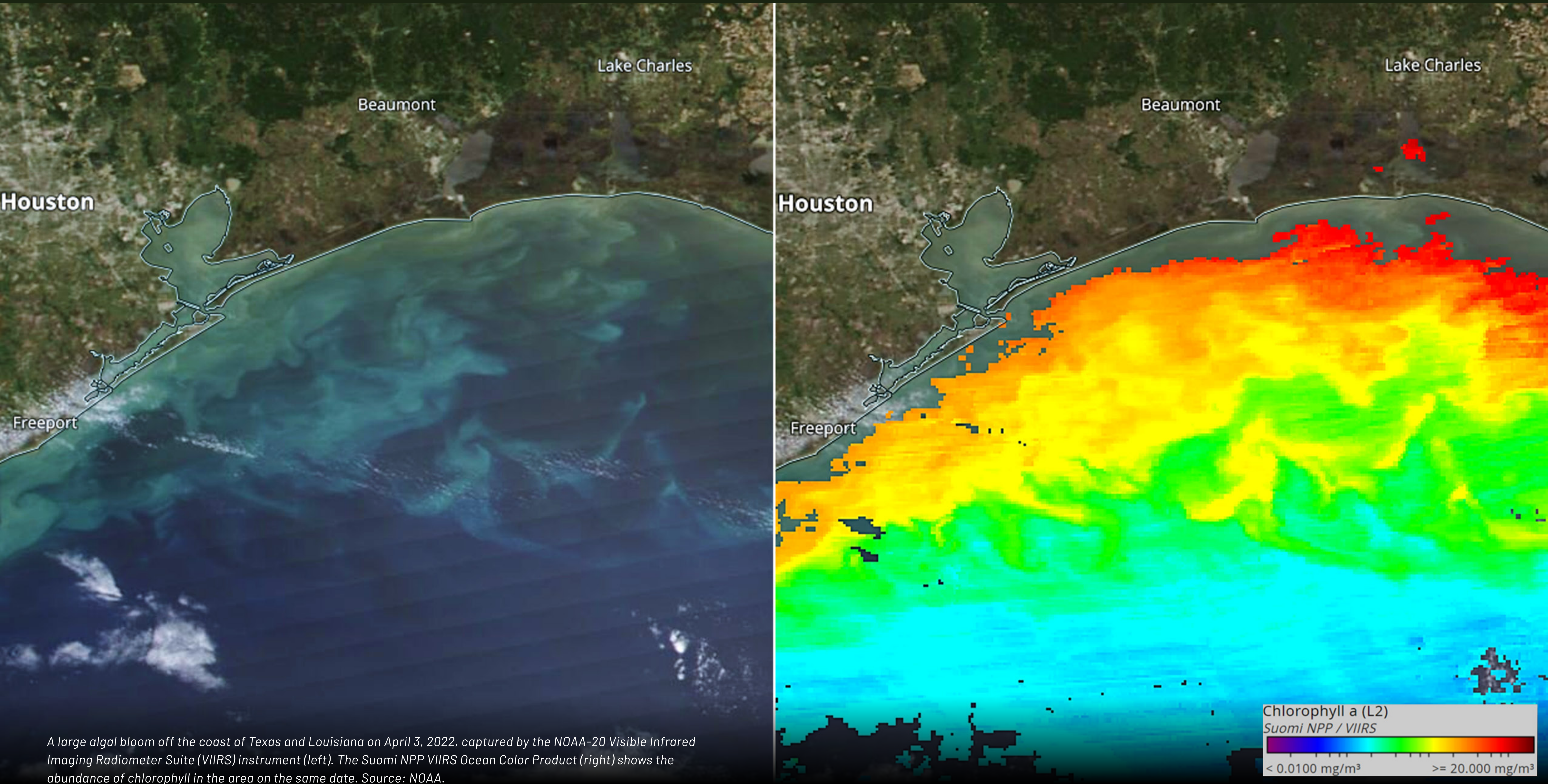
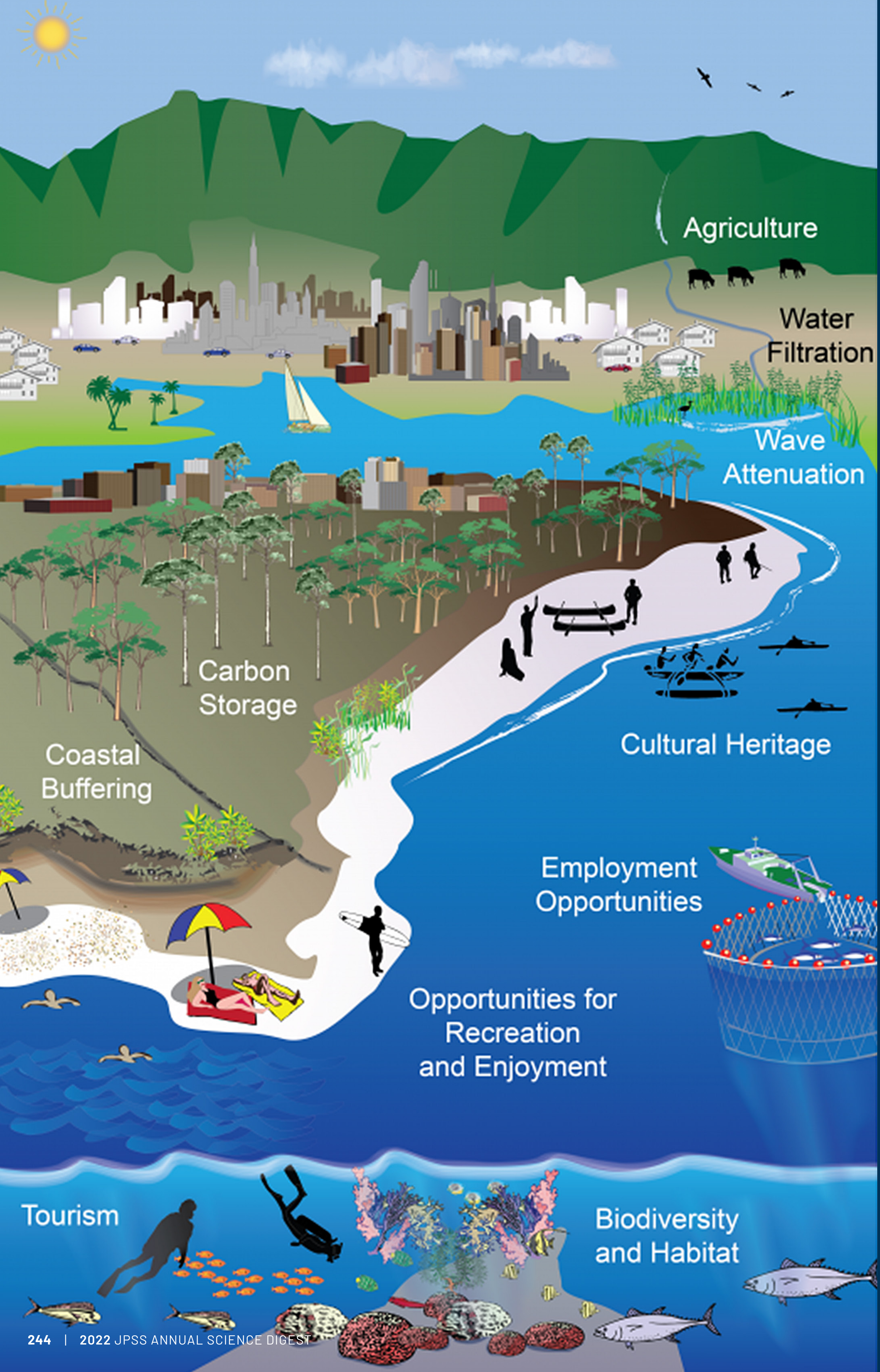
FEATURE 11

Exploring the Use of Ocean Biogeochemical Data in Marine Ecological Forecasting and Operational Weather Models



A large algal bloom off the coast of Texas and Louisiana on April 3, 2022, captured by the NOAA-20 Visible Infrared Imaging Radiometer Suite (VIIRS) instrument (left). The Suomi NPP VIIRS Ocean Color Product (right) shows the abundance of chlorophyll in the area on the same date. Source: NOAA.



Coastal ecosystems are unique and dynamic environments between the land and open ocean that play an essential role in regulating Earth's temperature, protecting coasts from erosion and flooding, and generating valuable marine resources. They are powerful "carbon sinks" capable of trapping carbon in their soils for thousands of years—greenhouse gas that would otherwise contribute to a warming climate—and absorb energy from the waves of tropical storms, effectively slowing down damaging storm surge.

The economic value of coastal zones cannot be understated. It is estimated that nearly half of the global economic value of ocean fisheries and related industries are associated with coastal areas. Also consider the tremendous benefits from recreational and cultural activities—millions of people worldwide visit beaches each year for recreation, sport, and cultural activities that support human health and wellbeing. About 40% of the U.S. population, around 130 million people, live in coastal communities, to put the importance of coasts into perspective.

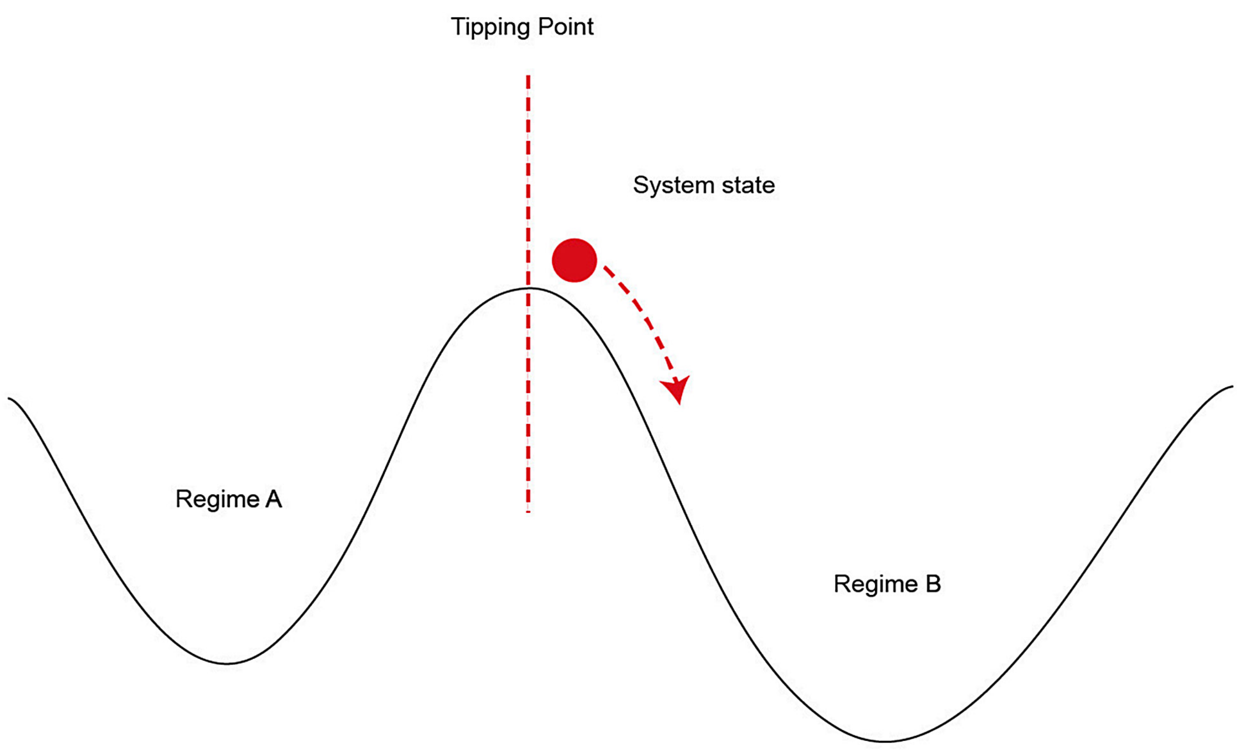
Coastal ecosystems are under threat from stressors like rising sea surface temperatures, nutrient and sediment runoff, overfishing, dredging, and air pollution, with some regions already experiencing a loss of ecosystem services from the destruction of coastal resources. It is not just the potential economic loss that is cause for concern, but also longer term weather and climate impacts like sea level rise, shifts in precipitation, and more frequent and intense extreme weather events that are expected to occur as coastal ecosystems respond to environmental change. The question is: what can be done about it?

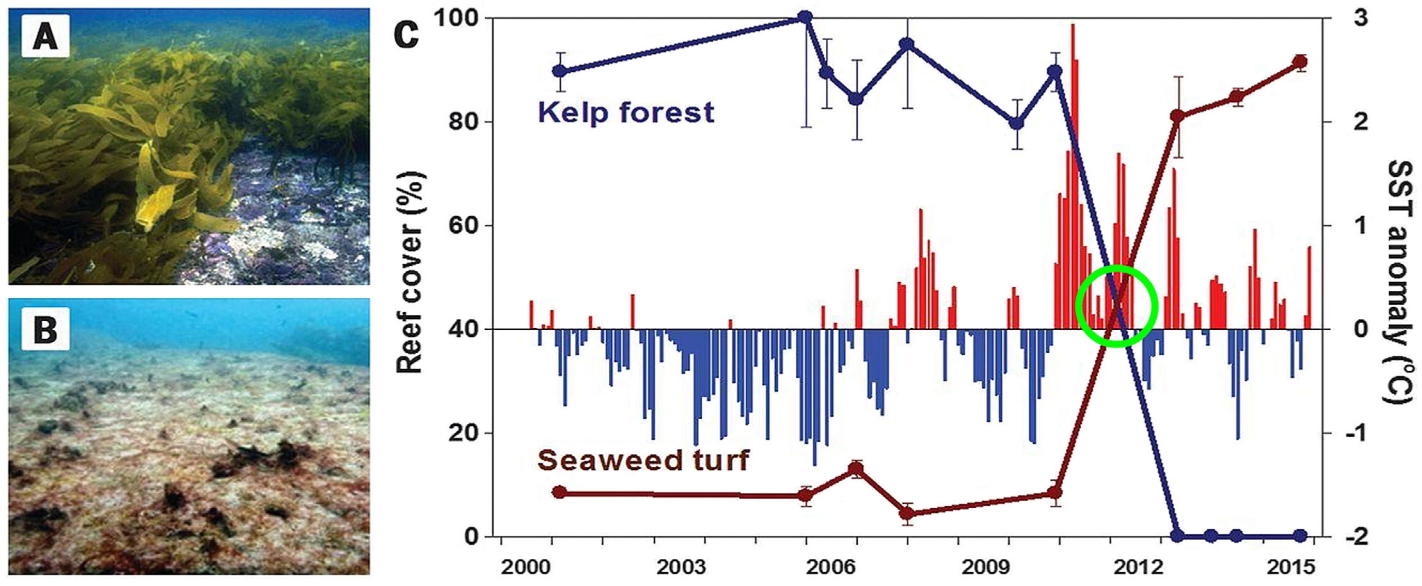
Left: Coastal ecosystems provide a suite of valuable benefits on which humans depend for food, economic activities, inspiration, and enjoyment. Credit: NOAA/NCEI. Source: Moser et al 2014.

A Point of No Return: Forecasting an Ecosystem Shift

Coastal ecosystem stressors can build up over time and reach a "tipping point." The Oxford English Dictionary defines a tipping point as "the point at which a series of small changes or incidents becomes significant enough to cause a larger, more important change." From an ecological perspective a tipping point indicates that an ecosystem can no longer cope with environmental change—its resilience is exceeded, and an abrupt and dramatic shift occurs in biodiversity and function. The shift is usually permanent or, at best, very hard to reverse. For example, coral reefs that have undergone mass bleaching can take decades to grow back, if they do at all, even if their habitat returns to pre-tipping point conditions. Tipping points pose a major threat to coastal economies that rely on marine environments for tourism, recreation, and commercial activities, such as fishing, aquaculture, shipping, and energy.

The ocean is home to many ecosystems that have already reached a point of no return. Just one of countless examples: kelp forests help prevent coastal erosion by acting as a barrier between the land and open ocean, provide shelter and food for important marine species, and absorb and store carbon. In 2011, rising sea temperatures in western Australia devastated a tall canopy of dense kelp along 100 kilometers of coastline well stocked with diverse

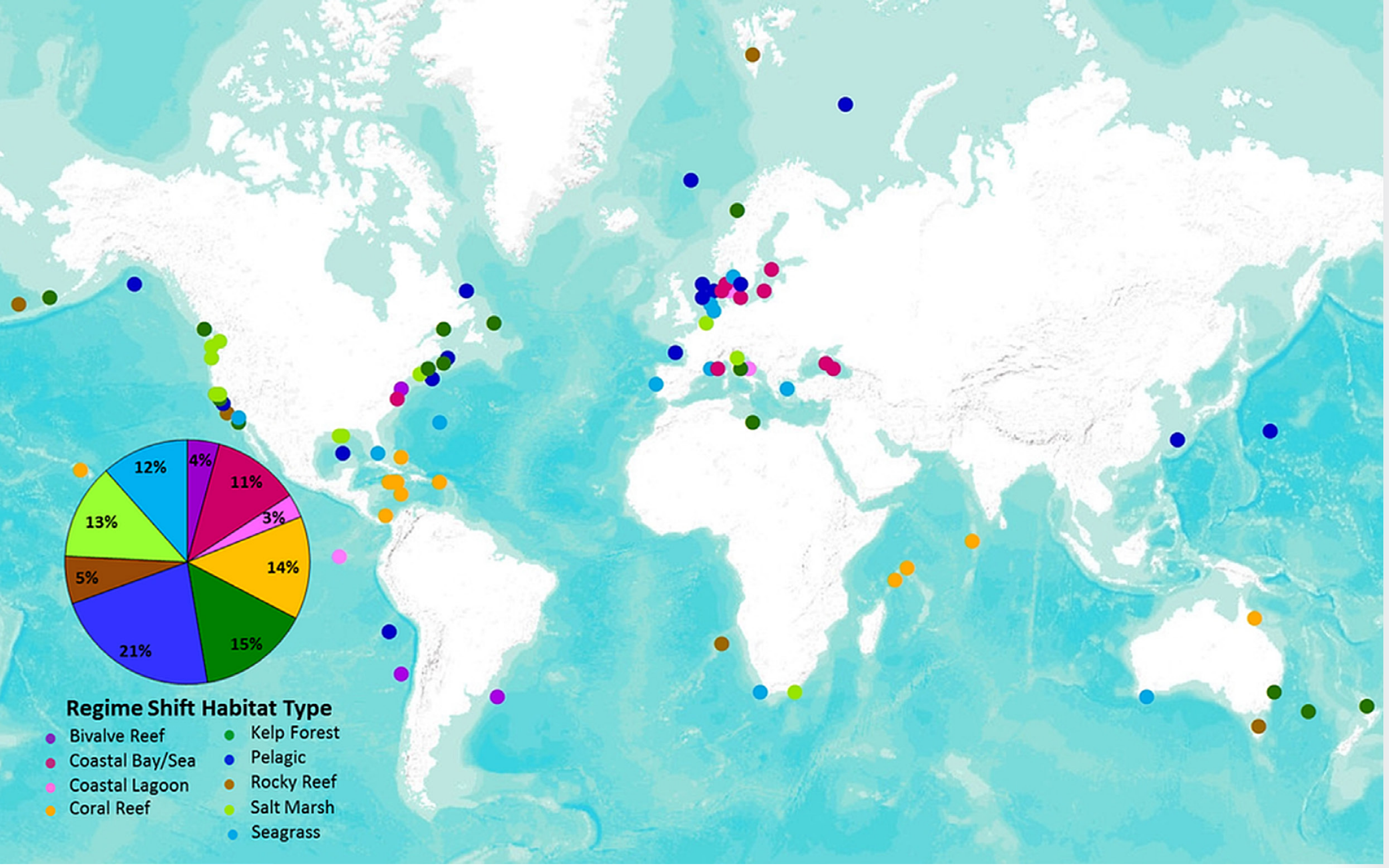




An example of an irreversible ecosystem shift from kelp forests to seaweed turfs after the 2011 marine heatwave in western Australia. The disappearance of dense kelp forests (A) and replacement with seaweed turfs (B) along about 100 km of coastline were associated with increasing mean sea surface temperatures in 2011 (C, red bars). The "tipping point" is seen where the kelp forest cover (blue line) and seaweed turf cover (brown line) intersect (green circle). Source: Wernberg et al. 2016.

species of fish, invertebrates, and algae (above). With the kelp forest gone, more light reached the ocean floor allowing short seaweed turf to flourish, resulting in a simpler habitat stripped of its rich diversity. What happened? No longer able to endure the surging ocean temperatures, the kelp suddenly disappeared—it reached its tipping point—and was replaced by a different ecosystem regime, one that cannot support the profitable rock lobster and abalone fisheries that once thrived along Australia's western coast.

Because of the complexity and regional variability of ecosystems, tipping points are hard to predict and often occur without warning, quietly building with few obvious hints that they are coming. Understanding the drivers and signals that precede an ecosystem shift is of critical importance for monitoring and heading off an irreversible shift before it is too late. For oceans, researchers use in-situ sampling and satellite observations to study ecosystem drivers—physical variables like sea surface temperature, currents, and salinity, as well as biogeochemical processes like primary and secondary productivity, oxygen concentration, and carbon dioxide uptake.



CLICK IMAGE TO ENLARGE. Map of known marine ecosystem shifts around the world. Note that the higher frequency of regime shifts in temperate waters is probably a reflection of sampling effort as these areas have historically been better studied. Source: Ocean Tipping Points.

Marine ecological forecasts help provide early warnings of ocean biogeochemical and physical changes to support proactive decision making. Models are key tools used in ecological forecasting, and coupling biogeochemical models to ocean circulation models has been shown to be beneficial for marine ecosystem and climate prediction. But ocean biogeochemical observations are not part of the current generation of operational weather forecast systems, which limits the ability to understand the changing marine environment, and their impact on our weather system and global climate. In response, researchers at the NOAA National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) are working to enhance NCEP's physical and ecological forecast capabilities through biogeochemical modeling, data assimilation, and analysis/reanalysis activities. At the August 15, 2022 JPSS Science Seminar, Drs. Xiao Liu and Avichal Mehra at NOAA/NCEP/EMC provided an overview of their work and progress.

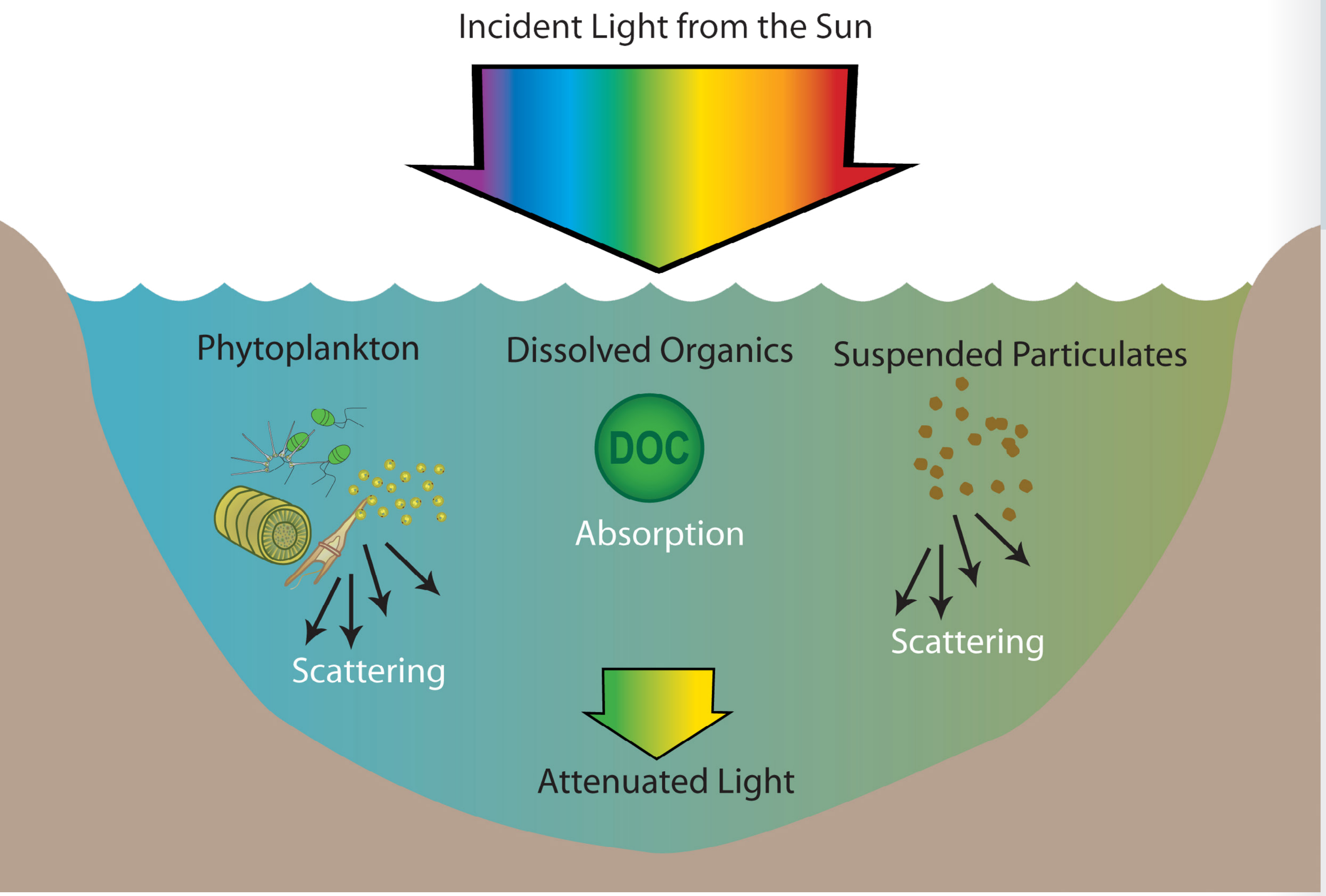
ENHANCING MARINE ECOLOGICAL FORECAST CAPABILITY AT NCEP

The health of our coastal communities, economy, and ecosystems depends on understanding the complex and fluctuating conditions of the marine environment. Marine ecological forecasts help predict ecosystem changes, identify environmental drivers, and provide information about how people and economies may be affected so that action can be taken before a tipping point is reached. They are used to assess variability in ocean conditions, and are critical for coastal area management, climate change adaptation and mitigation, and ensuring ecosystem and human health.

Compared to physical forecasting systems, predicting ecological variability has been challenging. Integrating ocean biogeochemical data into models is a key requirement for enhancing weather forecast capability, and for detecting and predicting critical changes in marine ecosystems, which is an ongoing focus of research at NCEP. Of particular interest is the development of a subseasonal-to-seasonal (S2S) application in the coupled United Forecast System, which has been targeted for operational implementation at NCEP in FY2024. Mehra and Liu's team is exploring several approaches to support this goal, including testing data assimilation of satellite ocean color observations, implementing ocean biogeochemical models, and conducting multi-year ocean physical-biogeochemical reanalysis using the United Forecast System.

Data Assimilation of Satellite Ocean Color Observations

The ocean is more than just water—it is home to plants, animals, dissolved material, and particles that provide important feedback to ocean and weather systems through complex ocean biophysical and air-sea interactions. "These ocean constituents and their change dynamics can modulate carbon cycles and ecosystem structures by absorbing and scattering light," explains Liu. Pigmented particles, like phytoplankton and particulate organic matter, affect light penetration (radiative heat) into the deep ocean, which in turn impacts sea surface temperature and other variables, as well as weather. However, current operational forecast models do not account for such feedback. For short range forecasts of a few hours or a day or two this may not be an issue—ocean biogeochemical feedback is generally insignificant at this scale. But for longer term prediction out several weeks to several months (subseasonal-to-seasonal scale), the biogeochemical impact may accumulate and no longer be trivial. "This is our motivation to explore the options of adding an ocean biogeochemical component to the next generation of operational weather forecast systems," Liu says.



An illustration of light attenuation in water. When light penetrates ocean water, substances either absorb it (dissolved organics) or scatter it (particles, like phytoplankton). The light that eventually reaches lower levels is attenuated (reduced) and possesses much less energy than before it hit the water. Source: Smithsonian Environmental Research Center.

DA, JEDI, & SOCA

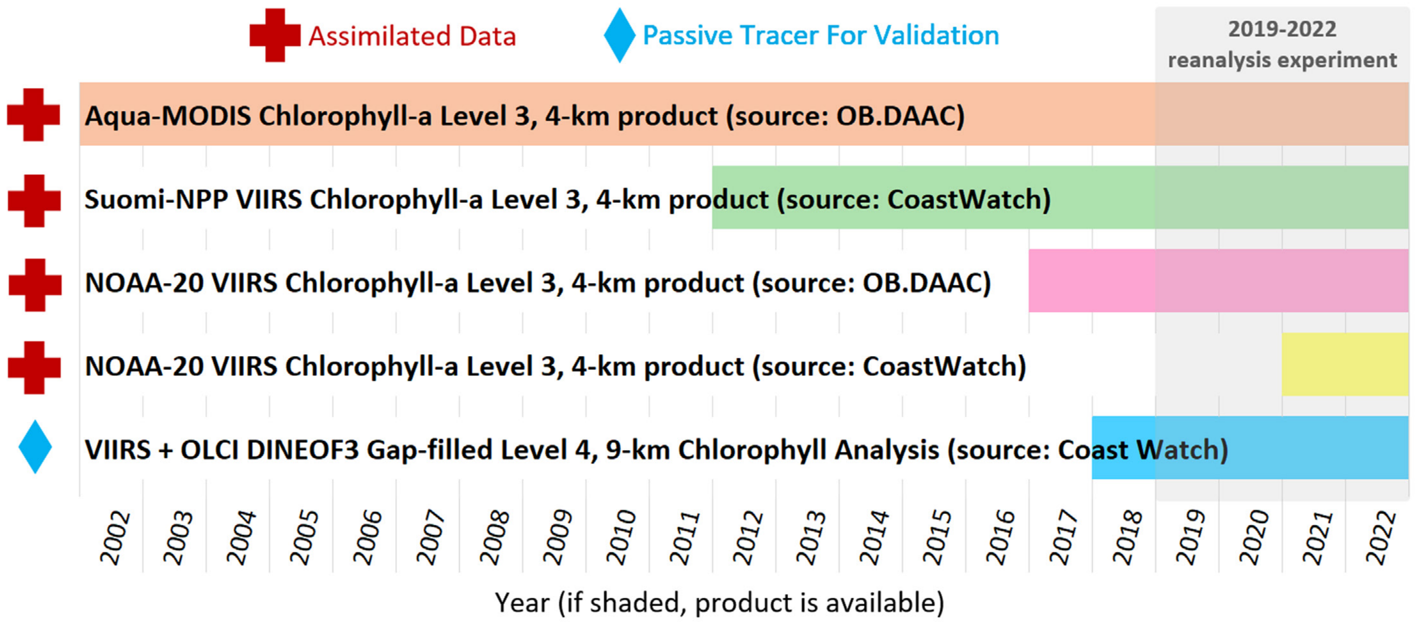
Data assimilation (DA) *is the process by which observational data is brought into models. The* ***Joint Effort for Data assimilation Integration (JEDI)*** *is a versatile data assimilation system for Earth System Prediction developed through the* ***Joint Center for Satellite Data Assimilation (JCSDA)****, a multi-agency research center committed to improving and accelerating the quantitative use of research and operational satellite data in weather, ocean, climate, and environmental analysis.*

The JEDI-based ***Sea-Ice Ocean and Coupled Assimilation (SOCA)*** *project focuses on meshing atmospheric and marine data assimilation efforts to create innovative data assimilation systems.*

One of the team's goals is to exploit data assimilation techniques for more accurate biogeochemical modeling using ocean color observations. Ocean color provides information on the abundance of pigmented particles in the water and is used to assess their impact on light attenuation, absorptions, and radiative heating in the ocean. Satellite instruments like the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard JPSS satellites and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) sensors are uniquely qualified to provide near real-time ocean color data since each offer nearly global coverage of the Earth with repeat daily cycles. To leverage these valuable observations, Mehra and Liu's team developed the required tools and software in JEDI and SOCA (see callout) to perform daily assimilations of VIIRS and MODIS ocean color products. The data is included in a comprehensive ocean/sea ice retrospective observation database that is part of an ongoing, multi-year 0.25 degree horizontal resolution, global ocean physical-biogeochemical reanalysis effort by the team.

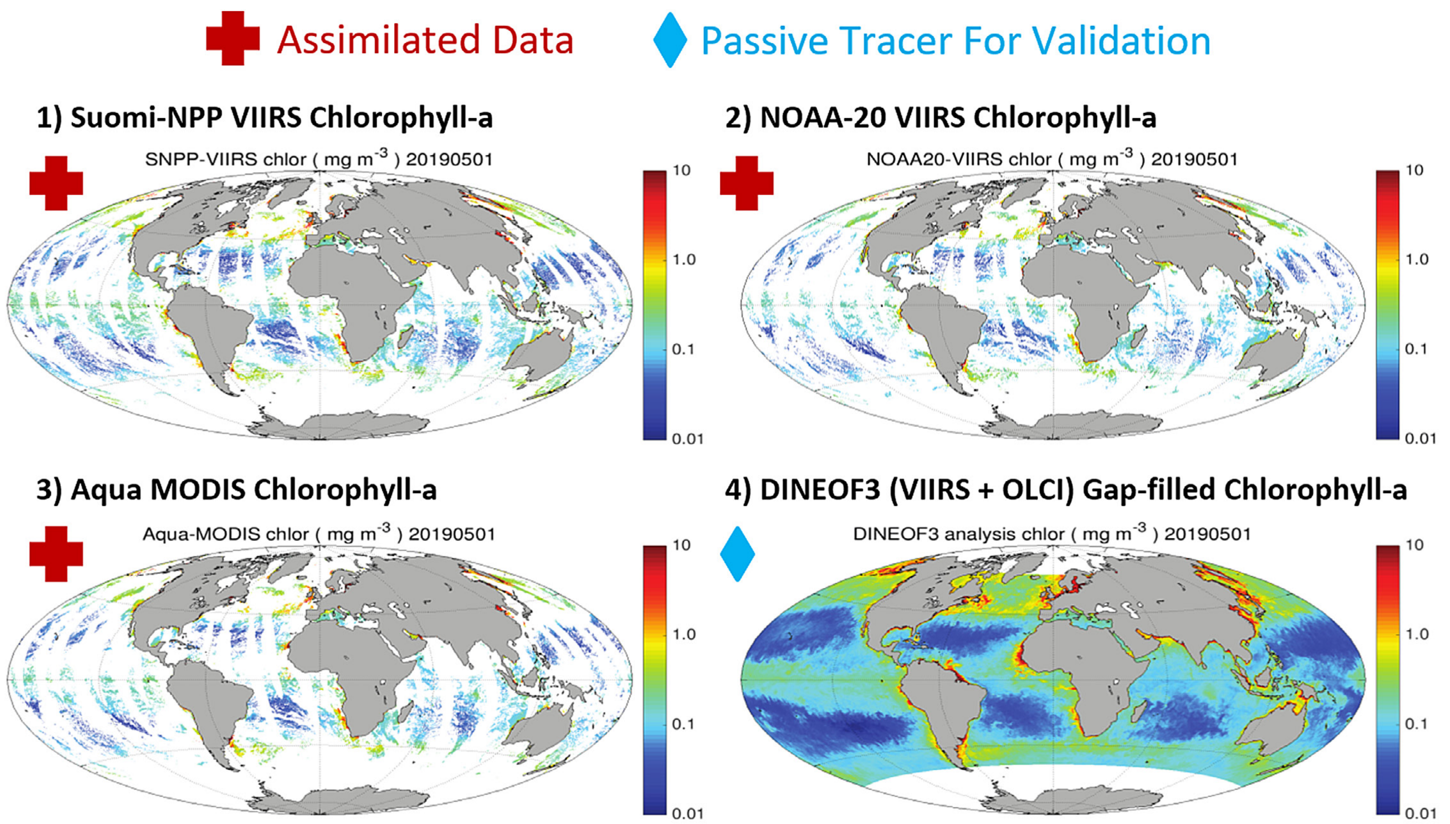
The figure below shows the availability of near real-time VIIRS and MODIS ocean color products that measure chlorophyll-a, a color pigment found in plants, algae, and phytoplankton; these products were assimilated and ingested into the global reanalysis. Passive tracers were also ingested for model validation: gap-filled Level 4 chlorophyll analysis derived from VIIRS (VIIRS + OLCI DINEOF3) and surface-based Argo (drifting buoy) observations that are independent of the assimilated satellite products.

Ocean Color Products Used in Data Assimilation & Ingested in Reanalysis Experiment: Product Availability By Year



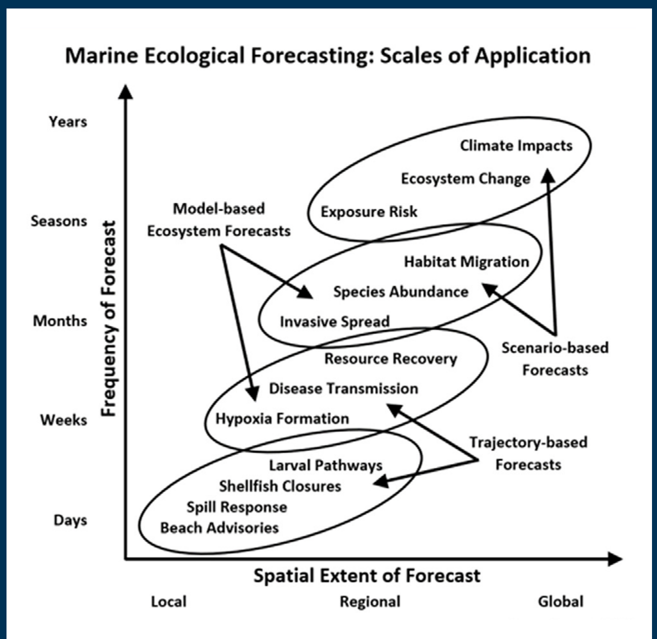
Coverage of the daily ocean color observations ingested from these sources can be seen for May 1, 2019, in the examples below. With the daily assimilated satellite ocean color data, Mehra and Liu addressed another project objective: to implement an ocean biogeochemical model in the Unified Forecast System.

Daily Ocean Color Observations Ingested in Data Assimilation (May 1, 2019)



The Importance of Subseasonal-to-Seasonal (S2S) Forecasting

Subseasonal *is defined as the period from 2 weeks to 3 months, and* ***seasonal*** *ranges from 3 months to 2 years.* ***Subseasonal-to-seasonal (S2S) forecasting*** *is vital in bridging the gap between medium-range weather and seasonal forecasts and is influenced by atmospheric conditions as well as slowly changing ocean conditions, such as sea surface temperature. Prediction of marine habitat shifts or ecosystem stress on an S2S scale—ecological forecasting—is of tremendous benefit to managers and stakeholders, especially since many stressors have a cumulative impact on the ecosystem. Like atmospheric weather forecasts, knowing ocean weather in advance can help minimize the potential for reaching a tipping point and give decision makers and communities time to act.*

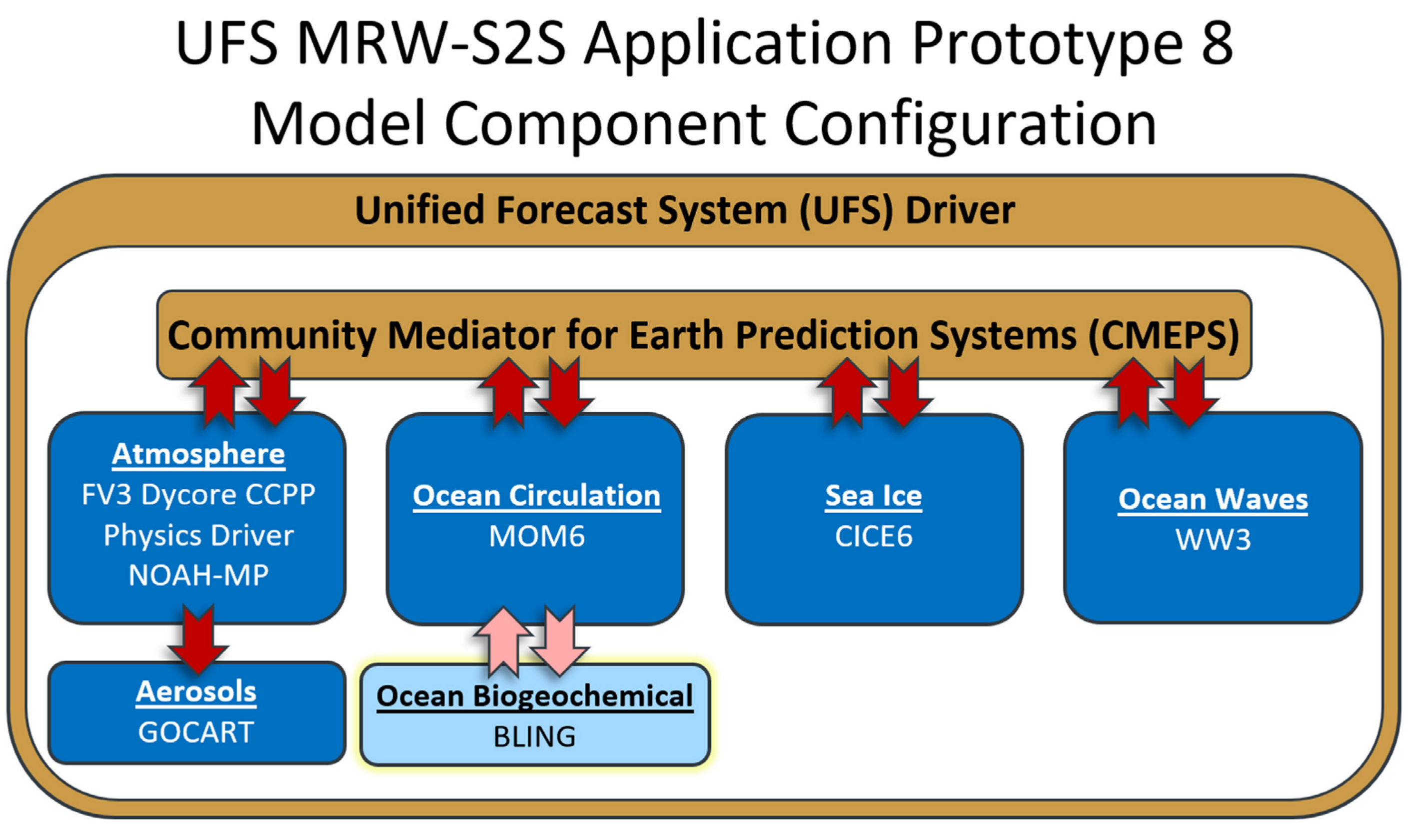


Applications of marine ecological forecasts at representative spatial and temporal scales. Source: Green et al 2009.

Implementing a Simple Ocean Biogeochemical Model in the Unified Forecast System

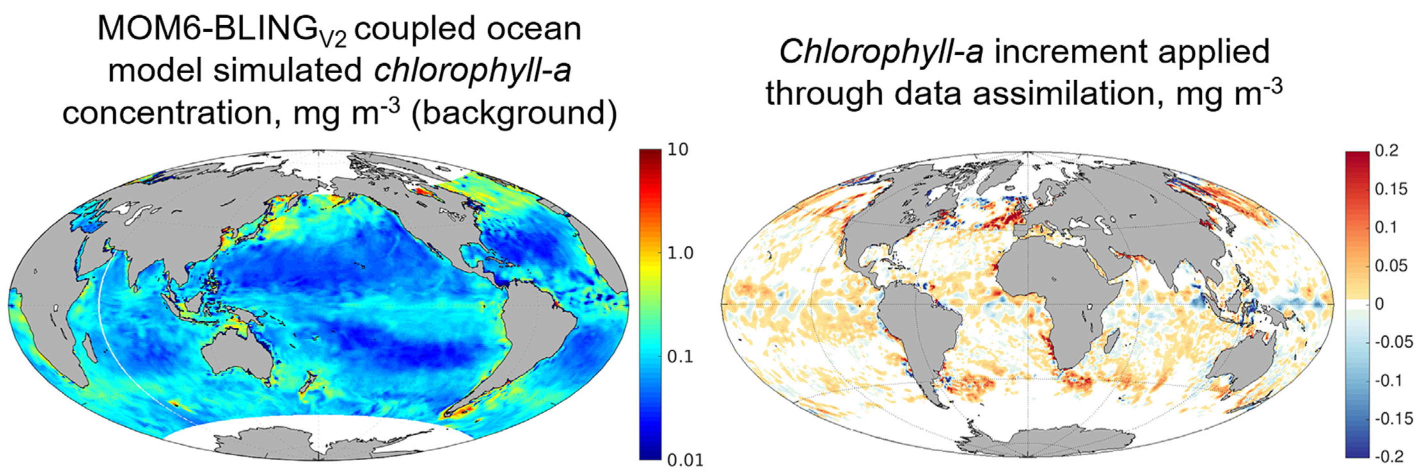
The Unified Forecast System (UFS) is a community-based, coupled, comprehensive Earth modeling system, and is designed to support NOAA/NCEP's operational numerical weather prediction applications. The Subseasonal-to-Seasonal (S2S) application of UFS fills the gap between weather prediction (up to a few days in advance) and climate-scale prediction (from months to hundreds of years in advance). The current iteration of the UFS, prototype 8, includes modules for the atmosphere, aerosols, sea ice, ocean waves, and ocean circulation, but it lacks an ocean biogeochemical component needed to fine tune model predictions to the impact of ocean biogeochemical feedback.

To fill this gap, Mehra and Liu's team coupled an ocean biogeochemical model called BLING ("Biology Light Iron Nutrient and Gas") to the MOM6 (short for "Modular Ocean Model version 6") ocean circulation model (see configuration, right). Liu explains, "For the BLING model, chlorophyll is a derived property from the simulation, which provides feedback to ocean opacity—such as how sunlight gets absorbed and scattered or reaches the deeper ocean—computation in the MOM6 physical model." In other words, daily assimilated VIIRS and MODIS ocean color data are used to adjust the BLING simulation, and then enhance MOM6 and the overall UFS S2S prototype model. Mehra and Liu's team is also considering adding other biogeochemical modules like the more comprehensive Carbon Ocean And Lower Trophics (COBALT) model.



The Unified Forecast System (UFS) Medium-Range and Subseasonal-to-Seasonal (MRW-S2S) application prototype 8 is made up of models for the atmosphere, aerosols, ocean circulation, sea ice, and ocean waves. These model components are coupled through the Community Mediator for Earth Prediction Systems (CMEPS), a mediator used for coupling Earth system model components. Mehra and Liu's project explores adding the BLING model for ocean biogeochemical data as a companion to the existing ocean model component, MOM6. Figure adapted from global UFS-coupled team.

The figure below is an example of how data assimilation improves model prediction. On the left is simulated chlorophyll-a concentration from the coupled BLING-MOM6 model simulation on May 1, 2019. On the right is the adjustment made to chlorophyll-a concentration applied through daily data assimilation of VIIRS and MODIS ocean color products—incremental improvements in the ongoing reanalysis effort. The assimilated ocean color (chlorophyll-a) data is the feedback to light attenuation needed to fill gaps in the MOM6 model that result in more accurate biogeochemical modeling.



Left: Simulated chlorophyll-a concentration from the coupled MOM-BLINGV2 component of the coupled global UFS application (snapshot of background at 12 hours on May 1, 2019). Right: Chlorophyll-a increment applied through JEDI-based data assimilation using a 3DVar scheme covering 2019-2022 and is a 24-hour data assimilation cycle. Both the coupled global UFS application and the data assimilation application have a resolution of 0.25 degrees for the global ocean.

Assessing the Impact of Biogeochemistry Data Assimilation on Prediction Skill

"One of the primary goals of this project," says Liu, "is to improve forecasts by improving ocean initializations through near real-time ocean data assimilation." To evaluate their system and assess the impact of ocean biogeochemical data assimilation—daily assimilation of VIIRS and MODIS ocean color products—on physical ocean prediction skills, Mehra and Liu's team conducted several ocean reanalysis sensitivity experiments using sea surface temperature. Liu explains, "We used sea surface temperature as an example because it's a very important property for air-sea exchanges, which is important for weather and climate systems."

Physical v. Biogeochemical

Ocean physical properties involve ocean physics and include temperature, salinity, velocity, and other variables that can be directly measured.

Ocean biogeochemical properties refer to biological, geological, and chemical processes and their interactions with the atmosphere and land—processes like primary productivity, carbon dioxide uptake, oxygen and nitrate concentration, and so on.

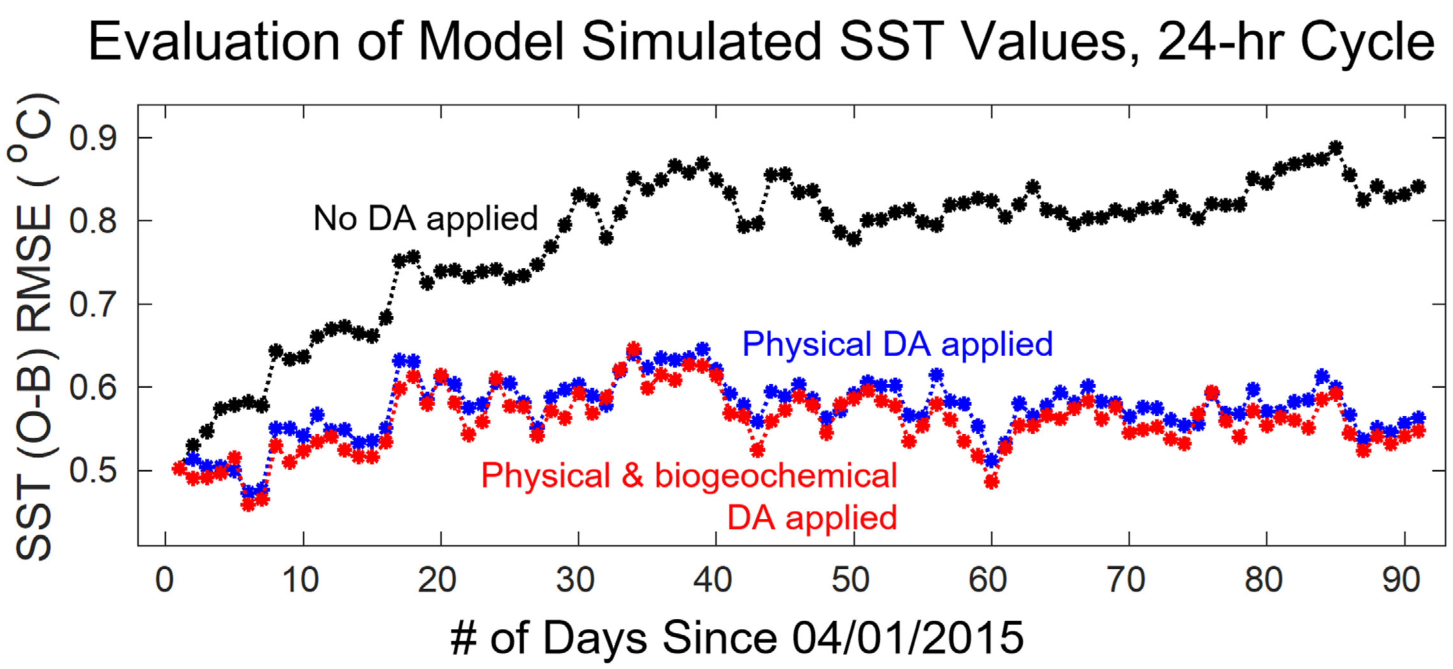
SST Prediction Skill Over a 24-Hour Forecast Cycle

For this experiment Liu asked, "What is the impact of doing biogeochemical data assimilation on physical marine predictions?" The preliminary results on the next page answer this question by showing the prediction skill of SST over a 24-hour forecast using a 2015 example as a benchmark. The figure shows the globally averaged model observation SST root-mean-squared error (RMSE) for three experiments: (1) no data assimilation applied (black line), meaning that the model ran without any observations from marine data assimilation; (2) only physical marine data assimilation applied (blue line); and (3) both ocean biogeochemical and physical marine data assimilation applied (red line). RMSE is a commonly used method for evaluating the quality of model predictions. It is a measure of the differences between values predicted by a model and observed values (truth data). Here, the lower the SST RMSE, the better the SST prediction skill on a global level, and vice versa.

Why SST?

Sea surface temperature (SST) is often a leading indicator and/or important driver of marine ecosystem fluctuations. Being able to predict changes in SST can allow time for adaptation or mitigation before a tipping point is reached.

SST is also an essential physical variable for understanding, quantifying, and predicting complex air-sea interactions that are linked to many different weather and climate-related events, like hurricanes, coastal fog, and changes in ocean biodiversity.



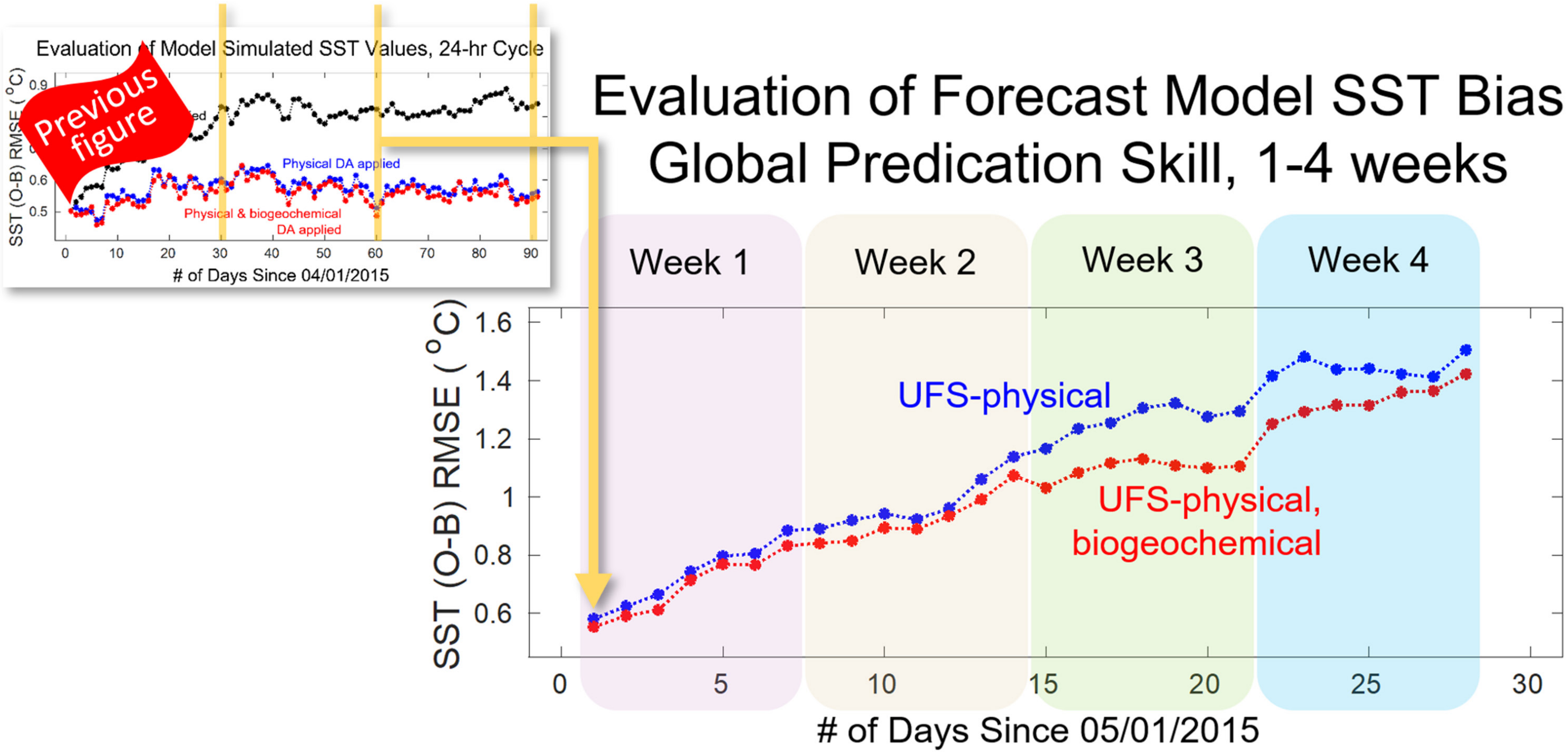
"You can see that adding ocean biogeochemical data assimilation to the physical data assimilation model [red line] has a very small impact on sea surface temperature bias reduction," says Liu. "This was expected," she continues, "because the impact of ocean biogeochemical feedback is created through the lens of the model's 24-hour forecast period between each data assimilation cycle, which is a small period." In other words, impact is small when the forecast period is short. Things changed when the team looked at the impact of ocean biogeochemical feedback in the coupled global UFS forecast model at a subseasonal timescale.

SST Prediction Skill at an Subseasonal Timescale

"It's important that we also evaluate the impact [of biogeochemical feedback] in the coupled UFS model, so we assessed the forecast skills of SST after initializing the system from initial ocean conditions generated by our reanalysis sensitivity experiments," explains Liu. Two versions of the coupled global UFS (prototype 7c) were used for this assessment: one with the BLING biogeochemical model added ("UFS-physical, biogeochemical forecast") and one without, the baseline system ("UFS-physical forecast"). The forecast period was extended to a subseasonal timescale because, Liu notes, "the impact of ocean biogeochemical feedback may accumulate and no longer be negligible" during a longer forecast period, unlike the 24-hour forecast experiment.

The graph below shows preliminary results of SST RMSE (SST prediction skill) over a forecast period of four weeks in the coupled global UFS model starting at day 60 of the previous experiment. Liu clarifies, "Here, we are looking at the impact of adding the ocean biogeochemical component in the data assimilation and in the UFS forecast model for sea surface temperature prediction."

Comparing the SST RMSE values for the two UFS model versions, the results show a greater improvement in SST prediction skill during week 3 and early week 4 for the model with the added biogeochemical component (red line). Remember, the lower the RMSE (along the vertical axis), the better the SST prediction skill. "We can see by integrating the BLING biogeochemical model and biogeochemical data assimilation we reduced the forecast model's SST bias global skill," Liu summarizes. As she anticipated, the impact of biogeochemical feedback accumulated over time, showing maximum improvement in SST prediction in week 3 of the experiment.



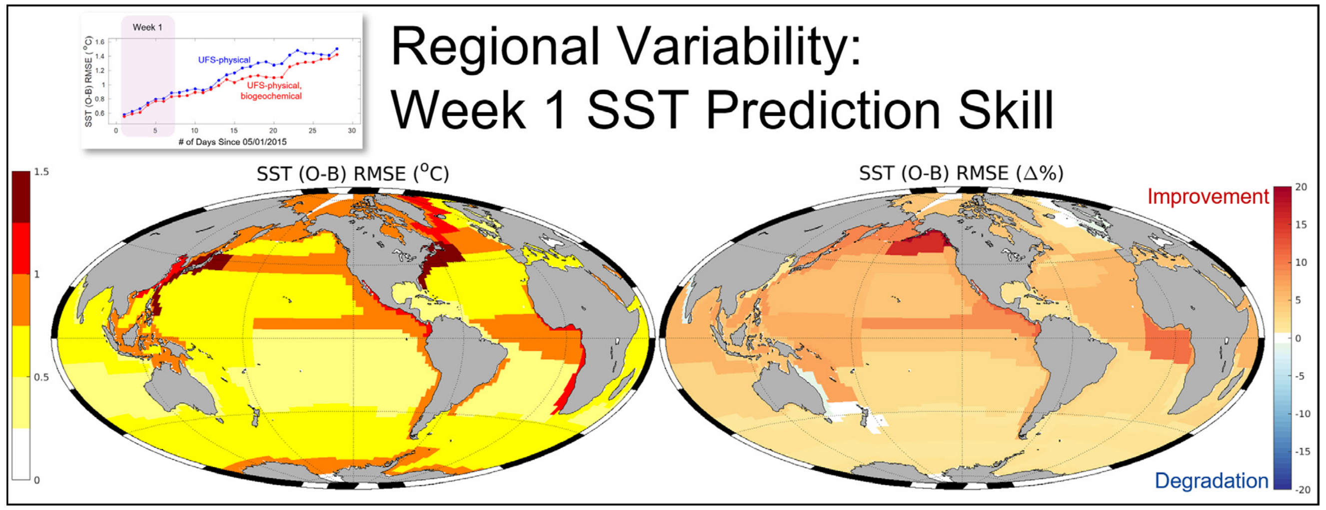
Regional Variability of SST Prediction Skill

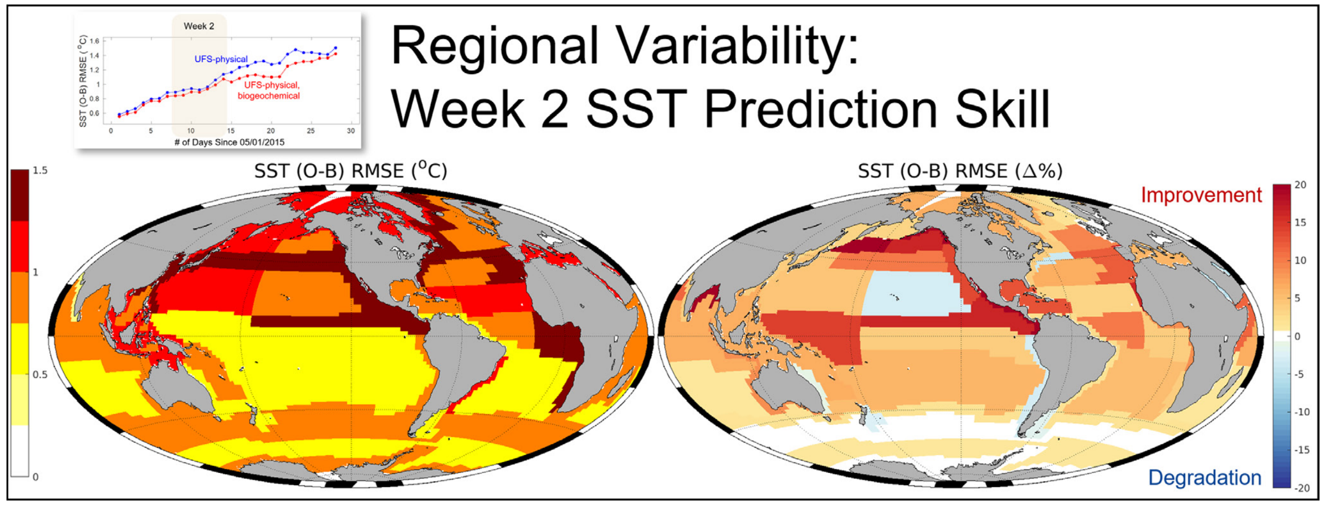
"Although SST prediction skill in our experiments is at a global scale, we also want to look at the regional variability—how the biogeochemical impact to SST prediction differs at basin and sub-basin scales," Liu says. To do so, she and her team divided the global ocean into 56 biogeochemical provinces—a standard geographical reference for ecological studies—and calculated the domain scales (such as global scale, national scale, etc.) and the impact at the domain scale and sub-domain scale levels. What they found was more evidence to support including ocean biogeochemical data (with assimilated satellite ocean color products) in subseasonal forecasts to better understand the cumulative impact of biogeochemical feedback on ecosystem change.

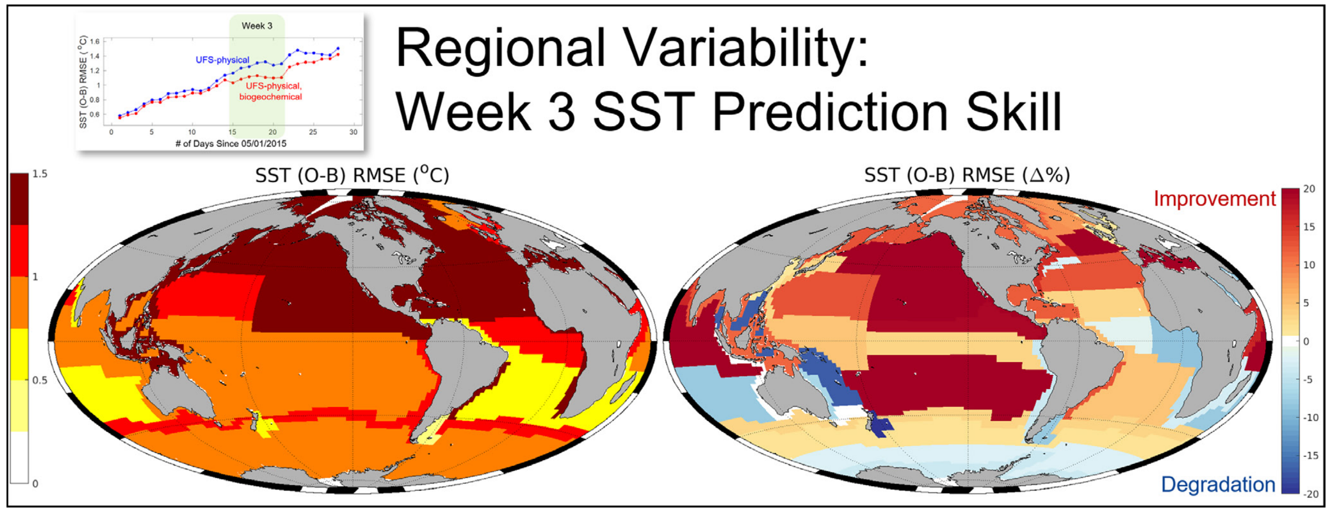
In the following figures showing regional variability, the left side is the domain scale average of SST RMSE. On the right is the difference (percent change), which is the improvement (red) or degradation (blue) in SST prediction skill (SST RMSE).

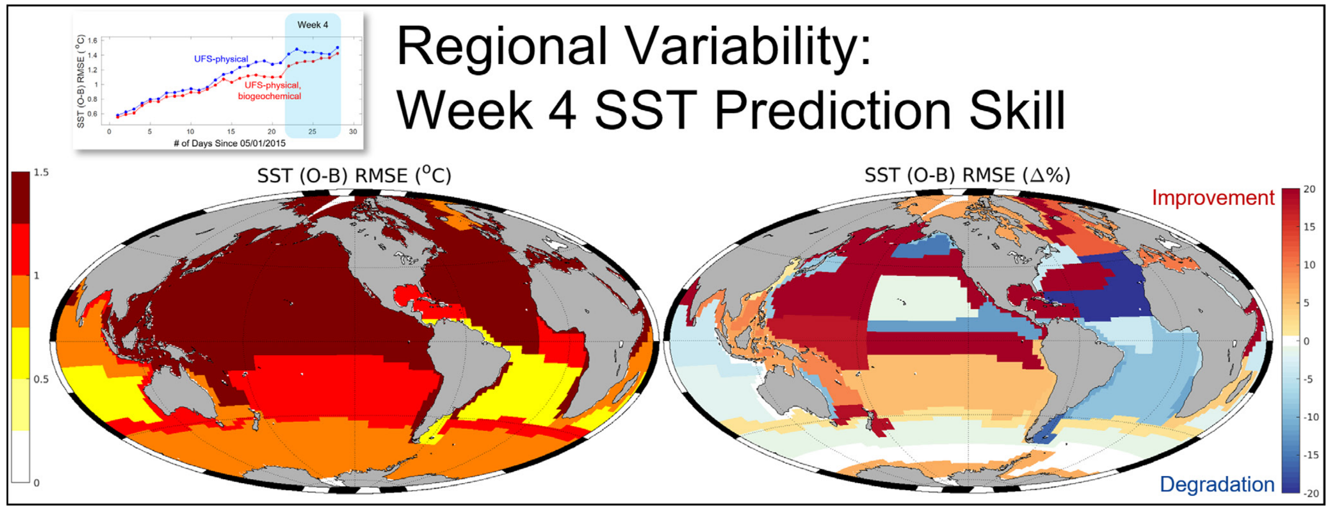
For week 1, the improvement is generally on a global scale with minimal regional variability. However, in week 2 and even more so in weeks 3 and 4, the biogeochemical impact accumulates showing greater impact over time (indicated by dark red), that is, a greater magnitude in SST bias reduction and prediction skill as time progresses. Stronger, distinct regional variability in improvement and degradation patterns is also seen as the weeks go on, which suggests possible model bias of unknown (at this time) cause.

While this example is from a single global forecast model marine initialization experiment for a 2015 benchmark case, Mehra and Liu's team is conducting ongoing experiments at a 0.25 degree global resolution using the latest version of the UFS model (prototype 8) to confirm what they have found up to now and to address the seasonal and regional variability of biogeochemical impact. "These preliminary results are very encouraging for us, not only showing the magnitude of biogeochemical impact on SST prediction, but also suggesting the need to do regional-scale bias correction for current marine data assimilation work before the biogeochemical component can be implemented in the next generation of operational UFS forecast models," concludes Liu.









The Value of Regional SST Prediction

Who benefits from improvements in regional SST prediction? The obvious answer is researchers, but in reality the value extends far beyond the research community. Regional SST prediction has importance for meteorology, ecological forecasting, climate modeling, coastal area management, marine policy planning, commercial fishing and shipping, hazard prediction and resilience, and protection of human health and the economy—any application touched by weather and climate. For example, regional SST forecasts at a subseasonal-to-seasonal scale could help reduce the socioeconomic impacts of marine heatwaves on coastal communities by providing advance warning—time to apply mitigation and adaptation measures—before damage occurs. Extreme SST events are already causing mass mortality of marine species and harmful algal blooms that cost the U.S. billions of dollars in lost ecosystem services. Forecasting these events more accurately on a regional scale is valuable to ensure the health and safety of coastal communities and their residents who rely on coastal ecosystems for food, recreation, and other economic and cultural resources.

ONGOING WORK AND REMAINING QUESTIONS

There is still a lot of work to do to improve the forecast system, address seasonal changes, and to better understand the reasons behind the distinct regional pattern that is suggested by these experiments. So far, the team's research has shown a mostly positive impact of integrating ocean biophysical feedback on SST prediction skill at a subseasonal scale. But how will this data be used to protect marine ecosystems and the communities that rely on them? Will it help predict ecosystem changes before a tipping point is reached? Many questions remain, which Mehra and Liu's team are working to answer.

Improvements, profiling, and testing of the coupled UFS forecast model continue. Among the team's activities, they are looking at regional models to evaluate whether a higher resolution can provide better results and are exploring ways to include data quality control for ocean color in regions where degradation patterns are present. Also ongoing is the multi-year 0.25 degree global ocean physical-biogeochemical reanalysis in which near real-time VIIRS and MODIS ocean color data is assimilated. This dataset is anticipated to be of great value to the scientific community as a daily global reanalysis product. Liu emphasizes, "We don't currently have ocean biogeochemical reanalysis data, especially a multi-year reanalysis at a 0.25 degree resolution—high frequency at daily intervals—available to the research community so we expect it to be a very useful dataset." She hopes to finish the first reanalysis run by the end of 2023, remarking, "we look forward to sharing the results with the broader community when they become available!" ✦

STORY SOURCE

The information in this article is based, in part, on the August 15, 2022, JPSS Science Seminar "Implementation of Ocean Color Data Assimilation in NCEP's Unified Forecast System" presented by Dr. Xiao Liu, I.M. Systems Group, Inc. (IMSG) at the NOAA National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) in College Park, Maryland. It features work led by Dr. Avichal Mehra (Principal Investigator), NCEP/EMC, with contributions from many, including Daryl Kleist and Guillaume Vernieres, NCEP/EMC; Jong Kim, Yi-Cheng Teng, André Van der Westhuysen, and Shastri Paturi, IMSG at NCEP/EMC; Eric Bayler, NOAA NESDIS Center for Satellite Applications and Research (STAR); Travis Sluka, The Joint Center for Satellite Data Assimilation (JCSDA); Hae-Cheol Kim, University Corporation for Atmospheric Research (UCAR) at NOAA Office of Oceanic and Atmospheric Research (OAR) Geophysical Fluid Dynamics Laboratory (GFDL); John Dunne, OAR GFDL; and Unified Forecasting System (UFS) and Joint Effort for Data assimilation Integration (JEDI) active developers and communities.

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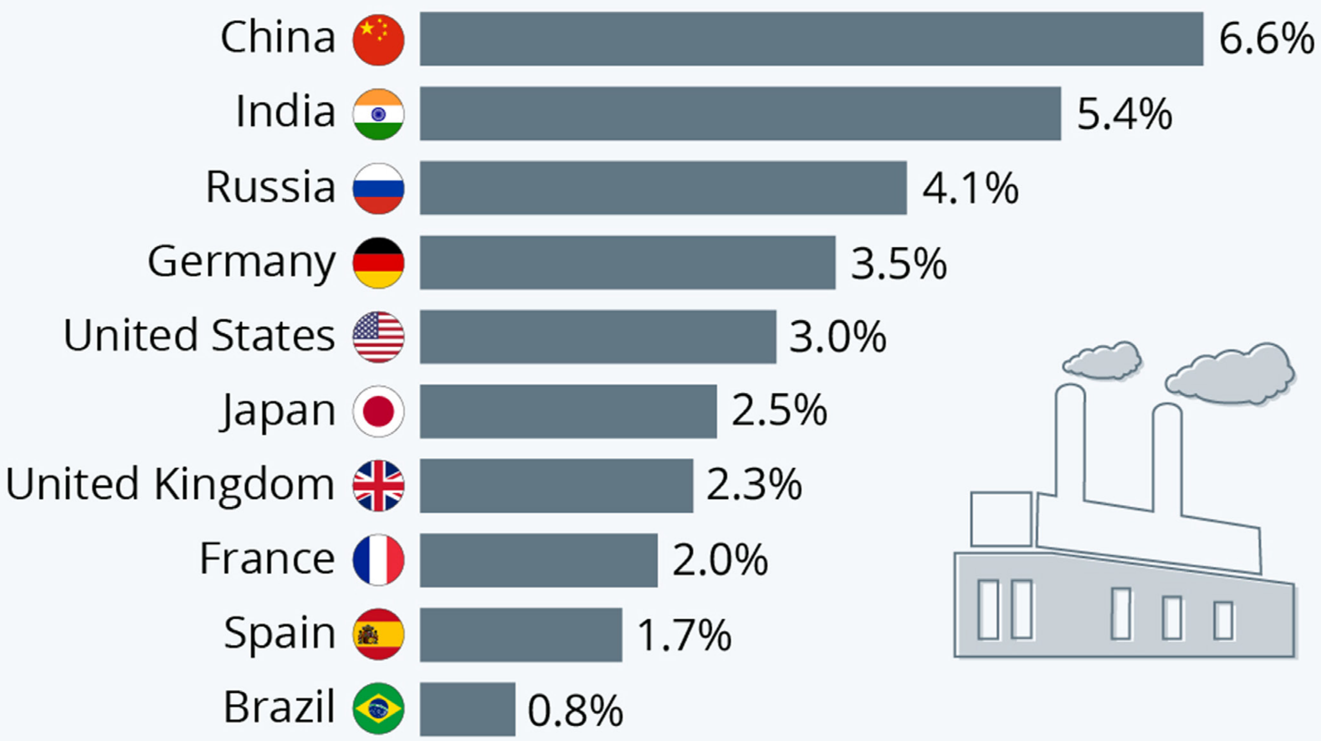
FEATURE 12

Expanding the Use of VIIRS Aerosol and Fire Products Through a Customizable Hands-on Training Program

Dust storm in Arizona. Source: University of Colorado Boulder, Western Water Assessment.

The Economic Burden Of Air Pollution

Economic costs of air pollution from fossil fuels as a share of GDP in 2018



Sources: Greenpeace, Center for Research on Energy and Clean Air

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Smoke, blowing dust, and haze are aerosols, tiny particles or droplets suspended in the air that are harmful to humans and the environment. They reduce visibility, play a major role in climate change, damage vegetation and insects, and cause poor air quality that is linked to a higher frequency of heart and lung diseases, emergency room visits, hospitalizations, and untimely death. Not only do air pollutants take a toll on human health and the environment, but they also affect the economy by reducing a person's ability to work, increasing health expenses, damaging cultural monuments and historical buildings, and decreasing crop yield, among other impacts.

Wildfires can start naturally from lightning strikes, but most are caused by humans from unattended campfires, cigarettes, debris burning, or arson.

Smoke from large wildfires can be harmful to people and the environment both near the fire source and hundreds of miles away. Prescribed burns—setting planned fires to maintain forest health—also produce smoke, but smoke management practices help limit the impact to public health. Nonetheless, prescribed burns can be a significant source of fine particulate matter ($PM_{2.5}$), which is harmful to ecosystems and people.

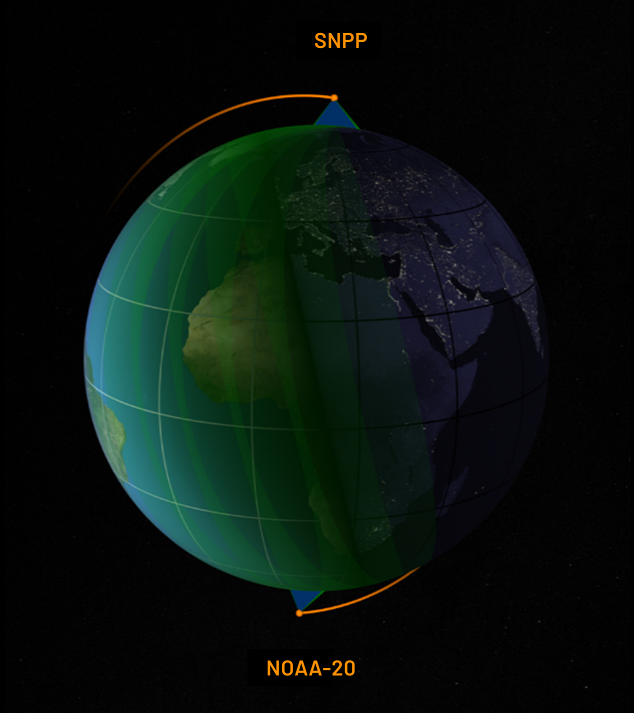
Atmospheric dust originates from deserts, dry lakes, and playas where loose, dry soil and sand is lifted into the air and carried by the wind, sometimes drifting thousands of miles. Take for example dust from the Sahara Desert that frequently reaches North America, most often in June through September, because of the trade winds that blow over the Atlantic Ocean.

Left: The McKinney Fire was the most destructive wildfire in California in 2022, burning more than 57,000 acres and killing four people. Source: InciWeb National Wildfire Coordinating Group (NWCG). Middle: A smaller scale, thicker dust storm, called a haboob, moved through Lubbock, Texas on June 18, 2009. Source: Todd Lindley, National Weather Service (NWS). Right: Smog in Shanghai, China, which is a mixture of pollution from coal, the primary source of energy for most homes and businesses in the region, as well as emissions from vehicles. Credit: Nigel Swinn. Source: National Geographic.

Haze aerosols are formed from precursor gasses—chemical compounds that undergo reactions in the atmosphere—that are emitted by vehicles, power plants, factories, and other manufactured sources, as well as natural sources like volcanic eruptions, sea salt spray, and trees. When atmospheric conditions are right, emissions from these sources can result in high levels of fine particulate matter that cause low visibility and poor air quality. One of the most famous haze events in history is the Great Smog of 1952 that occurred in London, England over five days in December 1952 and caused thousands of deaths. The toxic smog developed from a mixing of smoke from coal-burning factories and chimneys and high-pressure weather conditions.

"In recent years, the hazardous impacts of smoke and dust have become more frequent and severe due to extended periods of drought and hot weather," explains Dr. Amy K. Huff, Senior Research Scientist at I.M. Systems Group, working at the NOAA/NESDIS Center for Satellite Applications and Research (STAR). Haze follows a different narrative—enforcement of strict U.S. emissions regulations has limited its impact in the U.S. in recent years, but haze remains a major issue in countries with poorly enforced air quality policies, like India and China. "Because of the global impacts of smoke, dust, and haze, it's increasingly important for end users to be able to track the location and intensity of atmospheric aerosols and monitor fires," Huff notes.

The Visible Infrared Imaging Radiometer Suite (VIIRS) sensor provides critical products to help with wildfire and aerosol challenges. VIIRS delivers daily global observations at a high spatial resolution of 750 meters (m) for aerosols and 375m for fires. The VIIRS instrument flies aboard all JPSS satellites: Suomi National Polar-orbiting Partnership (Suomi NPP), NOAA-20, and NOAA-21 launched in November 2022. The swaths



JPSS satellites have relatively wide, overlapping swaths so there are no data gaps at the equator. Shown here are Suomi NPP and NOAA-20 (formerly JPSS-1). Their orbits are offset by 50 minutes, meaning that there are multiple observations per day. More data will become available when JPSS-2 reaches orbit.

of these satellites overlap, producing multiple VIIRS aerosol observations per day and fire observations at night.

Despite the utility of VIIRS data for aerosols and fire applications, there are barriers to their routine use in the user community. Satellite data and products can be challenging to access and interpret because of their complexity, especially for new users. Understanding data quality is crucial for identifying the right product for an application, as is understanding how to download, process, and transform the data into a usable format. All these steps take time and specialized skill that many end users of satellite data may not have.

The NOAA STAR Aerosols and Atmospheric Composition Science Team is answering the challenge to remove the barriers to more widespread use of satellite data within the atmospheric science user community. Through their free training program, the team offers tailored courses on aerosol, fire, and trace gas satellite products from VIIRS, GOES-R Advanced Baseline Imager (ABI), and the TROPOspheric Monitoring Instrument (TROPOMI). At the September 2022 JPSS Science Seminar, Dr. Huff gave an overview of the STAR Atmospheric Composition Product Training program and the VIIRS products featured in their offered courses.

THE VALUE OF VIIRS AEROSOL AND FIRE PRODUCTS

The VIIRS Aerosol Optical Depth (AOD) product and VIIRS Aerosol Detection Product (ADP) are used by operational forecasters and researchers to look at the impact of aerosols on air quality at ground-level where people live and breathe, and to track the movement of aerosol plumes. JPSS VIIRS aerosol products were developed and are maintained by the STAR Aerosols and Atmospheric Composition Science Team; contributing members (in alphabetical order) are Pubu Ciren, Amy Huff, Shobha Kondragunta, Istvan Laszlo, Hongqing Liu, and Hai Zhang.

VIIRS AOD & ADP

Aerosol Optical Depth (AOD) *is a* ***quantitative*** *measure of aerosols in a vertical column of the atmosphere*

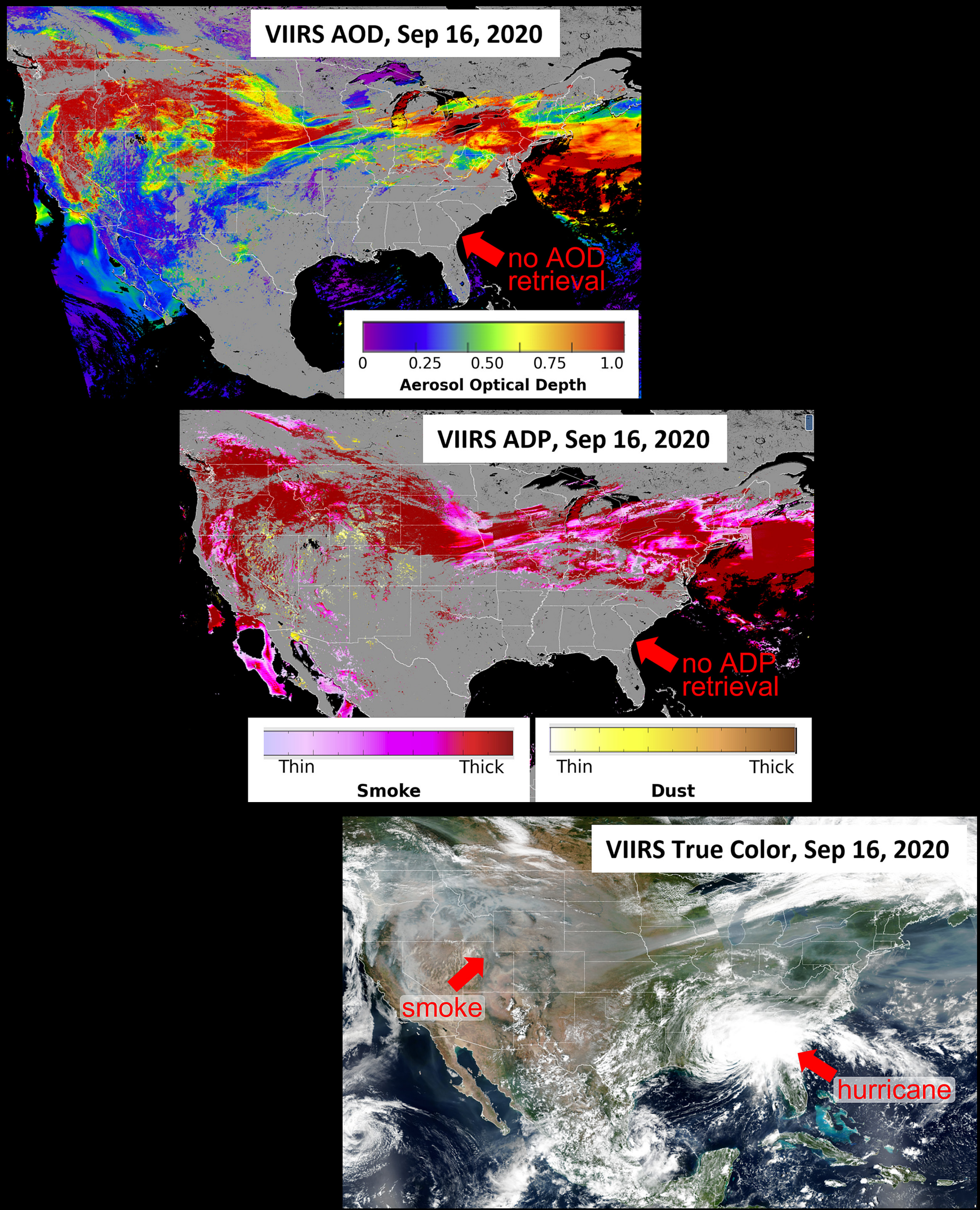
- *A measure of scattering & absorption of light by aerosols*
- *Used to estimate surface PM2.5 concentrations*

Aerosol Detection Product (ADP) *is the* ***qualitative*** *indicator of smoke & dust aerosols in a vertical column of the atmosphere*

- *Identifies location & intensity of smoke and dust*
- *Also called the "smoke and dust mask"*

VIIRS AOD quantifies the amount of aerosol in the atmosphere. In other words, it measures the solid and liquid particles suspended in the air, including smoke, dust, volcanic ash, and other aerosols. Forecasters use VIIRS AOD to help monitor and forecast air quality, which is important considering that the U.S. EPA estimates poor air quality costs Americans about $143 billion per year in health care bills. The product plays an important role in monitoring air quality conditions; as Huff explains, "because VIIRS AOD is quantitative it can be used to estimate surface PM2.5 concentrations [particles smaller than 2.5µm in diameter], which helps fill the gaps in the global regulatory monitoring networks." Air pollution can aggravate heart and lung diseases, so these data are critical to protect vulnerable populations like the elderly, children, and people with heart or lung conditions.

Complementing the VIIRS AOD product is VIIRS ADP, which detects and distinguishes between smoke, dust, and clear sky. VIIRS ADP is particularly useful for identifying the location and relative intensity of smoke and dust, which can be difficult to see otherwise. Smoke and dust detection is important

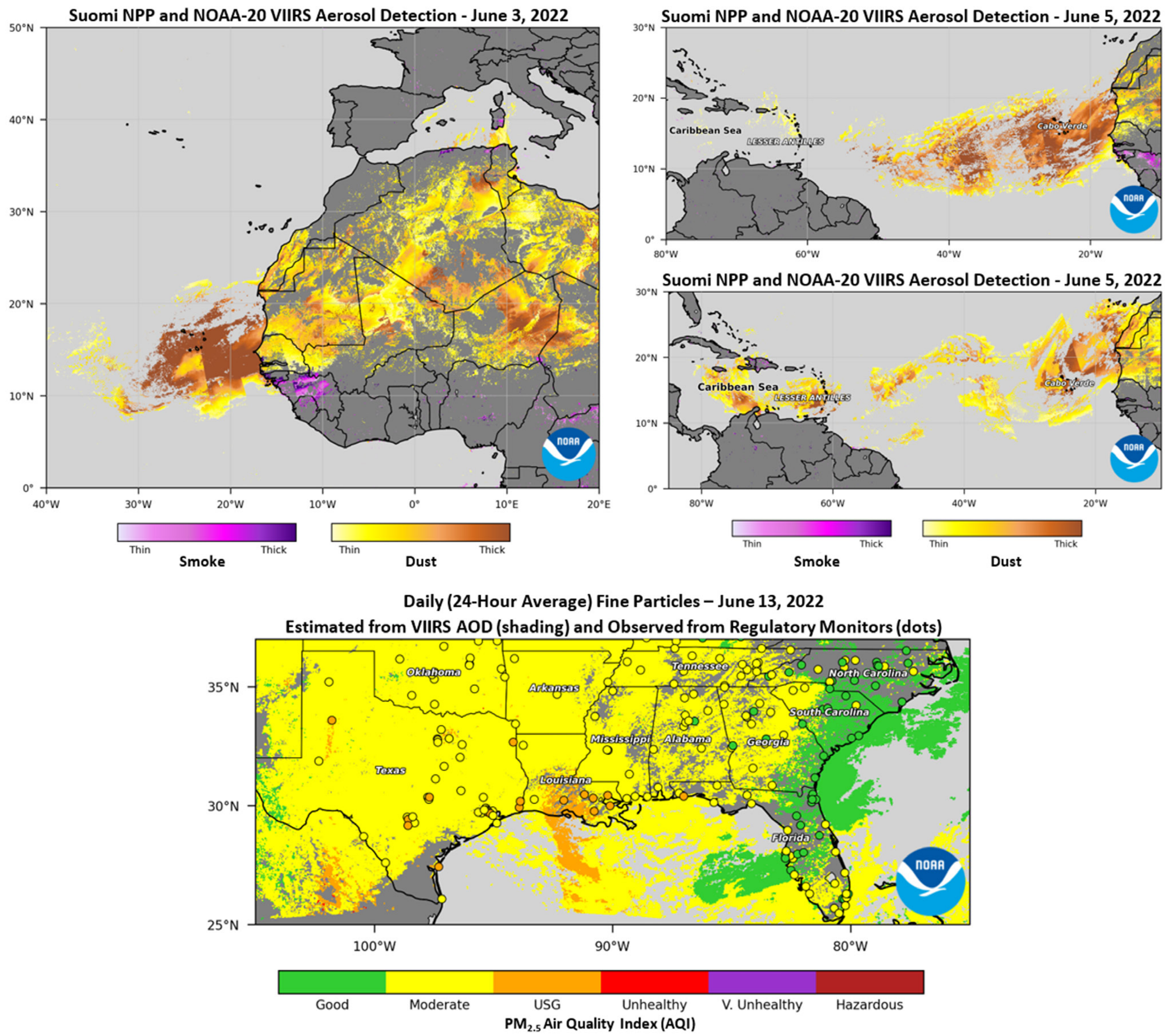


Top: VIIRS AOD on September 16, 2020, when thick smoke from wildfires in the Western U.S. was transported across the United States and reached the Eastern U.S. Large AOD values (yellow/orange/red) indicate higher aerosol concentrations, whereas low AOD values (purple/blue) indicate clean or clear atmosphere. Middle: VIIRS ADP from the same event. Pink/red indicates smoke and yellow/brown indicates dust. The darker the color, the thicker the smoke or dust. Bottom: VIIRS True Color image from the same event showing smoke transport across the U.S. (the gray shaded area).

for environmental monitoring, weather prediction, climate change modeling, and protecting human health. Both VIIRS AOD and ADP are daylight-only products, and neither can "see" through clouds, meaning that no data is retrieved over cloudy regions and during the night. Despite these challenges, VIIRS AOD and ADP are valuable products for tracking the movement and relative concentration of smoke and dust, as demonstrated in the following example.

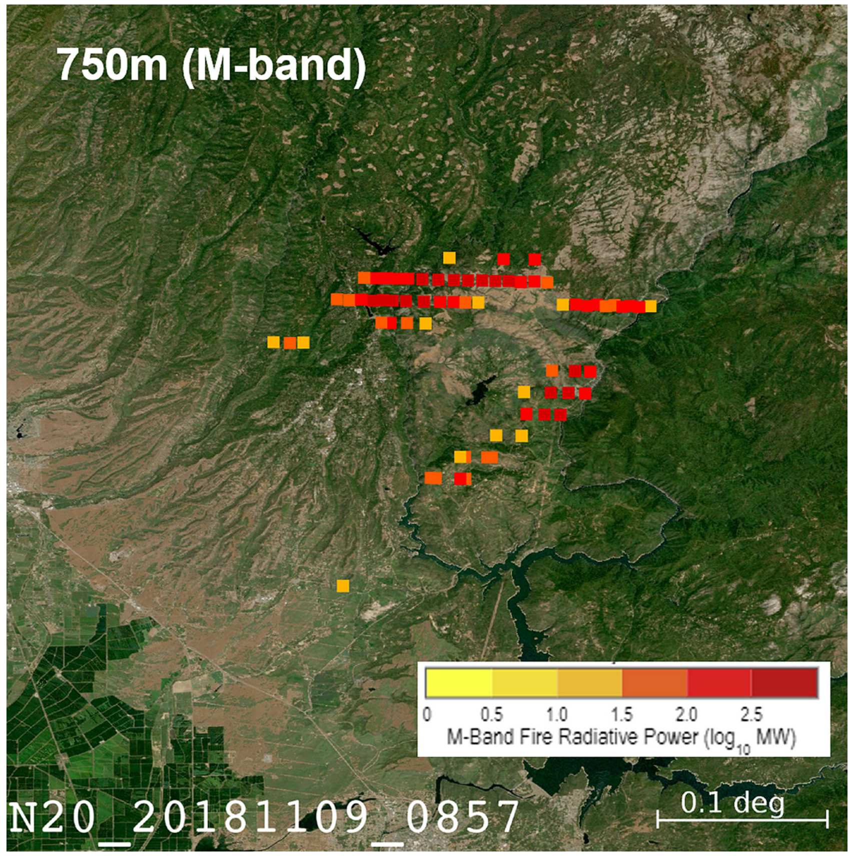
On the left, VIIRS AOD (top) and VIIRS ADP (middle) are shown for September 16, 2020, when wildfires were raging in the Western U.S., along with a VIIRS True Color image (bottom) for reference. Large VIIRS AOD values (orange/red shading), corresponding to thick smoke, can be seen spreading west to east across the northern states and out into the Atlantic Ocean, impacting populations hundreds of miles from the wildfires. VIIRS ADP clearly shows the areas of thick smoke (dark pink/red shading) compared to thinner smoke (light pink shading), and there is also some thin dust (yellow shading) mixed with the smoke in the Western U.S., which is very difficult to detect in the VIIRS true color image. VIIRS AOD and ADP are not available for the Southeastern U.S. on this date because clouds associated with Hurricane Sally impeded data retrieval. Even so, AOD and ADP provided critical information about the presence and intensity of western wildfire smoke for locations far from its source.

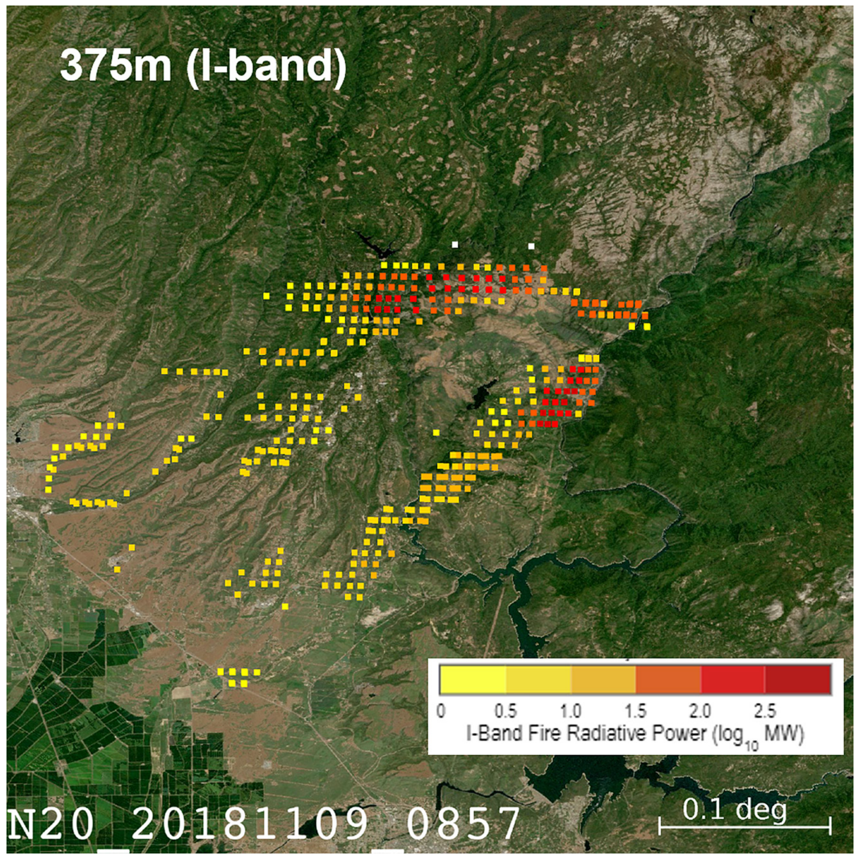
Harmful aerosols may not even come from the same continent, making detection and monitoring all the more important. In June 2022, for example, Saharan dust caused a multi-day Code Orange ("Unhealthy for Sensitive Groups") PM2.5 air quality event in parts of Florida, Louisiana, and Texas—more than 4,000 miles away from the Sahara Desert! Surface-level air quality monitors are clustered in urban and suburban areas (shown below by the green/yellow/orange dots in the bottom image), but VIIRS AOD allowed forecasters to estimate PM2.5 concentrations in areas where there are no ground monitors (shown by the green/yellow/orange shading in the bottom image) so that communities could take action. VIIRS ADP gave forecasters several days advance warning that the dust was heading toward the U.S. (top images).



CLICK IMAGE TO ENLARGE. Top images: Suomi NPP and NOAA-20 VIIRS ADP showing Saharan Dust (browns/yellows) from Africa on June 3, 2022, moving west across the Atlantic Ocean on June 5, 2022, and reaching the Caribbean on June 5, 2022. Bottom image: Daily fine particles corresponding to the PM2.5 Air Quality Index on June 13, 2022 (estimated from VIIRS AOD (shading) and regulatory monitors (dots)) for the Gulf of Mexico and southern and southeastern portions of the U.S.

The VIIRS Active Fires (AF) product is another valuable dataset from STAR that is featured in trainings. The VIIRS AF product detects active fire hotspots and includes fire radiative power (FRP), which is the amount of energy released by a burning fire at the time of observation. VIIRS FRP data are used in fire emissions, air quality, and smoke models.





NOAA-20 VIIRS Fire Radiative Power (FRP) measured by the VIIRS M-band (top) and I-band (right) for the Camp Fire in California on November 9, 2018.

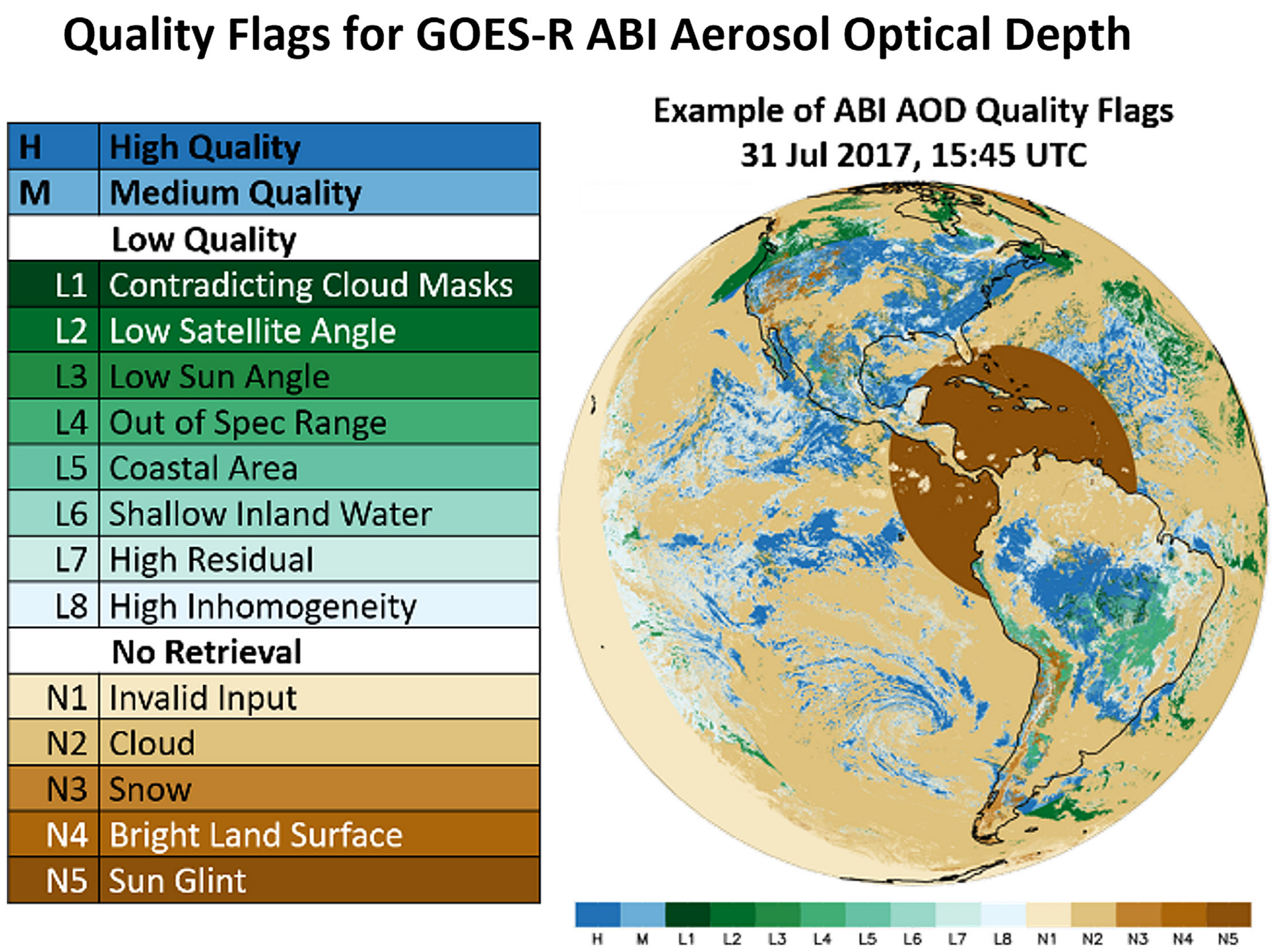
BRIDGING THE GAP BETWEEN VIIRS DATA AND END USERS

The STAR Aerosols and Atmospheric Composition Science Team interacts with a large and diverse community of end users of VIIRS data, from research institutions and academia to federal, state, and local governments. Huff notes, "A lot of our end users are operational air quality forecasters—they use aerosol and trace gas satellite data to help prepare operational forecasts of ozone and particulate matter for the public, while health researchers use the data to study the effects of air pollution on public health." Whether users are model developers, epidemiologists, or meteorologists, each has different needs and degrees of familiarity with VIIRS and other satellite data.

A Need For Training

"Through user engagement, we found that there are a lot of people that would like to use our data products, but they don't know how, and there are a lot of reasons why," says Huff. Finding and accessing the best product for a specific application can be a daunting task even for the most experienced users because of the nuances of satellite data. Downloading satellite data files programmatically, working with satellite data file formats, and interpreting metadata and quality flags can be significant barriers to product use. Simply put, a lot of users do not understand the data or how to appropriately apply them. "We realized that we needed a training program," explains Huff, "and we wanted it to do two things: make aerosol and fire satellite data accessible and understandable and promote proper use of the products for air quality applications in operations and research."

Today's STAR training program grew out of the outreach activities led by Dr. Shobha Kondragunta in the early 2010s as part of the GOES-R Air Quality Proving Ground. What started back then as two-day in-person workshops has evolved into a new program of tailored trainings designed to help users overcome barriers. "If end users don't know how to find or use the data, then we aren't meeting their needs," asserts Huff. The STAR training program puts the end user first by providing the most useful and usable products and services, which aligns with NOAA and NESDIS user engagement and customer experience initiatives.



An example of quality flags for GOES-R ABI Aerosol Optical Depth (AOD) on July 31, 2017 (VIIRS AOD quality flags are similar). Quality flags express product confidence and applying them is critical for the correct use of the product for qualitative or quantitative applications. Here, areas shaded in brown indicate no AOD is retrieved due to invalid input, clouds, snow, bright land surface, or sun glint. Areas shaded in green are low quality due to several reasons. High quality data, in dark blue, is recommended for quantitative applications like data assimilation, and high + medium (light blue) quality data are recommended for qualitative applications. Figure courtesy of Mi Zhou (IMSG) and Istvan Laszlo (NOAA).

STAR ATMOSPHERIC COMPOSITION PRODUCT TRAINING PROGRAM

Training Venues

Scientific Conferences	Specialized Groups
1.5 to 7.0 hours	4 to 10 hours
30 to 150 participants	5 to 20 participants
E.g., American Meteorological Society (AMS) short course	E.g., Maine Dept. of Environmental Protection customized course

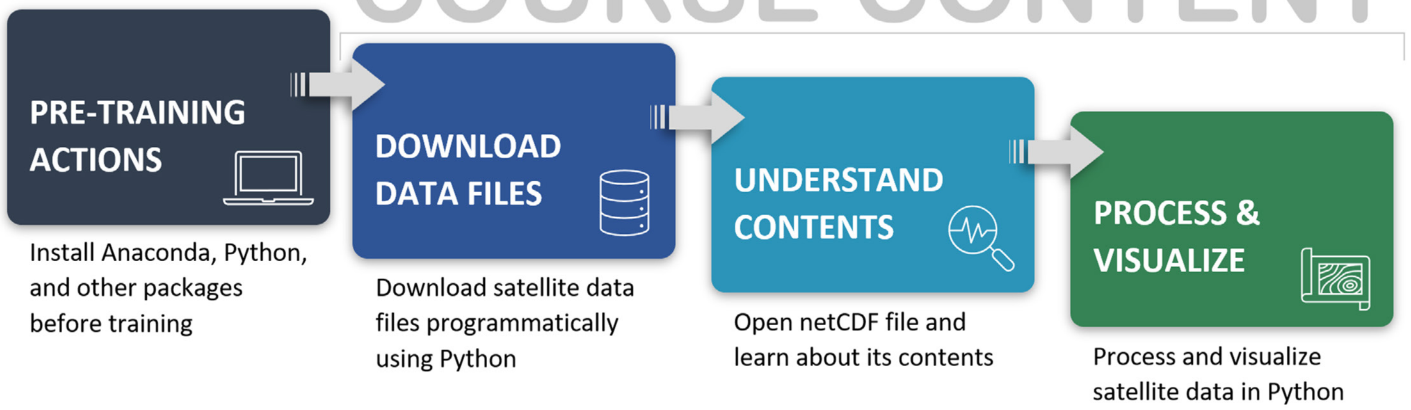
The new STAR Atmospheric Composition Product Training program started virtually in 2020 and plans to expand to a hybrid virtual/in-person model in early 2023. To reach as many end users as possible, the program targets both scientific conferences and specialized groups, like air quality forecasters. "We try to tailor content of each of the training courses to meet the needs of that specific audience," Huff says, "for example, focusing exclusively on AOD or fire data." The STAR training courses are free and open to the public, except when offered as part of a paid conference like the American Meteorological Society (AMS) annual meeting.

Different audiences have different needs, but all courses follow the same basic structure: a slide presentation on satellite products, live demos of NOAA's AerosolWatch[1] and JSTAR Mapper[2] satellite imagery websites, and hands-on activities with satellite data using the Python programming language. In addition to VIIRS products, the trainings also introduce GOES-R ABI products, which offer the high temporal resolution needed for operational applications, and Sentinel-5 Precursor (Sentinel-5P) TROPOMI trace gas products.

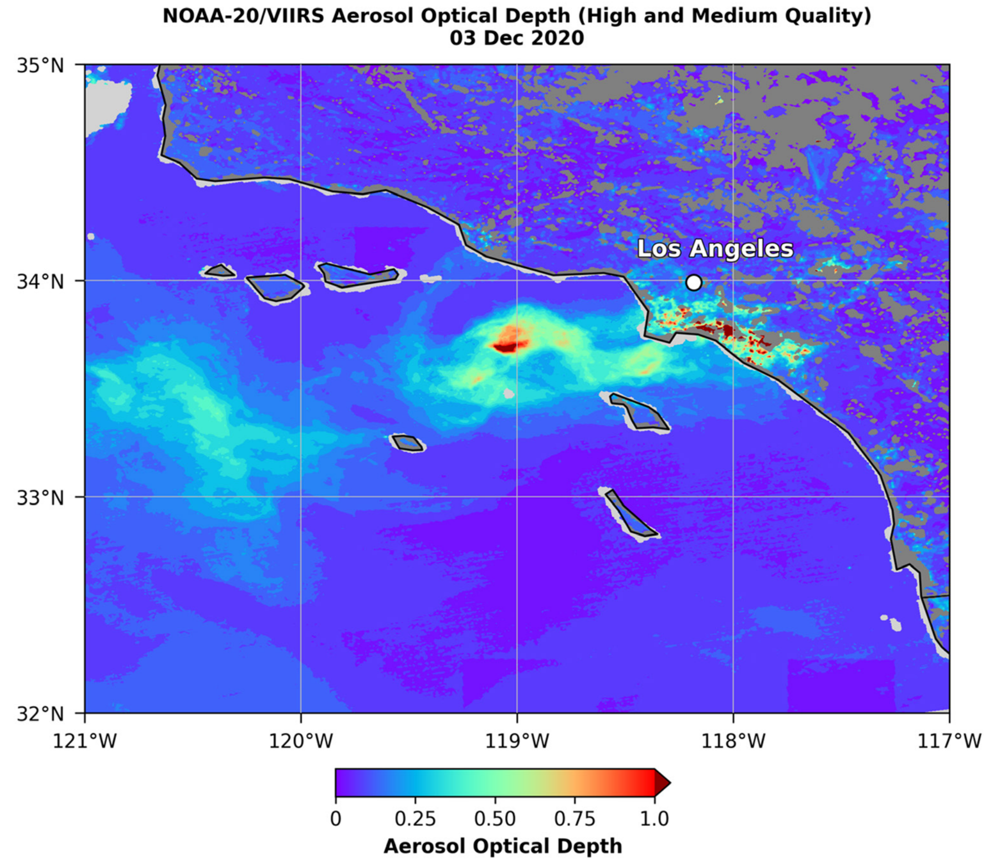
Real-World Learning

The STAR training program provides a hands-on learning approach that gives course participants the knowledge to become independent users of satellite data. "We teach participants how to use Python to work with satellite data for a recent event, from start to finish, using the proper workflow," explains Huff. Courses generally follow the workflow illustrated at the top of the next page. Unlike most satellite training programs that give participants data files, participants of the STAR Atmospheric Composition Product Training program learn how to find and download satellite data—skills that can be applied in the real world. Participants also learn how to open and read the contents of a netCDF file (a common file format of satellite data) because, as Huff explains, "We want to give the training participants the power to understand what is in the data file before they analyze the data." Finally, participants are shown how to process and visualize the satellite data, making high quality images like the VIIRS AOD example that follows below.

COURSE CONTENT



Many of the programming skills taught during STAR training courses are transferable to more advanced data analysis. On top of that, the courses are operated like a computer lab class where participants download and run Python scripts locally on their own computers. This allows participants to keep their files and output so they can access and use the Python code for their own applications, long after the course ends.

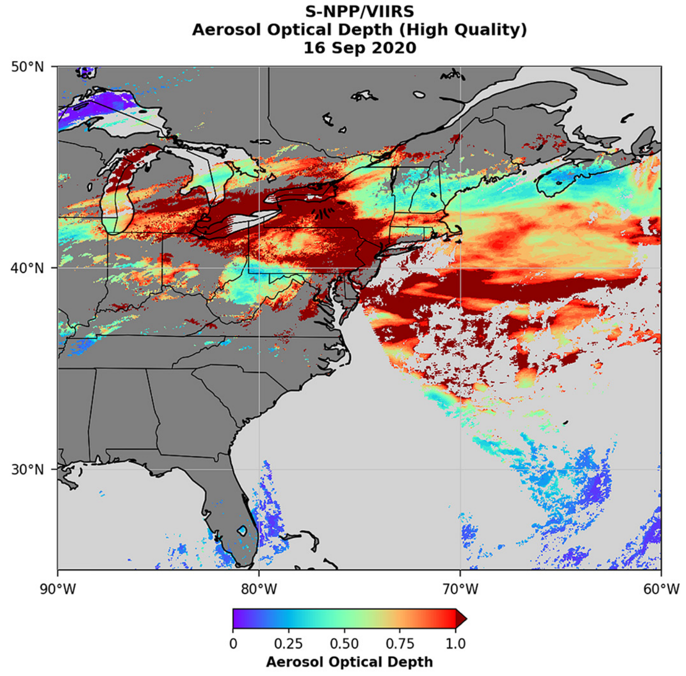


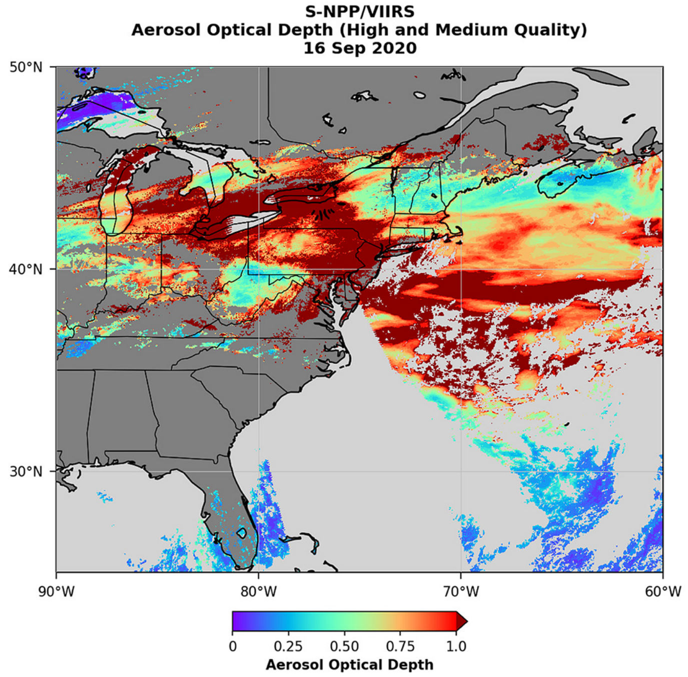
Example visualization of VIIRS Aerosol Optical Depth data created using Python.

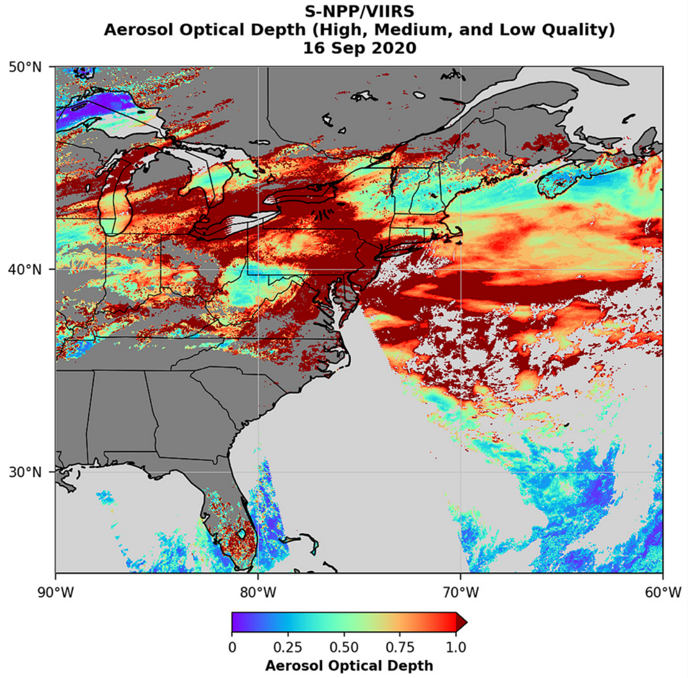
Example Training Exercises

VIIRS Aerosol Optical Depth for the Maine Department of Environmental Protection

The STAR Aerosols and Atmospheric Composition Science Team provided the Maine Department of Environmental Protection a specialized training tailored to processing and visualizing aerosol optical depth. Using smoke transport from Western U.S. wildfires on September 16, 2020, as a real-world example, participants found, downloaded, and plotted Suomi NPP VIIRS AOD data (corresponding to the smoke) from 14 granules onto a map of the Eastern U.S. Comparing coverage of AOD for different data qualities, they learned that adding medium quality data to high quality data (top right image) filled in data gaps in the high quality data (middle image). When low quality data was added to the combined medium and high quality data (bottom image), most areas of smoke plume filled in (indicated by red/orange), but at the expense of erroneous high AOD values over South Florida.



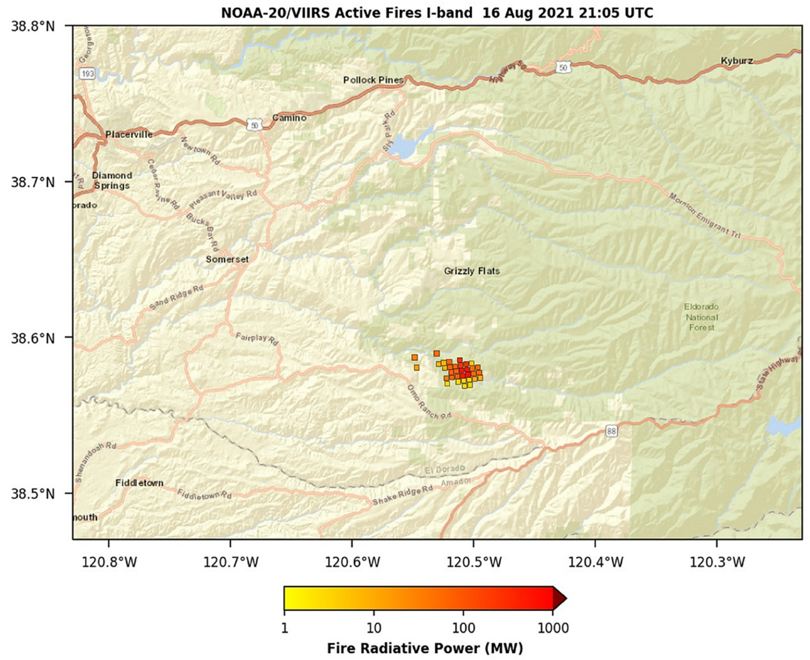


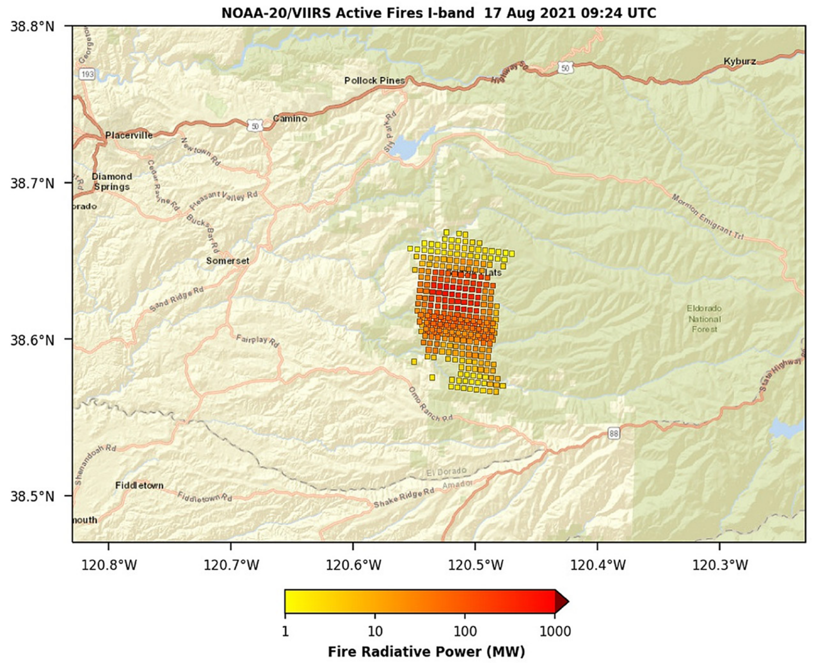


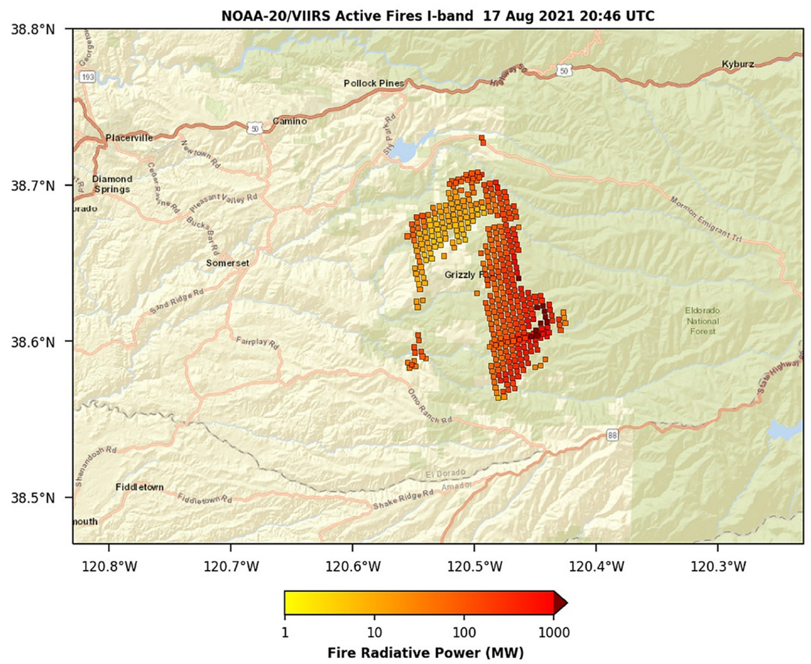
Suomi NPP VIIRS Aerosol Optical Depth (AOD) data for smoke from Western U.S. wildfires on September 16, 2020. The images show the transport of smoke across the U.S. Images include high quality data (top), high and medium quality data combined (middle), and high, medium, and low quality data combined (bottom).

VIIRS Active Fires I-Band for the 2022 American Meteorological Society (AMS) Short Course

At the 2022 American Meteorological Society (AMS) Annual Meeting, the STAR Aerosols and Atmospheric Composition Science Team led a segment in a short course for AMS attendees that focused on using VIIRS Active Fires I-band data to monitor the Caldor Fire in Northern California in August 2021. Participants plotted fire detections and Fire Radiative Power (FRP) from three granules on an ESRI World Street Map background to show fire growth and intensity changes over approximately 24 hours. The timestep images to the right, generated by course participants, show the fire burning through the town of Grizzley Flats in less than 24 hours; VIIRS FRP identifies spots with the most intense burning, shown by higher values (dark red areas).

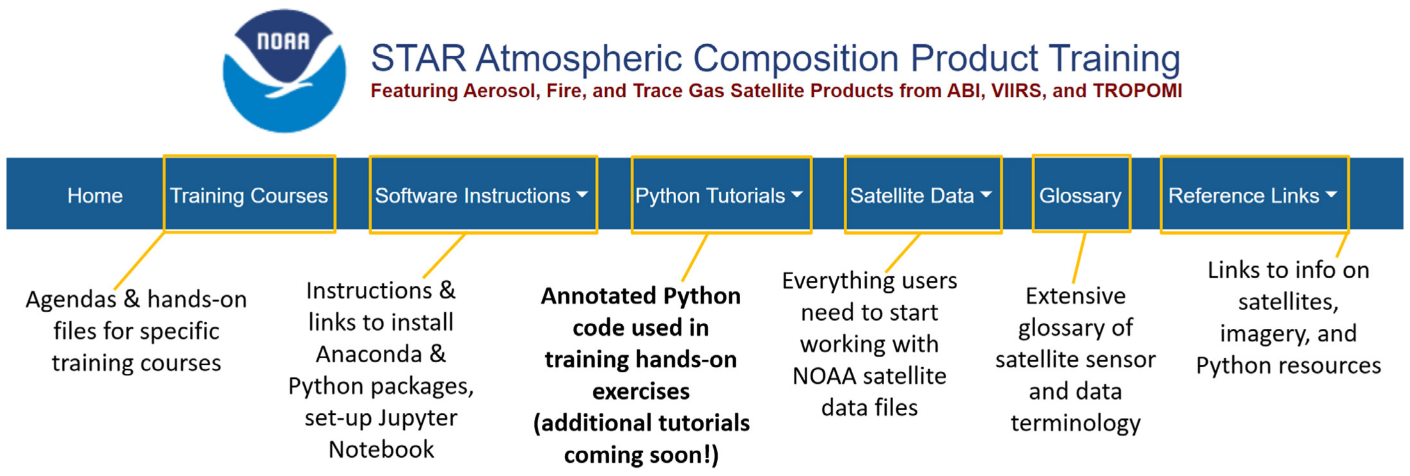






CONTINUING TO MAKE A DIFFERENCE

The STAR training program recently debuted a new website that is a one stop shop for new and existing users of aerosol, fire, and trace gas satellite data products. The site contains many free resources, including annotated Python code used in training exercises. The website is available at www.star.nesdis.noaa.gov/atmospheric-composition-training. Huff and her team also connect with the user community and media using Twitter at @AerosolWatch (https://twitter.com/AerosolWatch).



Elements of the new STAR Atmospheric Composition Product Training website.

Training courses have been very well received by participants and feedback shows that Huff and her team are meeting their goals of expanding and promoting proper use of STAR satellite products. As a result, more courses are in the works, including a full day Python course being offered at the 2023 AMS Annual Meeting. Also, customized training sessions are available for free to the atmospheric science user community (no prior Python or programming experience is required). To inquire, contact the STAR Aerosols and Atmospheric Composition Science Team at nesdis.star.aerosoltraining@noaa.gov.

Expanding the operational use of aerosol, fire, and trace gas satellite products is important to support timely air quality advisories, low visibility warnings, and other alerts across a greater number of communities. By putting the end user first, the STAR Atmospheric Composition Product Training program successfully provides the most useful and usable products and services to the atmospheric science user community. This focused approach promotes increased access to VIIRS and other satellite products and their proper use for air quality applications in operations and research. ✦

> "Everyone agreed that it was the best online class that we have had to date."
>
> CT DEEP

> "The python example was fantastic, keep it up! It makes the course much more useful, helpful, and valuable because it gives us a pathway to doing real work by providing very helpful examples."
>
> Attendee of AMS Short Course

STORY SOURCE

The information in this article is based, in part, on the September 19, 2022, JPSS Science Seminar "Expanding VIIRS Aerosol and Fire Products Utilization through Training and Outreach to End Users Featuring Python Tutorials" presented by Dr. Amy K. Huff, I.M. Systems Group at NOAA/NESDIS Center for Satellite Applications and Research (STAR), with contributions from many including Drs. Shobha Kondragunta, Istvan Laszlo, and Ivan Csiszar (NOAA/NESDIS/STAR), and Drs. Hongqing Liu, Pubu Ciren, and Hai Zhang (I.M. Systems Group at NOAA/NESDIS/STAR).

FOOTNOTES

1 https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/

2 https://www.star.nesdis.noaa.gov/jpss/mapper/

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FEATURE 13

Planning for the Next Generation of Satellite Sensors: Insights From NOAA Workshops

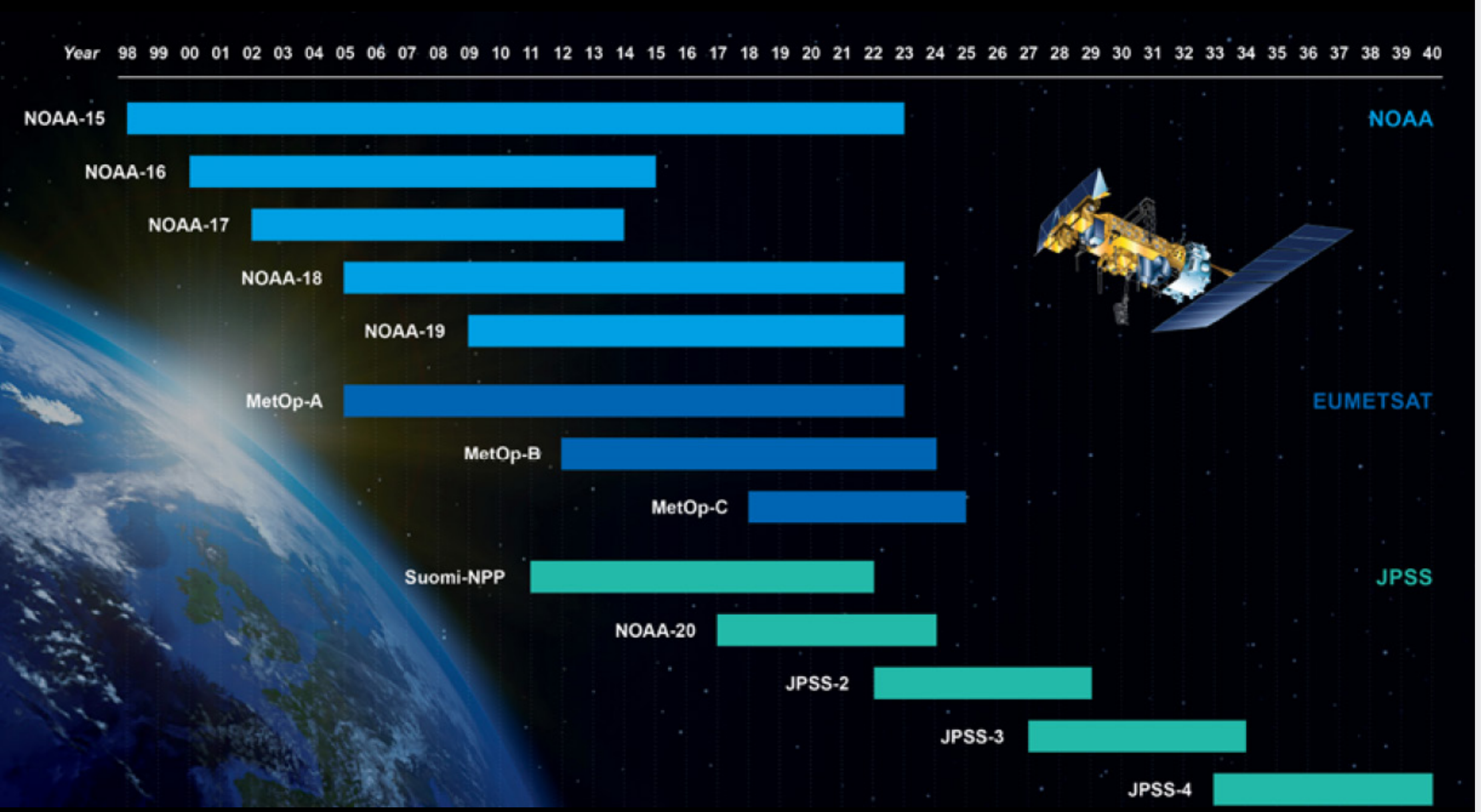
Clockwise from top left: NUCAPS sounding, a tornado, Suomi NPP VIIRS Day/Night Band nighttime lights imagery, a river ice jam, Suomi NPP VIIRS fire hot spots and smoke mask, and a forest fire. Sources: NOAA/NASA.

The Joint Polar Satellite System (JPSS) launched its first satellite in October 2011, the Suomi National Polar-orbiting Partnership (Suomi NPP), followed by NOAA-20 in November 2017 and NOAA-21 in November 2022. While these satellites are expected to continue providing Earth observations well into the next decade, NOAA is exploring new mission concepts to complement their current operational missions in a more agile way in the future. A critical part of planning for the next generation of sensors is understanding how the data from current sensors are used, their impacts, and opportunities for improvement. NOAA has held four virtual workshops since July 2021 to answer these questions.

The workshops brought together satellite data users from industry, academia, government, and research organizations from around the world to share information about data applications and perspectives on needs and improvements. Each workshop focused on a different topic: microwave (MW) sounders; infrared (IR) sounders; ultraviolet/visible/near infrared (UV-Vis-NIR) instruments; and the Visible Infrared Imaging Radiometer Suite (VIIRS). A high level overview of each workshop follows. Agendas and speaker presentations are available on the NOAA NESDIS website at www.nesdis.noaa.gov/current-satellite-missions/currently-flying/joint-polar-satellite-system/jpss-workshops-events.

MICROWAVE SOUNDER WORKSHOP

In July 2021, NOAA's JPSS Program Office invited global experts to a one-day virtual workshop to understand how microwave (MW) sounding data are used, the impacts of MW soundings on weather prediction applications, and



NOAA has been flying advanced MW sounders since 1998 on polar orbiting satellites operated by NOAA and EUMETSAT.

the outlook of these measurements to enable future mission planning. MW sounders on polar orbiting satellites, including the Advanced Technology Microwave Sounder (ATMS) onboard JPSS satellites, MW sounders on NOAA legacy Polar Orbiting Environmental Satellites (POES), and MW sounders flying on EUMETSAT satellites, have been the most influential remote sensing observations in numerical weather prediction (NWP) models for the past two decades. Through the next decade and beyond, both NOAA and EUMETSAT plan to launch and operate polar orbiting satellites with MW sounders in the midafternoon and midmorning orbits, respectively, to provide these critical measurements to NWP centers.

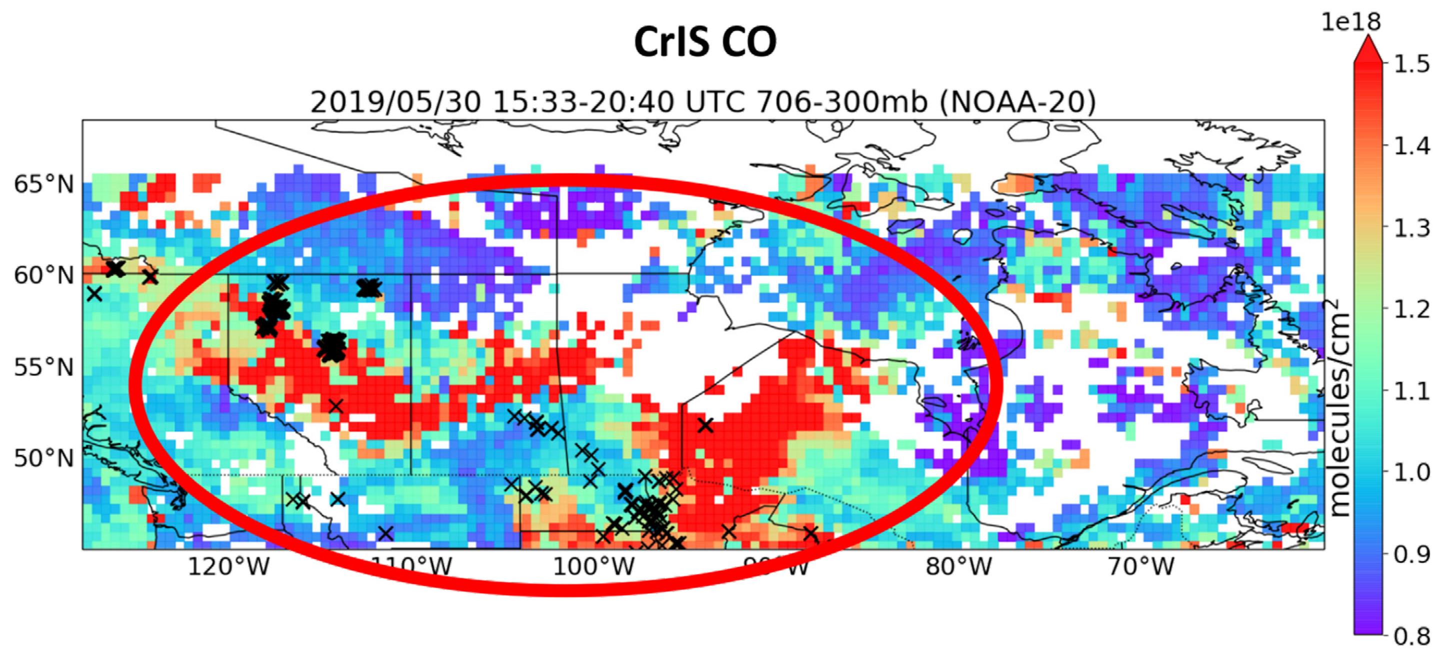
In parallel, the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) is exploring innovative technologies in MW soundings for demonstration in the 2020s to augment and eventually potentially replenish the JPSS program of record. The experience gained in exploiting this extensive data record provides a unique opportunity for NOAA and other operational weather satellite operators to assess the impact, utility, and criticality of these data when planning and designing future MW sounders.

At the MW Sounder Workshop, expert scientists from several global NWP centers and other organizations provided inputs and guidance for use in future mission planning. Discussions included using MW sounding measurements in NWP models and other non-NWP applications, like precipitation remote sensing, tropical cyclone monitoring, and retrieval of atmospheric profiles for use in rain, snow, and ice products. Participants provided recommendations on an ideal MW sounder constellation configuration and agreed that continuity of measurement remains a key feature. Beyond continuity, experts noted that future systems must address the need for increased temporal coverage. Data access, long sensor lifespans, and stable calibration were also noted as critical to end users. A technical report summarizing workshop outcomes in detail is available at https://doi.org/10.25923/WKGD-PW75 (NOAA Technical Report NESDIS 155).

INFRARED SOUNDER WORKSHOP

On December 6, 2021, NOAA NESDIS hosted a virtual Infrared (IR) Sounder Workshop to gather input on IR sounding use in data assimilation, numerical weather prediction, air quality monitoring, climate change studies, and other applications. Feedback from this workshop offers valuable insight into user needs as NOAA begins to formulate future IR sounder satellite missions in low Earth orbit (LEO).

During the workshop, global experts in meteorology and atmospheric chemistry presented their perspectives on the importance of various infrared measurements, required sensor capabilities, and desired improvements for future IR sensors. Participants discussed the performance and use of current polar orbiting instruments, including the JPSS Cross-track Infrared Sounder (CrIS) and the Infrared Atmospheric Sounding Interferometer (IASI) on European Space Agency (ESA) MetOp-A/B satellites, as well as IR sounders onboard geostationary satellites like the Atmospheric Infrared Sounder (AIRS) on NASA's Aura satellite, among others. A detailed meeting summary with recommendations on future sensor capabilities was published in the Bulletin of the American Meteorological Society and is available at https://doi.org/10.1175/BAMS-D-22-0054.1.



In addition to use in data assimilation for NWP, IR sounders provide data about major air pollution sources, like wildfires, that is complementary to data from other satellite instruments. This figure shows carbon monoxide concentrations across Canada from the CrIS instrument onboard NOAA-20 on May 30, 2019.
Credit: Rebekah Esmaili, NOAA.

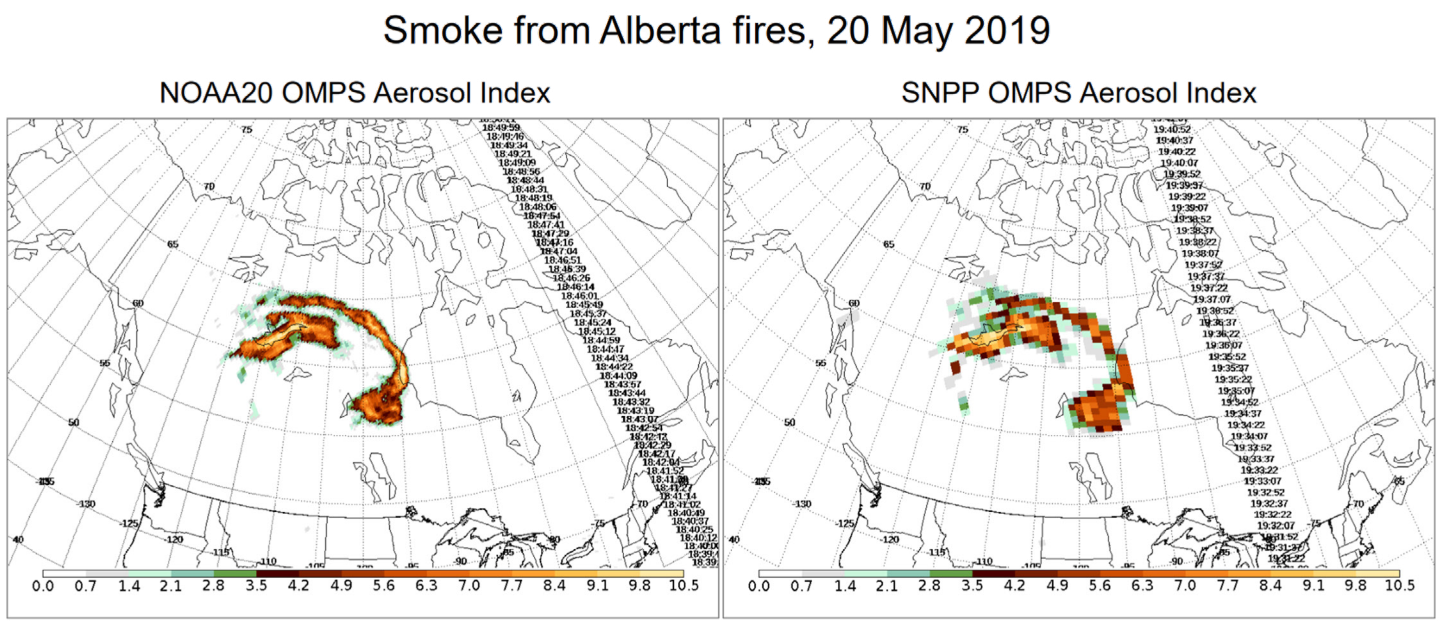
The aim of this workshop was to better understand the measurements, resolution, frequency, wavelengths, and other specifications that are needed by data users to make sure that soundings remain impactful for numerical weather prediction and other Earth system and climate applications. The information obtained through the workshop and other engagement opportunities will help support new sounding instrument design and formulation of an optimal, agile, and cost-effective constellation of LEO observing systems.

UV-VIS-NIR WORKSHOP

The NOAA Office of Atmospheric and Oceanic Research's Climate Program Office (CPO) organized a two-day virtual workshop on June 14-15, 2022. One of the objectives of the workshop was to gather input from the Atmospheric Composition community about UV-Vis-NIR measurements for future operational NOAA LEO missions. Presentations and discussions focused mainly on global air quality and climate observations needed to monitor air pollution, greenhouse gasses, aerosols, volcanic ash, wildfire smoke, Saharan dust, and other atmospheric constituents that impact human and environmental health.

Several LEO instruments were discussed in detail including the JPSS Ozone Mapping and Profiler Suite (OMPS), JPSS Visible Infrared Imaging Radiometer Suite (VIIRS), ESA TROPOspheric Monitoring Instrument (TROPOMI), NASA Moderate Resolution Imaging Spectroradiometer (MODIS), NASA Ozone Monitoring Instrument (OMI), and NASA Orbiting Carbon Observatory 2 (OCO-2). Geostationary satellite instruments were also considered, including NOAA's current GOES satellites and two future NASA missions: the Tropospheric Emissions: Monitoring of Pollution (TEMPO) Mission and the Geostationary Carbon Cycle Observatory (GeoCarb) Mission. TEMPO is targeted for launch in early 2023 and GeoCarb is by the end of 2024. While recommendations for future improvements to UV-Vis-NIR sensors varied by user application, stakeholders generally expressed a desire for better spatial resolution, more timely updates, and improved bias and drift correction.

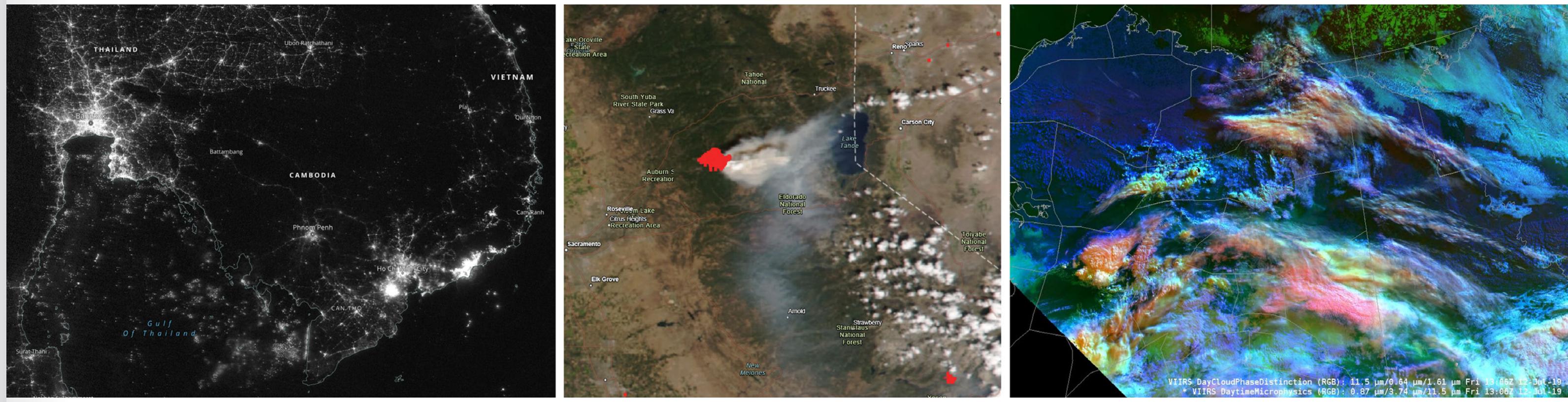
Like the other NOAA workshops, the goal was to collect information from data users about applications of UV-Vis-NIR observations and desired and required sensor capabilities. As NESDIS explores moving towards a disaggregated and distributed LEO architecture, the information from this workshop will be critical for architecture studies and planning for the next generation of UV-Vis-NIR satellite sensors.



Aerosol index data from NOAA-20 and Suomi NPP OMPS sensors showing smoke from Alberta, Canada fires on May 20, 2019. Credit: Colin Seftor, SSAI/NASA GSFC.

VIIRS USER MEETING: CELEBRATING 10 YEARS OF SUOMI NPP

October 28, 2021, marked the 10th anniversary of the Suomi NPP satellite, a critical risk reduction and preparatory mission for JPSS, and 10 years of observations from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard Suomi NPP. In celebration of this milestone, the JPSS Program Office held a two-day virtual workshop on June 29-30, 2022. In this workshop, key users briefed about the benefits of VIIRS products and applications to their organizations to help them serve their stakeholders and society. Information gathered from the workshop enables NOAA to assess the impacts of VIIRS to society and provide information on future mission formulation.



CLICK IMAGE TO ENLARGE. From left to right: Nighttime lights imagery from VIIRS Day/Night Band (source: NASA WorldView); the VIIRS Fire Product with VIIRS Corrected Reflectance (true color) imagery showing active fire/hotspots and smoke from the Mosquito Fire in Foresthill, CA on September 8, 2022 (source: NASA FIRMS); the VIIRS Day Cloud Phase Distinction (RGB) product that is used to evaluate the phase of cooling cloud tops to monitor convective initiation, storm growth, and decay, which is used by the aviation community (source: Geographic Information Network of Alaska (GINA)/ University of Alaska).

VIIRS is the primary visible and infrared imager on all JPSS satellites and provides advanced global imaging capabilities for operational meteorology and other environmental assessments. Workshop participants discussed the broad applications of VIIRS data and products, including smoke and fire forecasting; nighttime lights imagery to measure economic development and disaster impact; sea ice and sea surface temperature analyses for navigation, fisheries, recreation, and wildlife monitoring; numerical weather prediction; tropical storm modeling; aviation safety; flood, wildfire, and air quality monitoring; marine habitat health for fisheries management; tracking illegal fishing vessels; emergency response; estimating flared gas volume with nighttime lights; vegetation health indices for crop yield estimation; military applications; and countless other uses. The large variety of applications discussed highlight the versatility of VIIRS data and its importance in decision making.

Recommendations for future improvements and expanded capabilities of the VIIRS sensor varied by need, but workshop participants agreed that increased spatial and temporal resolution would be beneficial, as well as new orbit times and more satellites to allow for better tracking of fast moving storms and other quickly evolving events. The outcomes from this workshop provide NOAA insight into the impact of VIIRS data on a broad range of applications from a variety of users, needed improvements for the next generation of multipurpose imagers, and opportunities for partner missions to supplement VIIRS data.

LOOKING TOWARD THE FUTURE

A key part of the JPSS mission is to work closely with end users to enable full use of JPSS data to maximize the benefits of the mission to NOAA and society. User workshops are one way JPSS and NOAA obtain a better understanding of end user needs so that future missions can meet those needs, new products can be developed, trends and advancements can be exploited, and new business models and partnerships can be formed. LEO data plays a major role in meeting a variety of applications beyond numerical weather prediction, and future global systems will require more measurements at higher accuracy, refresh rate, and spatial resolutions. Through user engagement and outreach, JPSS is committed to evolving to support changing user needs and ensuring the operational use of LEO data and products is optimized. ✦

STORY SOURCE

The information in this article is based, in part, on content from the NOAA Microwave Sounder Workshop held on July 28, 2021, NOAA Infrared Sounder Workshop held on December 6, 2021, the NOAA UV-Vis-NIR Workshop held on June 14-15, 2022, and NOAA VIIRS User Meeting held on June 29-30, 2022.

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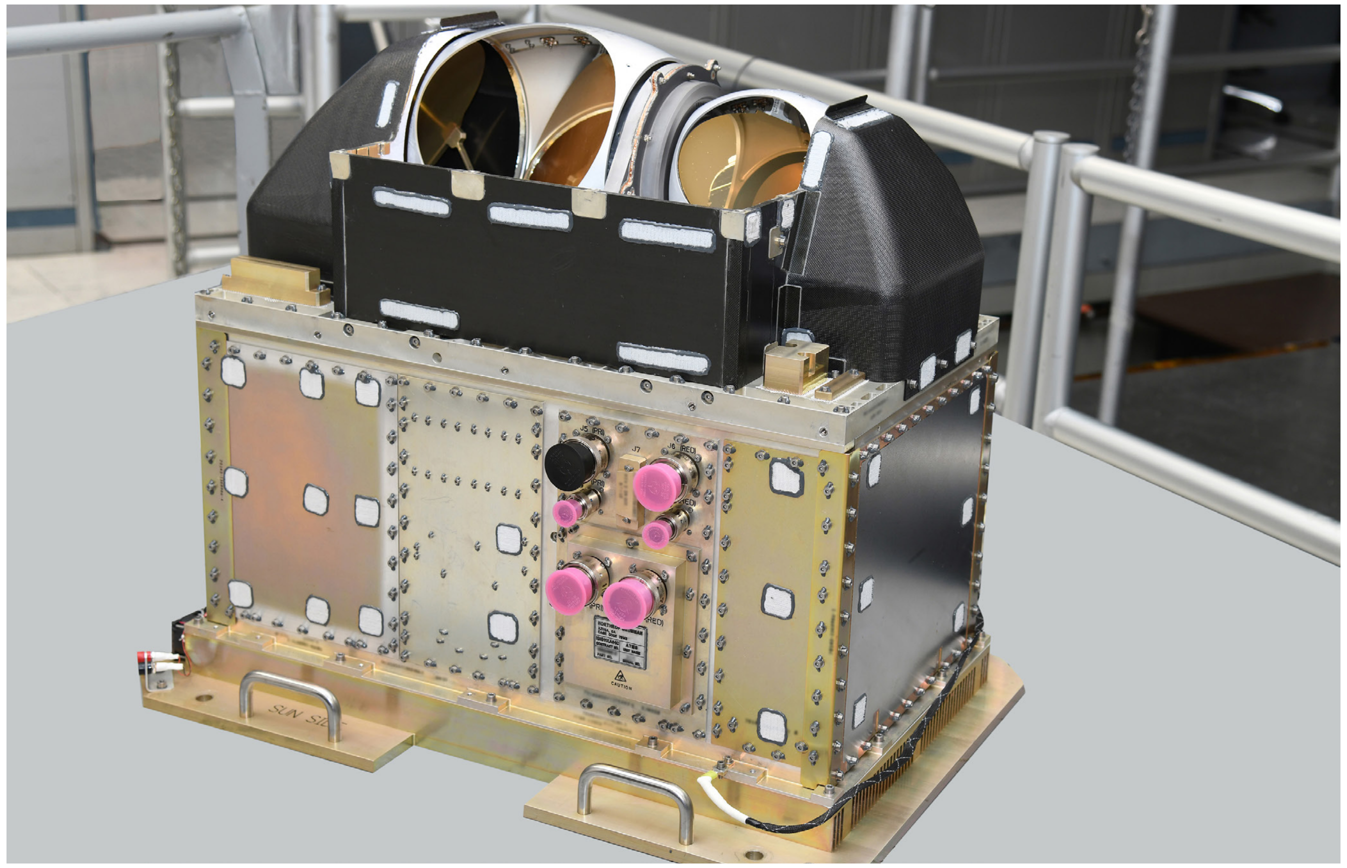
OCTOBER 7, 2021

THE MOST IMPORTANT INSTRUMENT YOU'VE NEVER HEARD OF

Jenny Marder
Senior Science Writer, Joint Polar Satellite System
NASA Goddard Space Flight Center

Some instruments launched into space spend so much time in the spotlight that their missions become household names: Hubble, Perseverance, the James Webb Space Telescope. Others do their job quietly, delivering a steady flow of data that slips unnoticed into decisions we make every day: Simple decisions, like rain boots or sunscreen. But pressing ones too, involving sandbags and boarding up windows; finding shelter or preparing to evacuate.

Introducing the Advanced Technology Microwave Sounder, the most important scientific instrument you've never heard of. ATMS is the size of a mini fridge, and it's hitched to the Joint Polar Satellite System's NOAA-20 and Suomi-NPP satellites, which fly 512 miles above our heads.

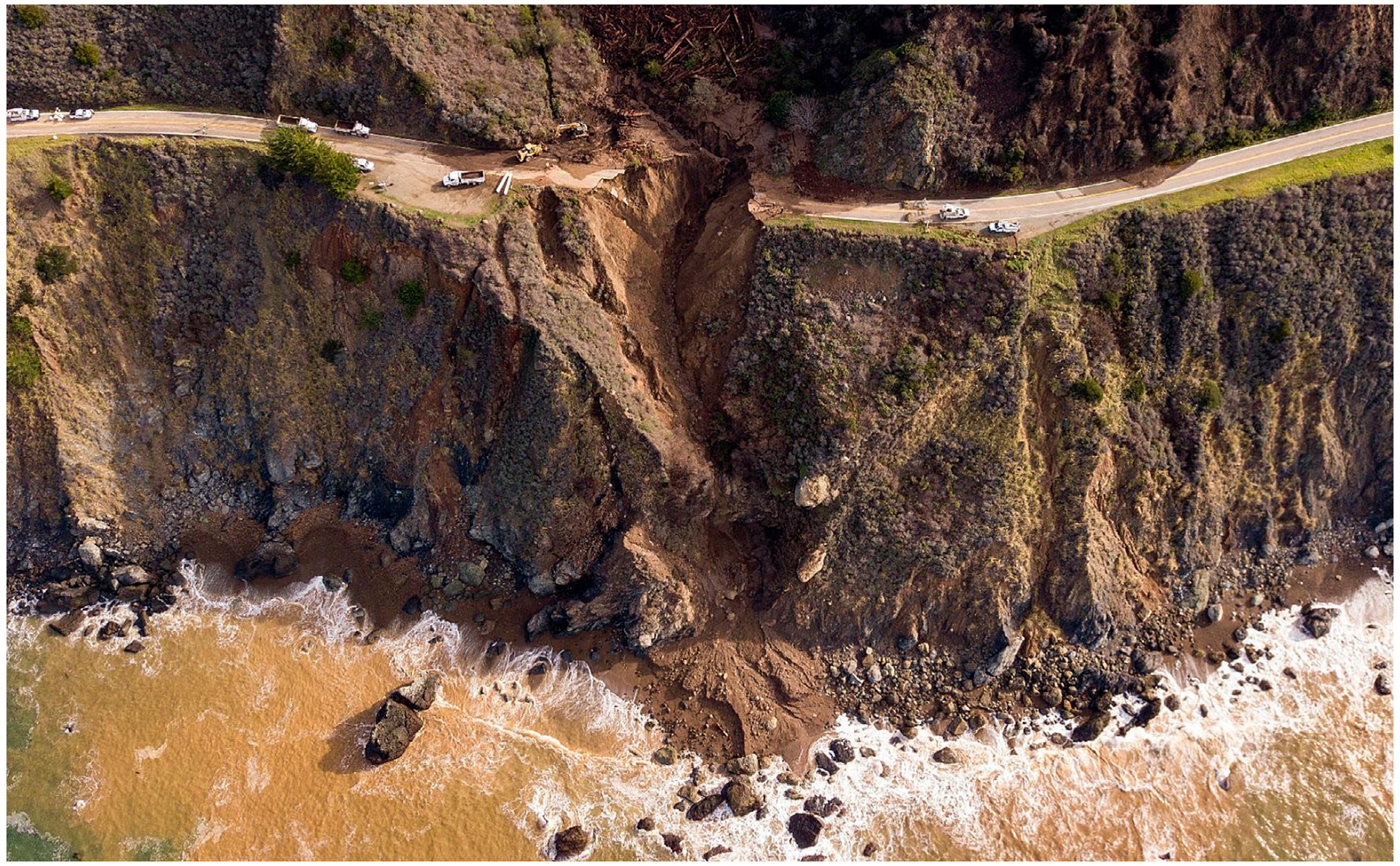


The Advanced Technology Microwave Sounder for the JPSS-2 satellite in a clean room at the Northrop Grumman facility. ATMS is the successor to the Microwave Sounding Unit and the Stratospheric Sounding Unit, which were both deployed in 1978, and the Advanced Microwave Sounding Unit, which launched in 1998. Image by Mike Solis/Northrop Grumman.

It is one of about 17 microwave sounders that have been orbiting Earth since the first one launched in November 1978. And it has a profound, behind-the-scenes impact on our daily lives, especially when extreme weather is approaching.

Consider, for example, the heavy rains in January 2021 that unleashed damaging mudslides down California slopes, which had been stripped bare of vegetation by wildfires months earlier. Flowing mud and debris smashed into homes and washed a 150-foot section of Highway 1 into the Pacific Ocean.

In the days leading up to this event, microwave sounders probed the atmosphere vertically, piercing through the clouds to capture multi-layered data on temperature and moisture. Their measurements alerted forecasters to an atmospheric river, a narrow storm system that transports tremendous amounts of moisture through the atmosphere. An atmospheric river moves as much as 15 times more water through the air than the amount that flows through the mouth of the Mississippi.

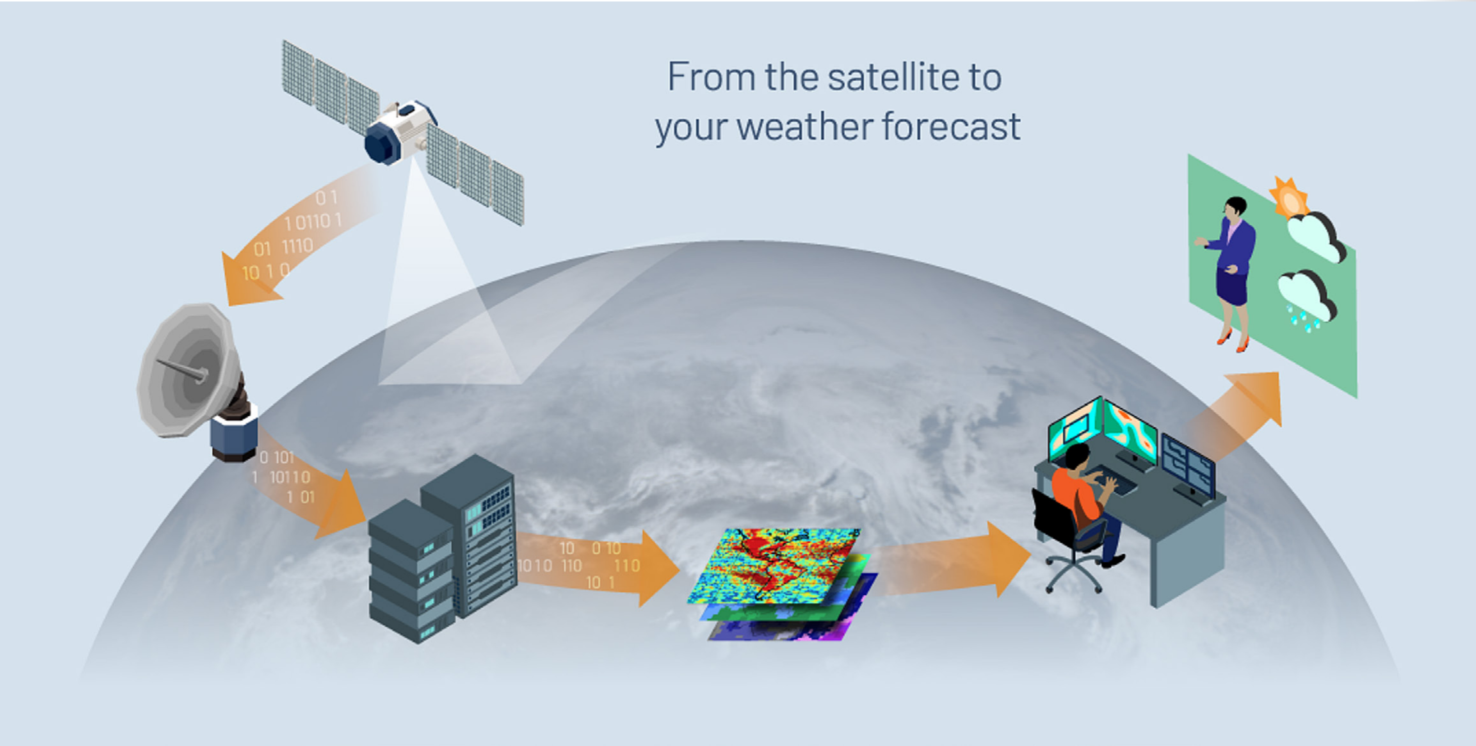


A section of Highway 1 collapsed into the Pacific Ocean near Big Sur, California, on January 31, 2021. Photo by Josh Edelson / AFP via Getty Images.

The satellites beamed the data from the sounders back to Earth. The data were collected by giant antennas on the ground and fed into global weather models. The models were studied by forecasters. And forecasters gave residents in Monterey, San Francisco Bay and the Sierra Nevadas early warning on severe weather headed their way.

"The forecast is the tip of the spear," said Dr. Mitch Goldberg, chief scientist for NOAA's National Environmental Satellite, Data, and Information Service. "But behind the forecast is the hidden secret agent, the unspoken hero, and that's ATMS."

ATMS, like other microwave sounders, measures atmospheric temperature and water vapor from Earth's surface to the upper atmosphere—all over the globe. And because the distribution of temperature and water vapor is the driver for accurate weather forecasts,—"the fuel for forecasting," Goldberg called it—"ATMS," he said, "provides one of the most critical datasets for weather prediction."

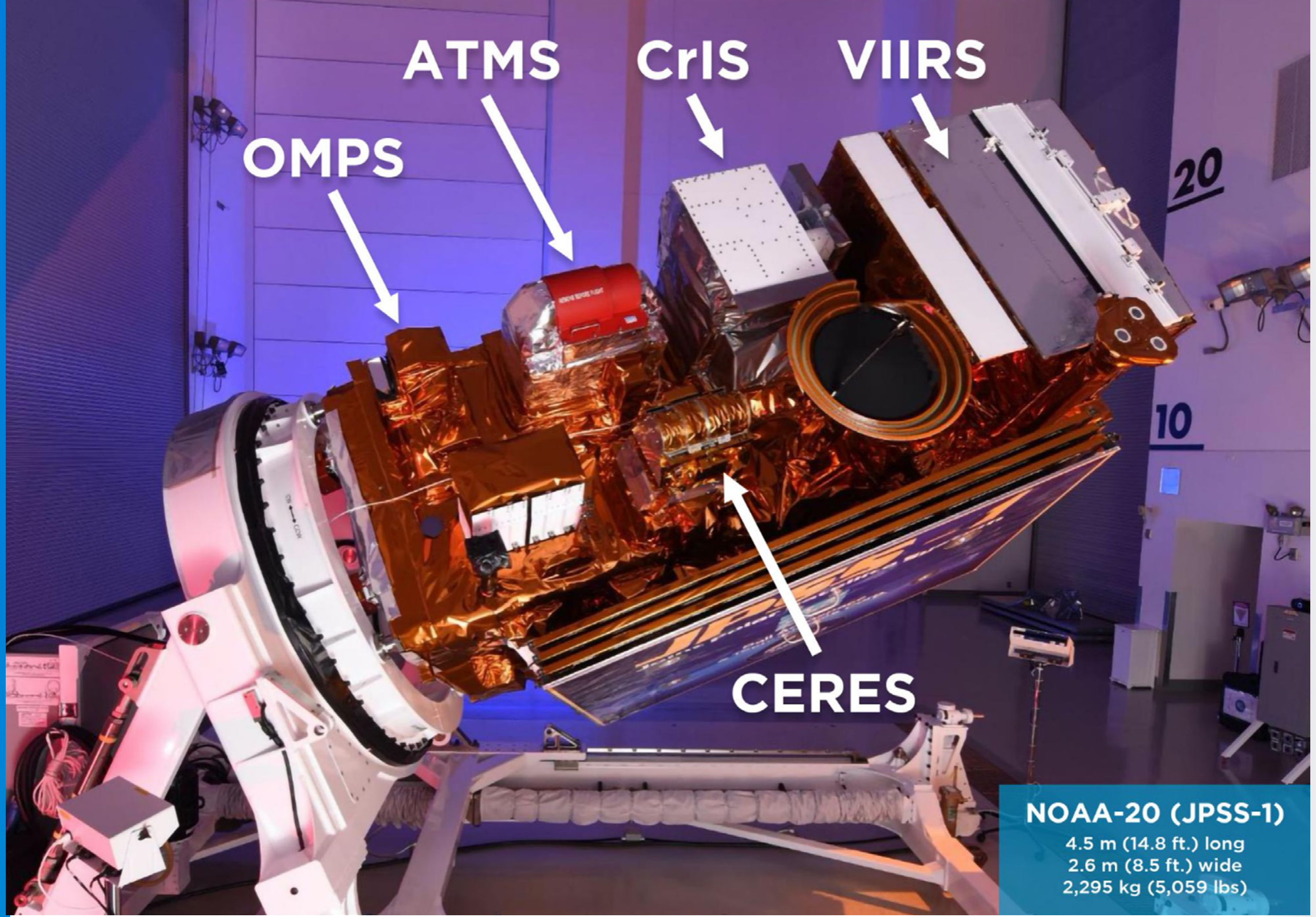


Graphic by Vi Nguyen, Senior Graphic Designer, Joint Polar Satellite System, NASA Goddard.

Danielle Gallegos, ATMS program manager for Northrop Grumman, with the ATMS instrument behind her. Credit: Northrop Grumman

The fuel for forecasting

At the Northrop Grumman facility in Azusa, California, Danielle Gallegos oversees a team of 100 people who build and test the ATMS instrument, and integrate it into the bigger spacecraft. There, engineers are hard at work building more ATMS instruments for three identical satellites that will follow NOAA-20, providing measurements until at least the late 2030s. ATMS, which includes an antenna, a motor, a radio frequency system and an electronic system, is made up of many custom-made components. And every component requires tuning and absolute precision in order to produce accurate measurements, said Gallegos, who is also a thermal engineer. "An engineer has to take the time to set screws in a certain spot, or put in jumper cables, and when I say jumper cables, they're tiny wires smaller than a piece of rice," Gallegos said. "Little tiny wires that actually will change the electrical characteristics of a part to help tune it."



ATMS and VIIRS are part of a suite of instruments on the NOAA-20 satellite. Credit: Ball Aerospace.

ATMS is not alone

ATMS is one of four or more instruments on the JPSS satellites that collect data on hurricanes, floods, fires, volcanoes, oceans, ice and air quality.

In the community of Earth science research, the VIIRS instrument is well known for providing striking images of natural disasters and phenomena, including the wildfires in Australia, a Saharan dust storm, bright phytoplankton blooms north of Finland, and the Northern Lights hovering over the Great Lakes.

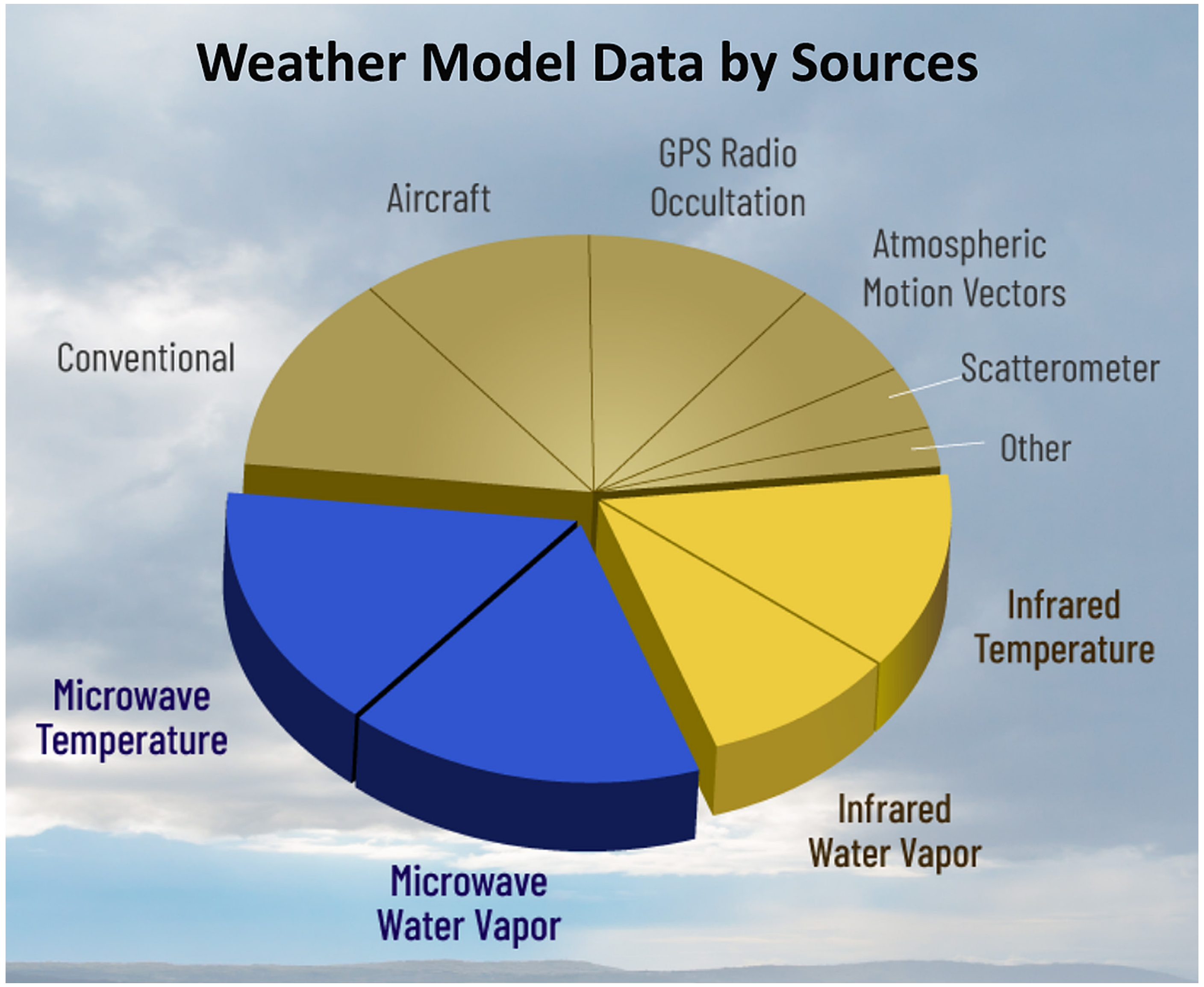
But ATMS does something critical that the other instruments don't: It sees through clouds. This is important because clouds are covering the Earth about 50 percent of the time. "If you look at an image from VIIRS, all you're seeing is the tops of the clouds. With ATMS, it's like X-ray goggles. You can see into the storm," said Dr. Edward Kim, a NASA scientist who works on ATMS.

Of all the sources feeding global weather models, microwave sounding data makes up the biggest slice of the pie. Infrared sounding, from instruments like the Cross-track Infrared Sounder, or CrIS, on JPSS, comes next.

Everything on Earth radiates energy. Clouds and oceans and dirt, but also the trees growing out of that dirt, the kid kicking a soccer ball under that tree—and even the soccer ball.

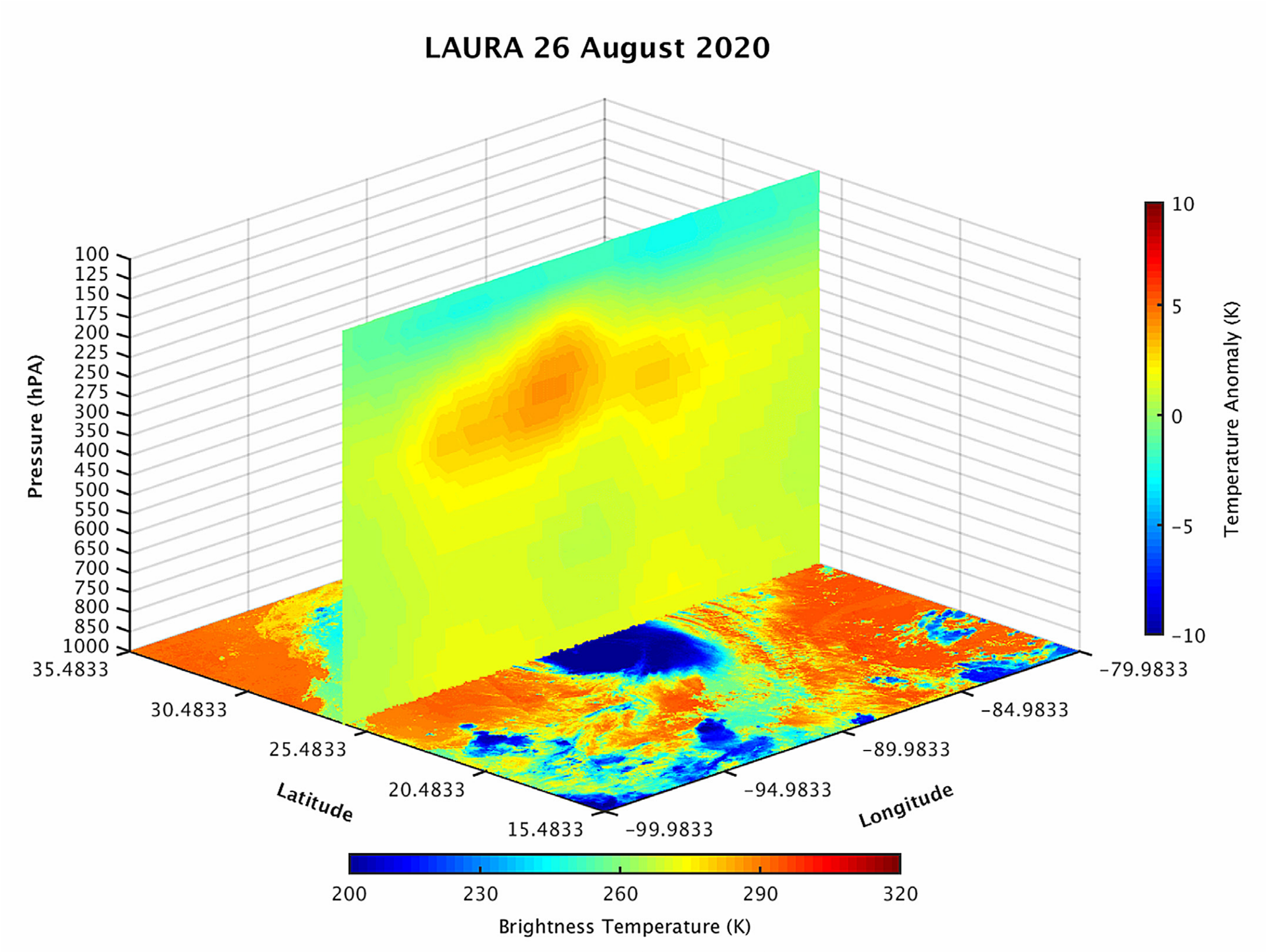
Also radiating energy are all the molecules in the atmosphere. As molecules vibrate, they're emitting energy that can be observed "in the same way that a hot piece of metal, like a burner on your stove, glows orange when it gets hot," said Dr. Carl Mears, vice president for research at Remote Sensing Systems.

Each type of molecule vibrates at certain frequencies and emits radiation at those frequencies. The warmer the gases are, the more vibration occurs, and thus the amount of emitted radiation increases. And by measuring at these different frequencies, scientists can determine the temperature and moisture at different layers of the atmosphere.



Graphic by Vi Nguyen, Senior Graphic Designer, Joint Polar Satellite System, NASA Goddard.

Sounders can also measure the insides of hurricanes. Knowing the temperature of different parts of the hurricane helps forecasters understand a storm's direction and its strength. Consider Hurricane Laura, which made landfall in August 2020, hammering the Texas and Louisiana coasts with 150 mile-per-hour winds. The storm destroyed buildings, blew windows out from high rises, downed trees and power lines, ripped the top off a bridge and triggered a fire at a chemical plant. Because of ATMS and other sounders, state officials had advance warning of the storm's potential path and intensity and were able to evacuate people, saving lives.



Screenshot of a 3D animation by Dr. Banghua Yan/Dr. Ninghai Sun/The NOAA STAR JPSS-ICVS Team.

Microwave sounders measure climate change

Microwave sounders do something else, something few anticipated when first designing the instruments: they give us long-term records of the temperature of our atmosphere—and they show us how it's changing.

Ben Santer, atmospheric scientist at the Lawrence Livermore National Laboratory, at Horsetooth Mountain in Colorado.

In the mid-1990s, Dr. Ben Santer, an atmospheric scientist who recently retired from the Lawrence Livermore National Laboratory after a 29-year tenure there, was convening lead author of Chapter 8 of the IPCC's second assessment report. As such, he wrote what would become one of the most important sentences in climate science history: "The balance of evidence suggests a discernible human influence on global climate."

The evidence then focused mostly on the warming of land and ocean surfaces, and the finding was met with fierce pushback. Scientists were challenged to show more evidence of a human-caused warming signal in ocean temperatures, rainfall, water vapor, and, importantly, satellite records of atmospheric temperature.

Santer's personal response, he said, was "to interrogate these microwave measurements of atmospheric temperature records." At that time, the record of microwave sounders was relatively short, spanning just 17 years. Still, Santer said, "it seemed critically important, despite the constraint of the very short record, to start looking at this data, and to see what it told us about global warming.

Fast forward to present day. The data record from microwave sounders now stretches 42 years, long enough to show clear trends in both the lower and upper atmosphere. And after years of rigorous work by scientists around the globe, the latest IPCC report, released in August 2021 said it is "unequivocal" that the climate is changing and humans are to blame. U.N. Secretary-General António Guterres called the report, released during a summer of massive wildfires, floods and drought, a "code red for humanity."

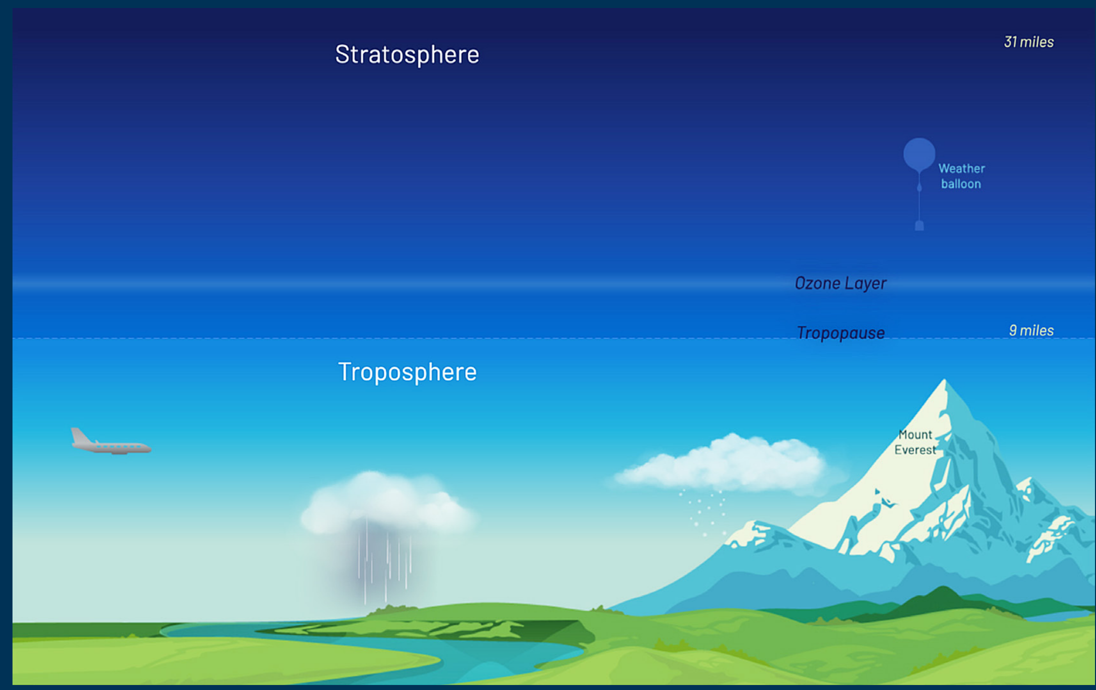
"The alarm bells are deafening, and the evidence is irrefutable," Guterres said in a statement : "Greenhouse gas emissions from fossil-fuel burning and deforestation are choking our planet and putting billions of people at immediate risk." But, he added, cleaner air, better health and prosperity are still possible "if we respond to this crisis with solidarity and courage."

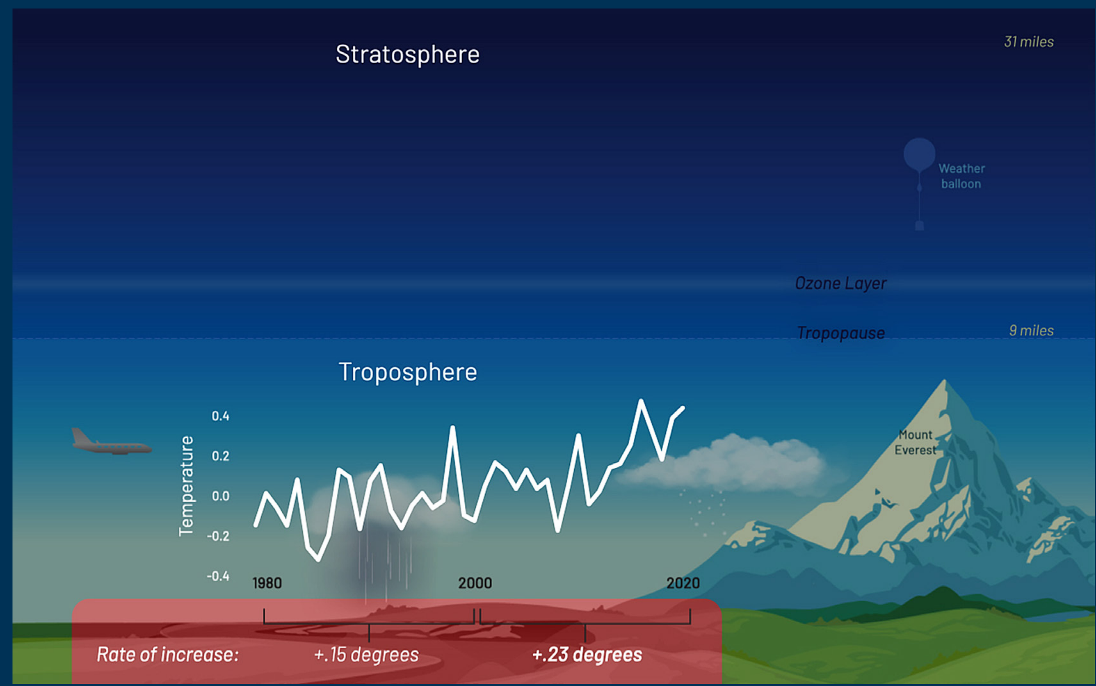
The lowest layer of Earth's atmosphere is the troposphere. That's where we live, and where weather happens. In the troposphere, temperatures cool with height. Above that, starting from an altitude of about 9 miles and stretching about 22 miles more, is the stratosphere, where the ozone layer is, and where temperatures rise with height. The tropopause marks the boundary between the two.

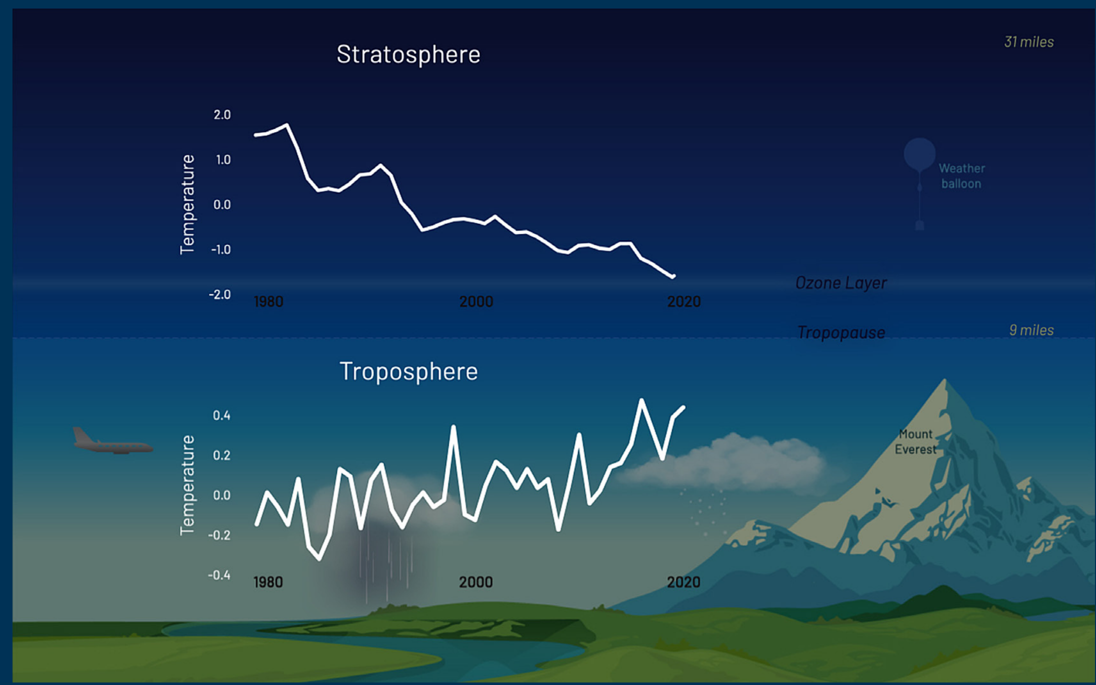
And you can see how the temperature of our atmosphere has changed from 1978 to present day. Temperature measurements captured by microwave sounders show unquestionably that the troposphere is warming, by .15 degrees Celsius per decade, and .62 degrees over the past 42 years, since the first sounder was launched in 1978, according to data from NOAA's Center for Satellite Applications and Research. And that rate is increasing. From August 2002 to December 2020, the warming rate had climbed to an average of .23 degrees Celsius per decade.

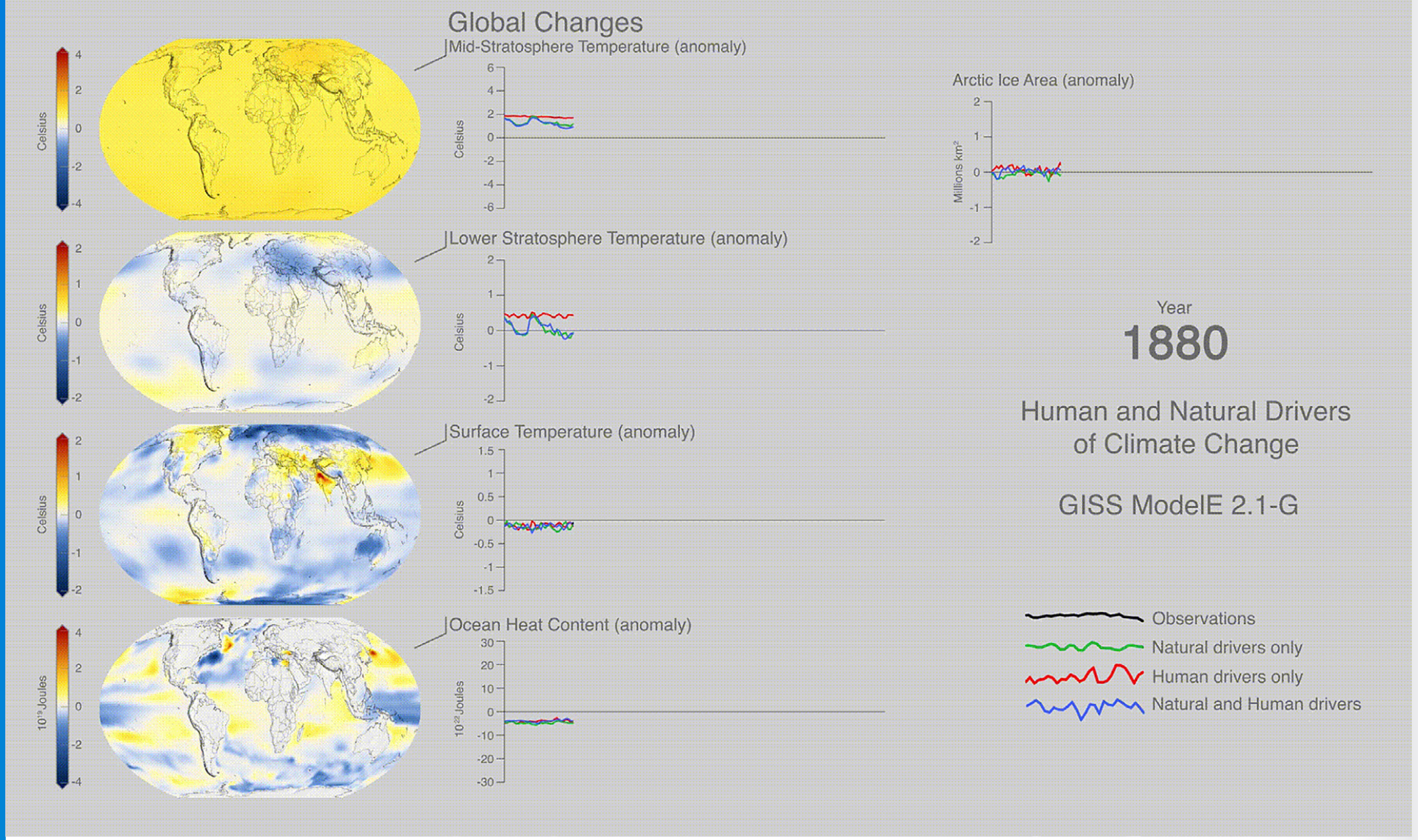
Meanwhile, in the upper stratosphere, temperatures are cooling. And this is where you can "most clearly and unambiguously see the signature of atmospheric CO_2," Santer said.

If Earth was warming for another reason, due to the Sun getting brighter, for example, both the stratosphere and the troposphere would warm. But, Mears said, "because the stratosphere is cooling, that's a fingerprint of putting a blanket on the Earth and keeping more heat close to the surface. And it means there's less heat available to heat the stratosphere." In other words, energy is being trapped in the troposphere by greenhouse gases.









Screenshot of an animated data visualization showing human and natural drivers of climate change for the period 1850-2018, showcasing data products from NASA's GISS Model E 2.1-G and observations. Credit: NASA's Scientific Visualization Studio (https://svs.gsfc.nasa.gov/4908).

Computer models of the climate have helped scientists separate natural changes in the Earth's climate, such as volcanic eruptions and changes in solar activity, from human influences, such as deforestation, particulate pollution, and the release of greenhouse gases from the burning of fossil fuels. When the models are run without human influences, you don't see much temperature change, Dr. Mears said: "Then we run them with human effects, and they agree fairly well with what we've observed." Those human influences can be seen in atmospheric temperature measurements, but also in the scores of different ways scientists evaluate global warming: measurements of surface temperature, water vapor and sea ice, for example. "All of these measurements point in the same direction," Mears said.

Getting the measurements right

The satellite records of atmospheric temperature have historically been a target of controversy. Multiple groups have used the sounding data to create satellite temperature trends. For years, the data were misanalyzed by one of these groups. The resulting trend showed less warming than was really occurring, and even cooling in the tropics where the atmosphere was in fact warming. These flawed findings were then used, Dr. Santer said, "to cast doubt on the reality and seriousness of global warming." Getting the satellite measurements right required overcoming a number of challenges: Most notably, the older satellites that carried microwave sounders weren't as well calibrated and their orbits drifted over time.

But over the years, these errors have been systematically corrected by teams of scientists studying these datasets. In fact, a paper published in the journal Science Advances in 2018 found that the errors that accounted for these differences in temperature trends have been nearly eliminated. Temperature measurements from ATMS have achieved what the paper's lead author Dr. Cheng-Zhi Zou, a research scientist with the NOAA's Center for Satellite Applications and Research, refers to as "absolute stability within .04 Kelvin per decade." A follow-up paper published in Geophysical Research Letters in June 2021 further reduced the uncertainty.

"The uncertainty is so small, the calibration is so well done—it shows these post-millennium measurements are well suited for climate change monitoring, said Dr. Qiang Fu, an atmospheric scientist with University of Washington and a co-author with Dr. Zou on the Geophysical Research Letters study.

A story of progress

The story of the microwave sounder is the story of scientific progress. To be able to stitch together climate-worthy data records from an instrument never meant for this purpose took hard work and ingenuity. It meant repeatedly finding new ideas and scrubbing old ones—and having different groups competing didn't hurt, Mears said. "That's the scientific method," Mears said. "You move forward, you notice something wrong, you change your hypothesis, and you move forward again."

There's still work to be done when it comes to splicing together the records from the older sounders and incorporating data from ATMS. It's not a thermometer in space, Santer pointed out. It's a complicated instrument. "But the bottom line," he said, "is that we've learned that these measurements not intended or designed to monitor long-term multi-decadal changes in climate are extremely useful for getting a better sense of long-term changes in climate."

WEB FEATURES

"The microwave sounder, which was often viewed as evidence of the absence of human-influenced climate change, actually provides just the contrary," Santer said: "Very powerful evidence of the existence of human fingerprints on the climate system."

The future of sounding

The downside of microwave sounders is that we don't have enough of them, said Dr. Sid Boukabara, principal scientist with the NOAA Center for Satellite Applications and Research. And we don't have enough observations of every inch of the atmosphere. "We need to understand what's happening now—and everywhere—to be able to accurately predict what's going to happen in the future," he said. "If we need a full picture of the globe every hour, for example, as will likely be expected for future weather prediction models, we need more satellites."

So scientists are looking at building a swarm of mini microwave sounders that will fly on Cubesats. TEMPEST-D, an experimental mission to test this idea, is currently flying a satellite no bigger than a cereal box with a miniature microwave sounder.

Meanwhile, the JPSS-2 satellite, which is slated to launch in 2022 with another ATMS instrument on board, will give us more eyes in the sky to monitor atmospheric rivers, severe storms and daily weather —and more data to feed the global temperature archive.

And it will give us the information we need to live our lives, whether that's knowing tomorrow's weather or what our world might look like in 50 years. ✦

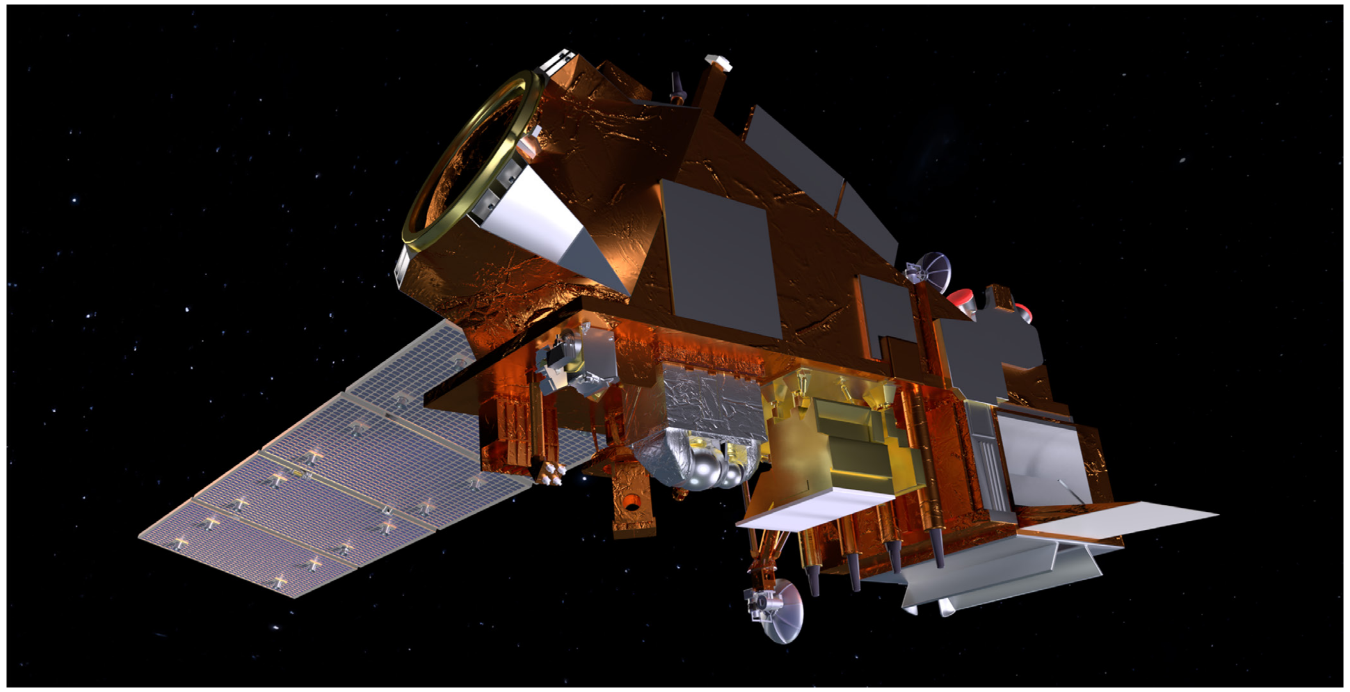
Story Source

This story was originally published by NOAA and NASA as a StoryMap available at https://storymaps.arcgis.com/stories/90de52ccc6e04ba1b50b68e0d1057bf7.

SPRING 2022

NOAA'S NEXT POLAR ORBITING SATELLITE PREPARES FOR LAUNCH

Jenny Marder
Senior Science Writer, Joint Polar Satellite System
NASA Goddard Space Flight Center



An artist's rendition of the JPSS-2 satellite in space. Credit: Lamont W. Harvey.

In September 2022, the third satellite in the Joint Polar Satellite System (JPSS) series is expected to launch from Vandenberg Space Force Base in California, providing data that informs weather forecasts, extreme weather events and climate change.

JPSS-2, to be renamed National Oceanic and Atmospheric Administration (NOAA)- 21 after launch, will continue the work of its predecessors, NOAA-20 and Suomi-NPP (National Polar-Orbiting Partnership), which launched in 2017 and 2011, respectively. The launch will mark the culmination of a decade of work by the team, and the challenges that came with it.

While most of the satellite instruments are identical to those of its predecessors, flight engineers had to overcome the obstacle of integrating these instruments into a brand new spacecraft bus. And they had to do this while simultaneously working on the next two satellites in the series, JPSS-3 and JPSS-4, which are expected to provide measurements into at least the late 2030s.

JPSS orbit and instruments

The JPSS satellites are polar orbiters, meaning they orbit from the North to the South Pole, circle our planet 14 times a day, and pass over every location on Earth at least twice. Like NOAA-20, JPSS-2 is built and launched by NASA, and once it reaches orbit, NOAA will take over operations.

JPSS-2 will carry four instruments, the Advanced Technology Microwave Sounder, or ATMS; the Cross-track Infrared Sounder, or CrIS; the Visible Infrared Imaging Radiometer Suite, VIIRS; and the Ozone Mapping and Profiler Suite, also known as OMPS. Combined, these instruments deliver important data on storms and weather events. They monitor wildfires and smoke, measure the insides of hurricanes, track the health of major crops worldwide and tell us about ocean temperature, health and air quality.

VIIRS is like the eyes of the satellite. It provides striking color images of hurricanes, wildfires, floods, dust storms and harmful algal blooms. It helps detect, map and monitor wildfires and measure the thickness and movement of wildfire smoke. Its Day-Night band sensor gives us nighttime images, like power outages after a storm and dazzling Northern lights.

The JPSS-2 satellite in the vibration chamber at the Northrop Grumman facility in Gilbert, Arizona. Credit: Northrop Grumman

OMPS tracks the health and concentration of ozone in the atmosphere. It measures particulate matter in pollution, dust, smoke and biomass burns. It also measures volcanic clouds and sulfur dioxide emissions from volcanoes.

CrIS takes highly detailed measurements of atmospheric temperature and water vapor that feed our weather forecasts.

And **ATMS** provides as much as 80 percent of the data that feed global weather models. It also gives us long-term records of our atmosphere, and shows us how the temperature in both the lower and upper atmosphere has changed over time.

"The public should be assured that we are taking care of the critical needs of numerical weather prediction," said JPSS program scientist Dr. Satya Kalluri. "We are part of the global backbone that provides the vertical structure of the atmosphere for temperature and water vapor — these are the two essential ingredients for hurricane formation, precipitation or the lack thereof," he said. Precipitation, he added, is caused by the instability of the atmosphere and the availability of moisture. "Too much and you can have floods; too little, and you can have droughts," Dr. Kalluri said.

Building a new bus

While Ball Aerospace built the bus for NOAA20, Northrop Grumman was responsible for building the JPSS-2 spacecraft bus. And at the time the spacecraft was chosen, all JPSS-2 instruments were already well into being built, said JPSS Flight mission systems engineer, Lou Parkinson.

> The only way this is all possible is because of the team.
>
> LOU PARKINSON
> JPSS FLIGHT MISSION
> SYSTEMS ENGINEER

"The ground rule was, we can't change the instruments," she said. "Anything we found that wasn't compatible, we had to change it on the spacecraft side of the interface."

The payload interface electronics, for example, were designed specifically to work with the existing instruments, and the spacecraft was updated to be more compatible with the ground system, Parkinson said. Some of these updates were straightforward, others were more challenging, she added, but in the end the team made it work in a way that accommodated both the instruments and the ground system infrastructure. "JPSS-2 was the pathfinder, so JPSS-3 and JPSS4 will incorporate the lessons learned from JPSS2," Parkinson said.

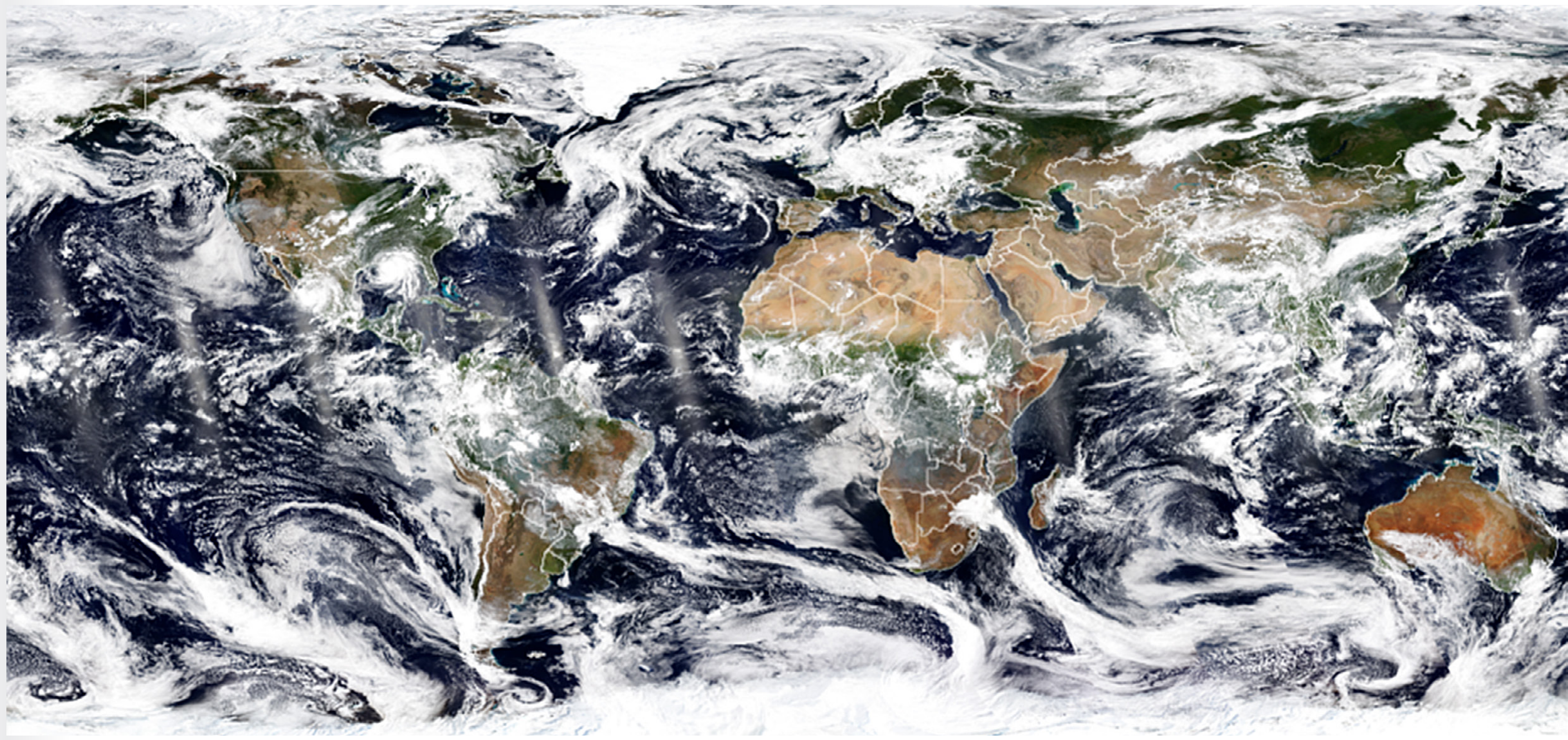
In a launch year, it's typical for an engineer to work exclusively on the spacecraft preparing for orbit. But in this case, many of the mission's engineers are simultaneously working on the two satellites that will launch in the years after JPSS-2. Instruments for JPSS-3 have finished most of their environmental testing and will soon be shipped to storage, Parkinson said. And instruments on JPSS-4 are in the process of being manufactured as the bus structure and components get built.

"The only way this is all possible is because of the team," she said. "The flight project team is great. Everybody is working together, pulling their weight, taking responsibility, and doing what they need to do, but with the proper checks and balances in place. That's the only way it works. Otherwise it's too big of a job for any one person to do."

Milestone timeline

Meanwhile, the JPSS2 satellite is currently undergoing thermal vacuum testing, a critical milestone, which involves stressing the system by exposing it to an environment similar to what it will encounter while orbiting the Earth, said Chris Brann, deputy project manager for the JPSS flight project, who has been with the mission since 2010. When completed, these tests will ensure that the satellite's hardware will function in the extreme temperatures and vacuum of space.

"The satellite has to keep itself warm enough in a cold state and cool when it's in a hot state, and still provide the science performance as it's going



A daylight image composite of Earth from August 29, 2021, captured by the NOAA-20 satellite's VIIRS instrument. Hurricane Ida makes landfall on the U.S. Gulf Coast, while Hurricane Nora spins in the eastern Pacific Ocean. Credit: NOAA through the temperature transitions," Brann said. "If it works at the two extremes of hot and cold, it will work in between."

After the thermal vacuum test, the satellite's solar array will be installed, and it will be put into a shipping container, which is controlled for temperature and humidity. It will then be shipped to the launch site in California, where it will go through a final series of tests before getting installed on the rocket, Brann said.

So much has to come together when planning for the launch, Parkinson said. "Not only do we build the satellite and test the satellite and launch the satellite, but then we need to be able to hand over a successfully operating satellite to NOAA to make sure they can continue operations." And the launch, if successful, "will be the culmination of many, many years of hard work and labor by hundreds, if not thousands, of people," Kalluri said. "You see a launch, and if you're associated with the mission, you have bragging rights to say, 'I had a part to play in the mission. There's a piece of this that I built." ✦

JPSS in Your Community

Check out how JPSS benefits your state or territory:

http://www.jpss.noaa.gov/jpss-in-your-community

Story Source

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AUGUST 15, 2022

JPSS-2 SATELLITE GETS ITS SOLAR ARRAY INSTALLED

Jenny Marder
Senior Science Writer, Joint Polar Satellite System
NASA Goddard Space Flight Center

On July 26, in a clean room at the Northrop Grumman facility in Gilbert, Arizona, NOAA's JPSS-2 satellite let out several loud pops as each of the five panels of its solar array detached from the body of the satellite and then unfolded, stretching out to its full 30-foot length. Under each panel, an engineer clad in a bunny suit flashed a thumbs up as latches clicked into place.

The deployment of the solar array, which had been installed three days earlier, marked the last major testing milestone of the weather satellite. JPSS-2 has now been boxed up and will be shipped to the Vandenberg Space Force Base in California for its Nov. 1 launch. The next time the solar array deploys will be in space.

"This is a culmination of seven years of work on this program," said Scott Capehart, Joint Polar Satellite System program director at Northrop Grumman Corporation, where the spacecraft is built and tested. "Its success establishes that we're ready for launch." (View the solar array getting installed on YouTube: https://youtu.be/9b1h2xwygZo).

Once launched, the JPSS-2 satellite, like its predecessors Suomi-NPP and NOAA-20, will race around Earth from pole to pole, taking measurements and snapping images that help us plan for hurricanes, snowstorms, floods, and other severe weather. The satellite will feed critical data to global weather forecast models.

"During stressful times, like running into an issue at the end of a long overnight shift, I always come back to the impact that JPSS-2 will have," said Adelina Nastasoiu, an instrument systems engineer at Northrop Grumman. "The weather models it's going to affect, the lives it's going to save, and that it shares data freely with the entire world."

JPSS-2 will also measure our oceans and atmosphere, map and monitor volcanoes and wildfires and tell us about the things that fill our air and lungs, like dust and smoke. Because of its wide swath, it will observe every spot on Earth at least twice a day.

In the clean room in Gilbert, the satellite sat upright, mounted on a rack on wheels. Multi-layered insulation resembling gold tinfoil blanketed the body of the spacecraft. Covers with "Remove before flight" signs protected each of its four instruments.

About 20 feet away, engineers checked connections and voltage on the spacecraft for JPSS-3, the next satellite in line to launch. And packed in boxes and stacked on wire shelves at the back of the clean room were the parts for JPSS-4, the final satellite in the JPSS series. Combined, the three satellites are expected to provide data into the 2030s.

Together, NASA and NOAA oversee the development, launch, testing, and operation of all the satellites in the JPSS program. NOAA funds and manages the program, operations, and data products. On behalf of NOAA, NASA develops and builds the instruments, spacecraft, and ground system, and launches the satellites, which NOAA operates. ✦

Story Source

This story was originally published on the NOAA NESDIS website at https://www.nesdis.noaa.gov/news/jpss-2-satellite-gets-its-solar-array-installed.

NOVEMBER 4, 2022

FORECASTING WEATHER FOR THE WEATHER SATELLITE LAUNCH

Jenny Marder
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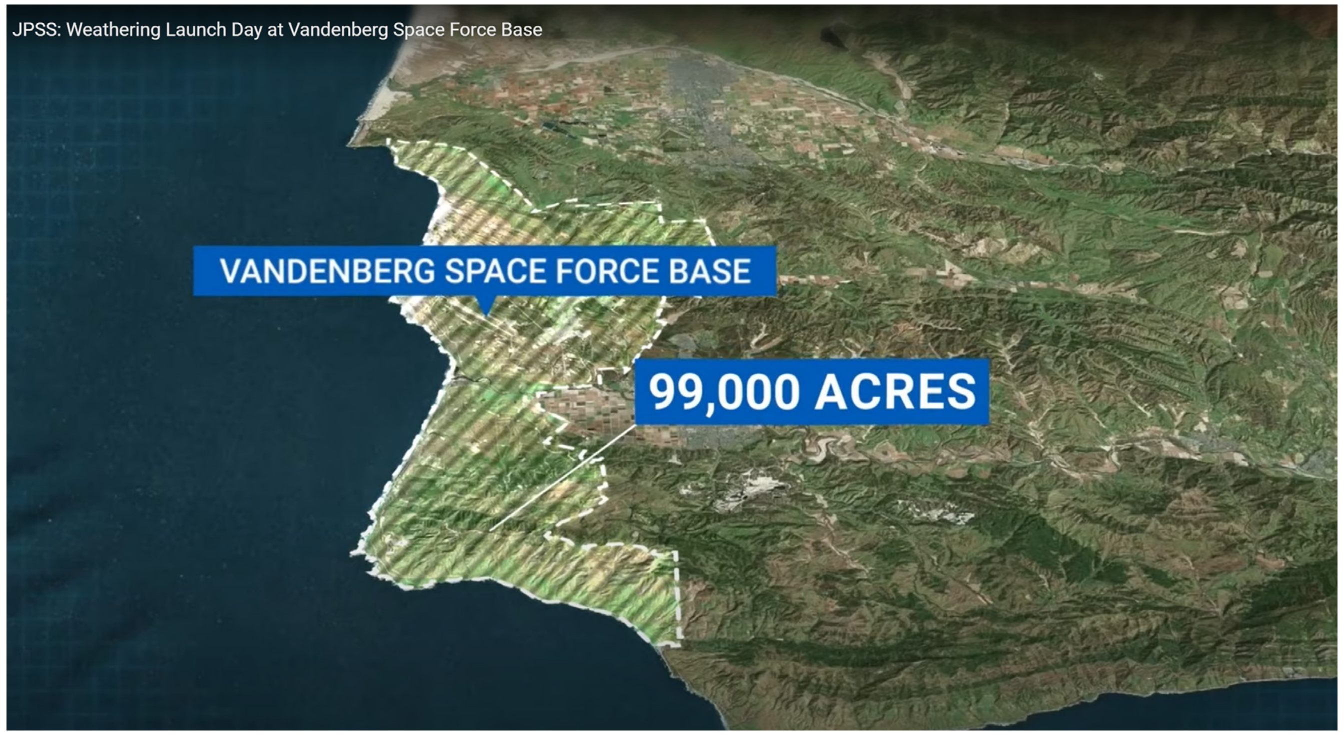
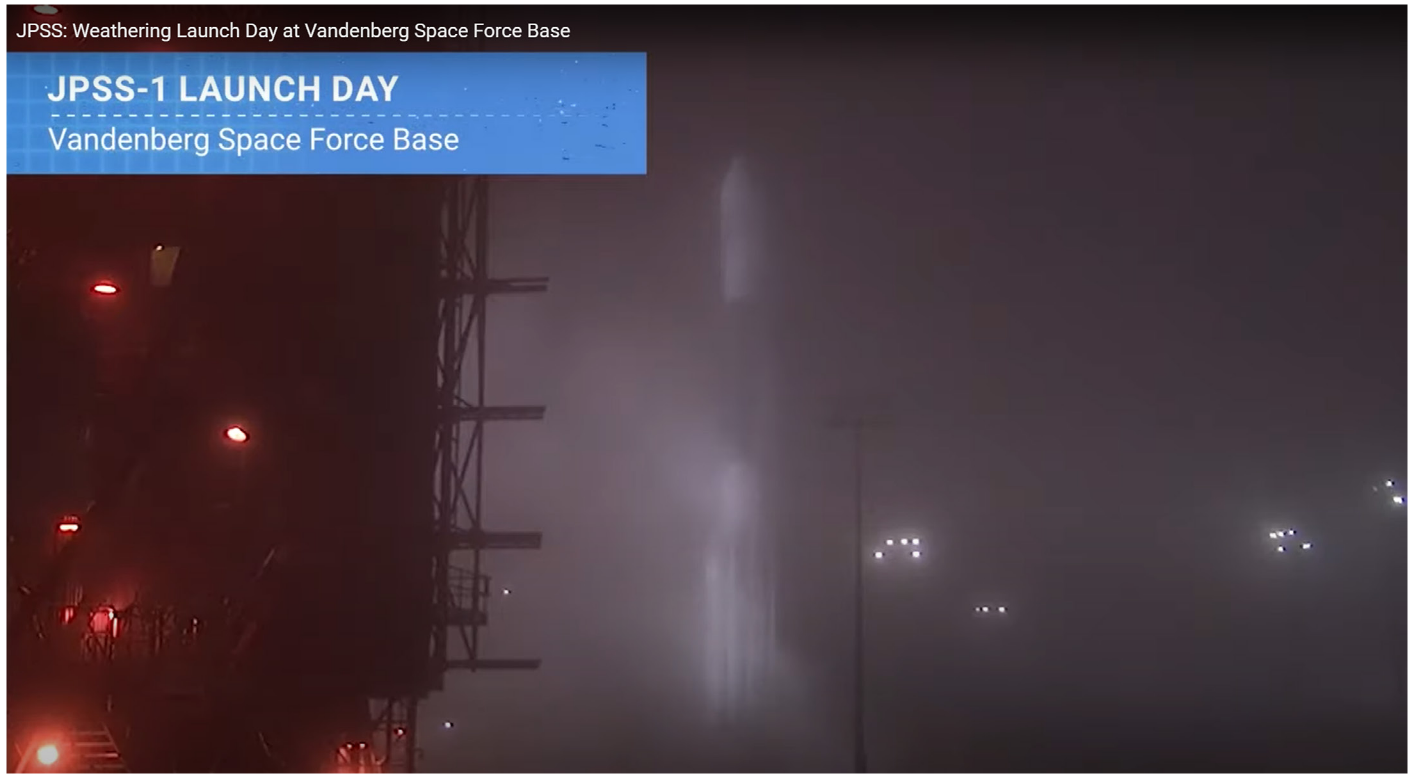


In the days leading up to a launch at Vandenberg Space Force Base, most of the attention is focused on preparing the rocket and payload for their trip to space. In this case, that's NOAA's Joint Polar Satellite System-2 (JPSS-2) satellite, and its secondary payload, LOFTID.

But there's another operation happening at the base that makes these launches possible. About 1.5 miles north of the Visitor's Center is the Weather Operations Center, or "The Weather Shop," where a 15-member team monitors the weather around the clock. And in a meeting of worlds, satellites from the JPSS series provide an important source of the data that feeds their weather forecast.

Vandenberg is located in the seaside city of Lompoc, California, an area known for the so-called marine layer that comes in overnight, blanketing the area with low clouds and fog.

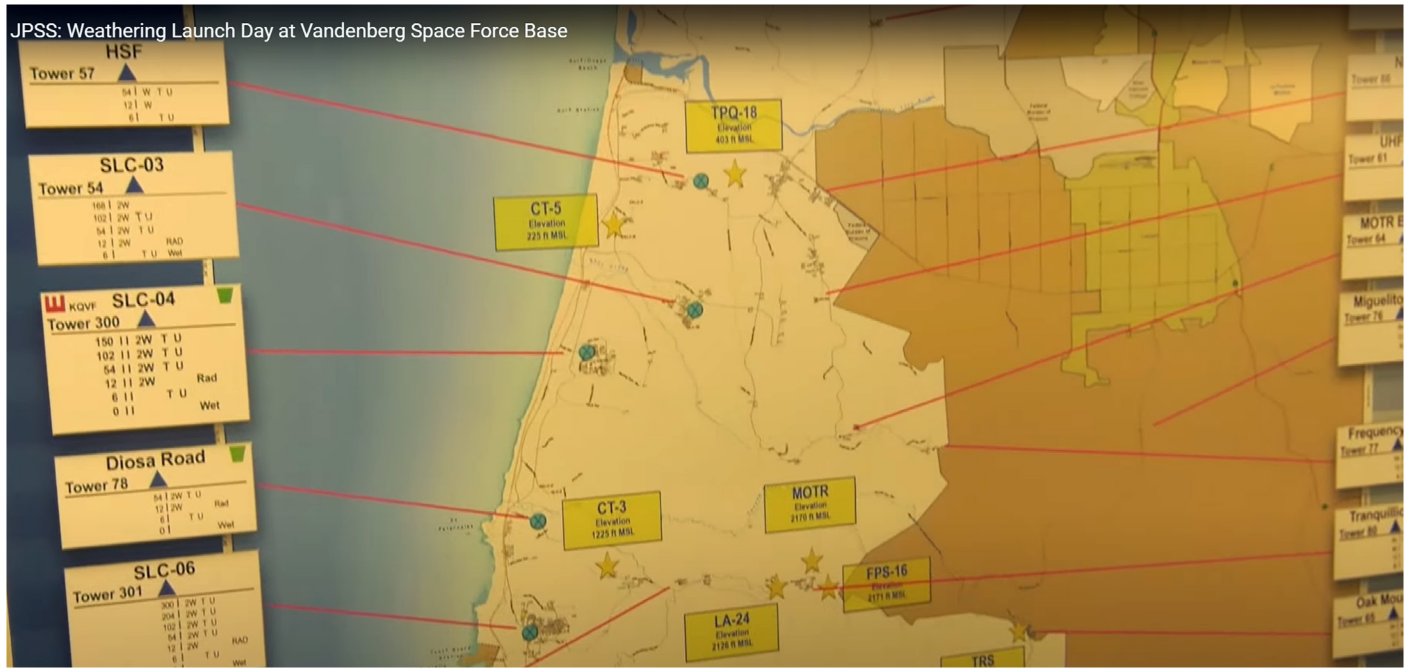
While the marine layer affects visibility, it's not a threat to launch safety. More hazardous to a launch are winds, rain and lightning, said Launch Weather Officer Capt. Zackery Zounes. In fact, he said, if the right conditions exist inside a cloud, a rocket itself can trigger lightning. Lightning is especially hazardous, because it can short circuit electronics and navigation systems.



The onsite meteorologists watch wind closely too. And Vandenberg is a windy place.

"You don't want the rocket to get pushed by the wind and tip over," Zounes said. "You don't want it to be pushed off its trajectory."

Fortunately, the 99,000-acre base has a robust network of instruments to help monitor weather conditions. On base are 26 wind towers with more than 200 instruments.



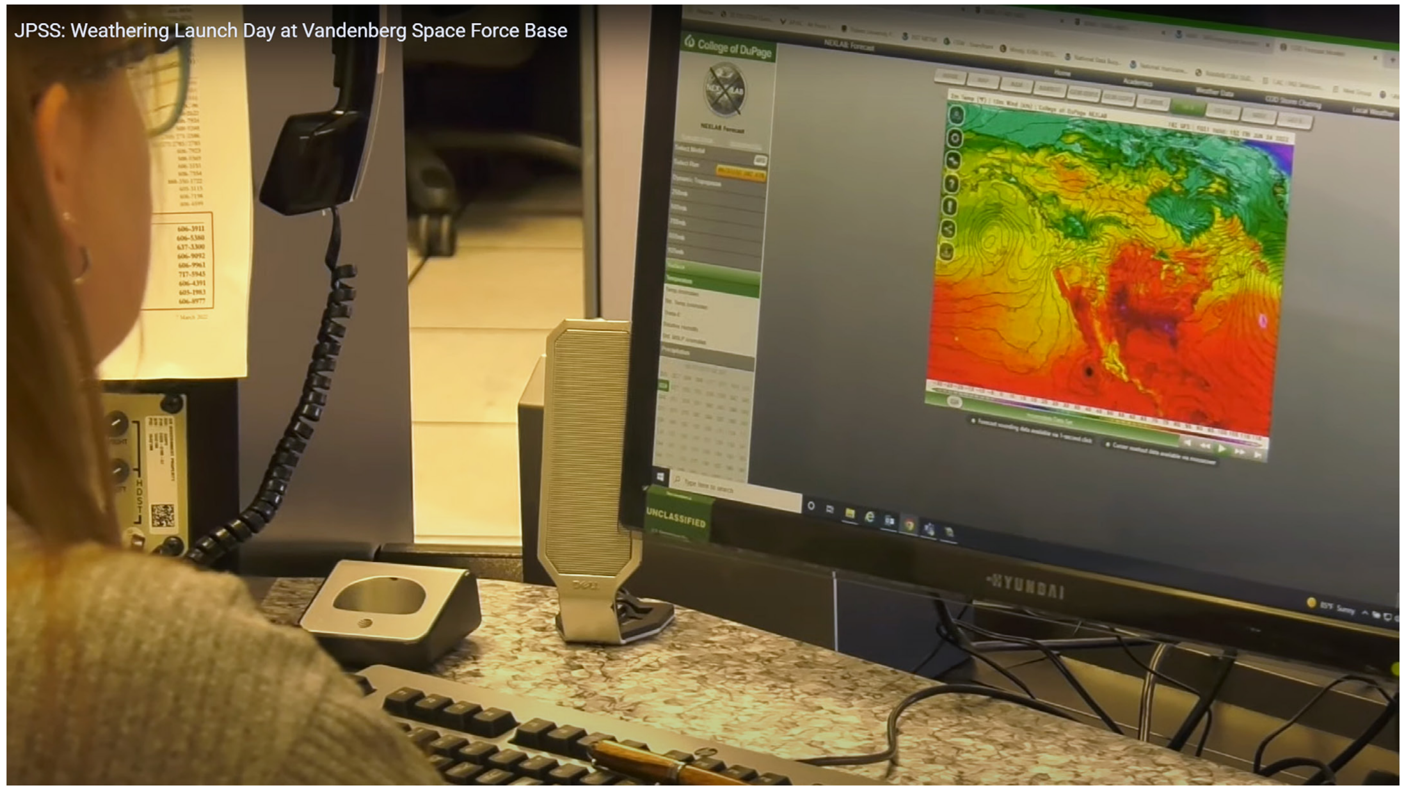
"Small changes in wind direction and wind speed have a huge impact on the space lift mission here. So we have to be very good at what we do," said Launch Weather Officer Captain Addison Nichols. "Thankfully, Vandenberg is one of the few places that has a robust weather instrumentation network that allows us to do our job."

Weather surveillance aircraft that fly through the area on launch day provide measurements of cloud heights, temperature and other important data to assess the risk of lightning.

But the planes don't fly higher than 30,000 feet. In order to track a developing thunderstorm, you need to know the conditions at a slightly higher altitude of 40,000 or 50,000 feet. And since rockets travel through the upper atmosphere, it's important to understand what's happening much higher than that.

Enter weather balloons.

At Vandenberg's Surface and Upper Air Observatory, Senior Weather Observers like Daniel Day launch weather balloons with instruments attached to the bottom called radiosondes. The radiosondes measure wind speed and direction, temperature, pressure and humidity high into the atmosphere. The balloons expand as they rise into the atmosphere until at their biggest, they're about the size of a greyhound



bus. They typically fly between 100,000 to 120,000 feet.

Weather safety officers track the data being fed from the balloons as they rise, and feed them into a model.

Weather models are fed by data from weather balloons, radar, ground-based instruments and weather satellites like JPSS-2. In fact, 85% of the data feeding today's weather forecast models come from polar-orbiting satellites like those in the JPSS fleet.

Adding more polar-orbiting weather satellites, like JPSS-2, could improve the accuracy of models by increasing the frequency and amount of data collected over the upstream oceans, Zounes said.

All this data will be stitched together to provide a reliable weather forecast for the JPSS-2 satellite's launch day.

"Out here, it is rocket science," Nichols said, "and so we have to be very, very precise. ✦

Story Source

This story was originally published on the NOAA NESDIS website at https://www.nesdis.noaa.gov/news/forecasting-weather-the-weather-satellite-launch. The full story and interviews are available on YouTube: https://youtu.be/AqOk0UxYym4.

SOCIAL MEDIA *Highlights*

Through social media, the JPSS Communications Team makes sure that the public is informed and engaged in JPSS missions and projects. Several times a week they share JPSS news, data in action, STEM activities, and fun facts on Facebook and Twitter. The following is a selection of popular JPSS posts from the past year.

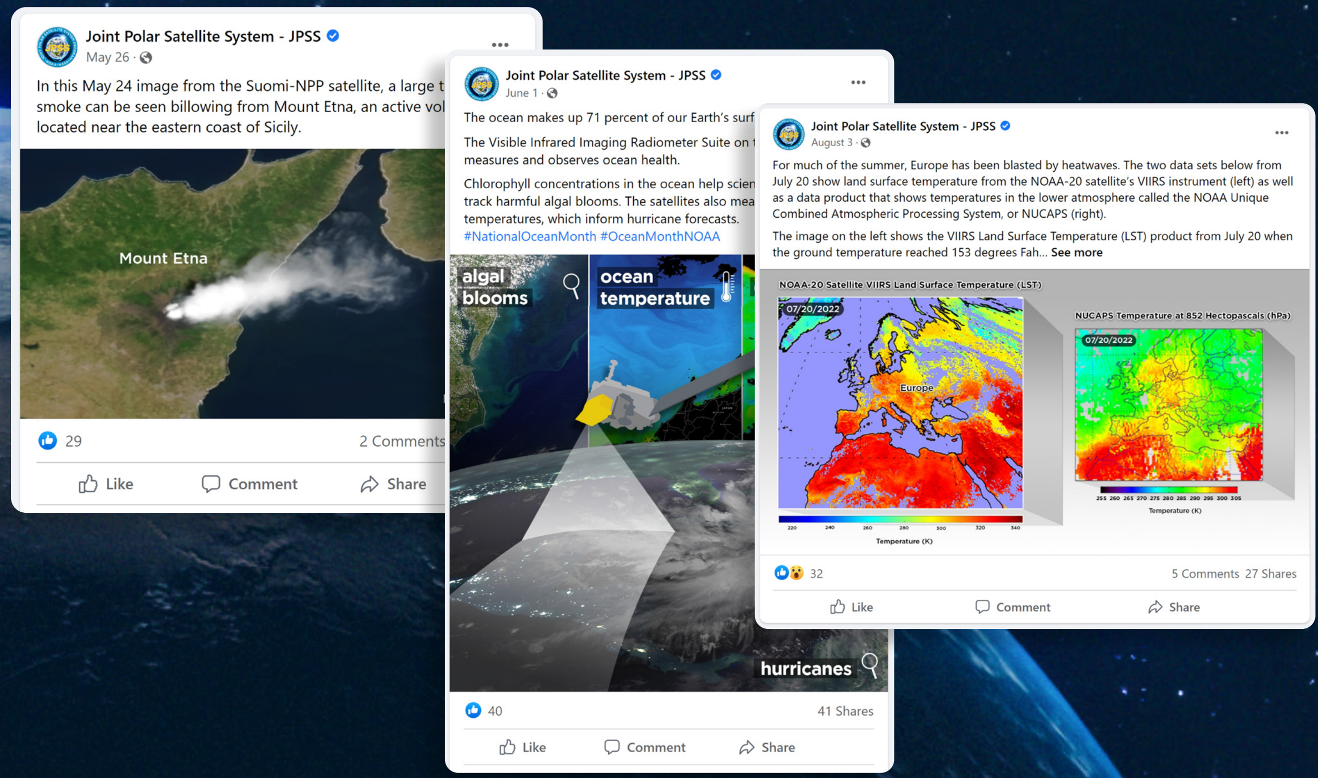
Follow, share, and be a part of the conversation with JPSS by joining us on our social media accounts!

FACEBOOK
JPSS.PROGRAM

TWITTER
@JPSSPROGRAM

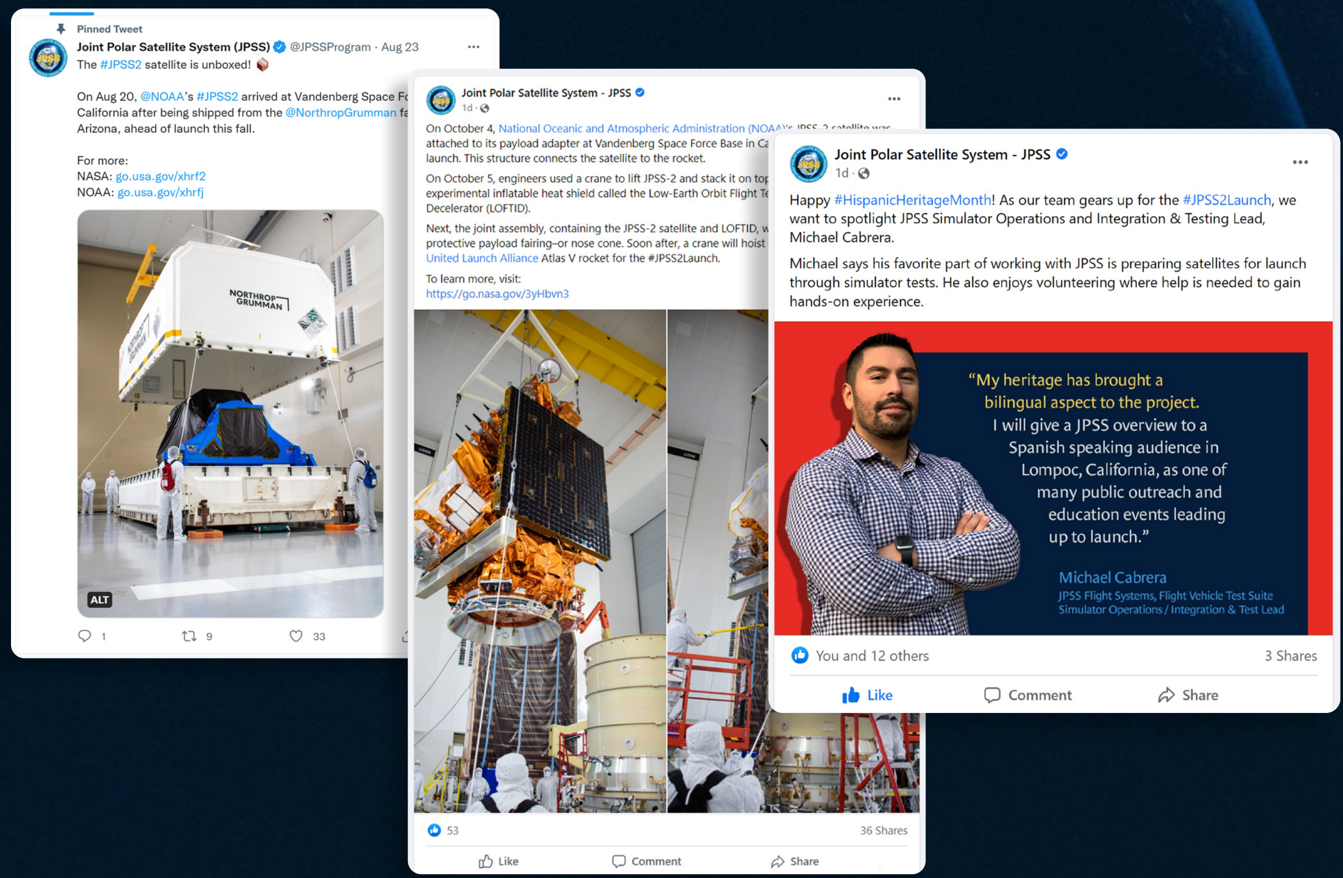
DATA IN ACTION

Click on an image to view original post.



JPSS-2 (NOAA-21) LAUNCH

Click on an image to view original post.



JUST FOR FUN

Click on an image to view original post.

NEWS STORIES

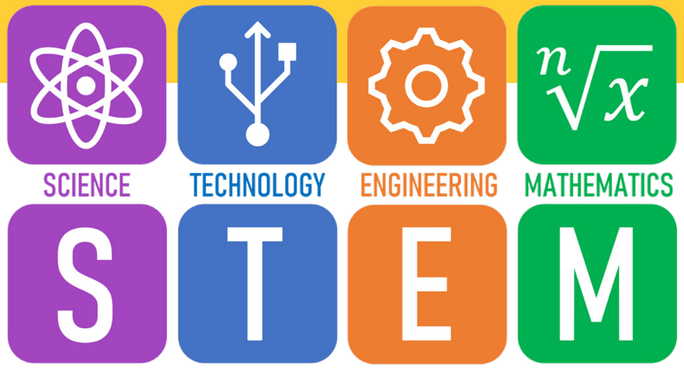
Click on an image to view original post.

STEM ACTIVITY

Click on an image to view original post.

Highlights
FROM PUBLIC OUTREACH & STEM ENGAGEMENT

Julie Hoover
Senior Communications and STEM Engagement Specialist, Joint Polar Satellite System
NASA Goddard Space Flight Center

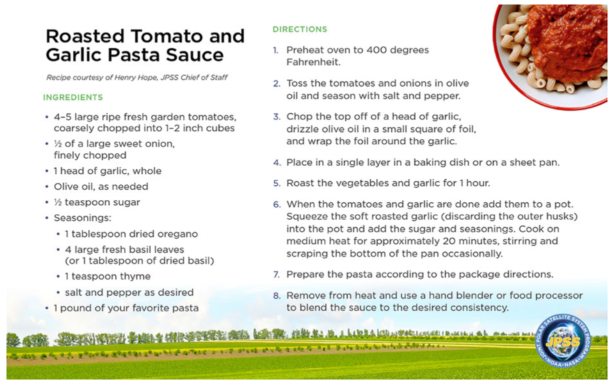


Public outreach and science, technology, engineering, and math (STEM) education are critical to the mission of the Joint Polar Satellite System (JPSS) because they help educate the public on how satellite data are used to make informed decisions about climate change, weather, disaster management, and other applications.

JPSS is positioned to offer a wide range of educational topics since the program is a NOAA/NASA joint partnership and the satellite system supports a huge swath of scientific research topics. The JPSS Communications and STEM Engagement Team not only communicates the mission of JPSS to the public but also teaches about the fundamental concepts that tie into the JPSS mission, such as climate change, water resource management, agriculture, and soil health. Explaining these concepts helps learners understand how JPSS observations are used and why they are important. Demystifying science and humanizing scientists and engineers have become imperative parts of any outreach designed to excite the community about STEM.

JPSS STEM engagement places a priority on meeting the needs of the audience and tailoring outreach activities for the specific community. This can be as simple as choosing a hands-on activity that meets the learning objectives of a classroom or as involved as a meeting with stakeholders to identify their needs and create activities to match their unique environment. Public outreach is not limited to event planning, and the JPSS Communications and STEM Engagement Team has developed a robust webpage with lesson plans and activities that users can incorporate into their educational endeavors (https://www.nesdis.noaa.gov/about/k-12-education/jpss-education). Highlights from a selection of 2022 activities are featured below.

Highlights from Public Outreach & STEM Engagement Activities



Roasted Tomato and Garlic Pasta Sauce

Recipe courtesy of Henry Hope, JPSS Chief of Staff

INGREDIENTS

- 4–5 large ripe fresh garden tomatoes, coarsely chopped into 1–2 inch cubes
- ½ of a large sweet onion, finely chopped
- 1 head of garlic, whole
- Olive oil, as needed
- ½ teaspoon sugar
- Seasonings:
  - 1 tablespoon dried oregano
  - 4 large fresh basil leaves (or 1 tablespoon of dried basil)
  - 1 teaspoon thyme
  - salt and pepper as desired
- 1 pound of your favorite pasta

DIRECTIONS

1. Preheat oven to 400 degrees Fahrenheit.
2. Toss the tomatoes and onions in olive oil and season with salt and pepper.
3. Chop the top off of a head of garlic, drizzle olive oil in a small square of foil, and wrap the foil around the garlic.
4. Place in a single layer in a baking dish or on a sheet pan.
5. Roast the vegetables and garlic for 1 hour.
6. When the tomatoes and garlic are done add them to a pot. Squeeze the soft roasted garlic (discarding the outer husks) into the pot and add the sugar and seasonings. Cook on medium heat for approximately 20 minutes, stirring and scraping the bottom of the pan occasionally.
7. Prepare the pasta according to the package directions.
8. Remove from heat and use a hand blender or food processor to blend the sauce to the desired consistency.

One of the first new projects of 2022 was a set of recipe cards that highlight JPSS science as it applies to weather, climate, and agriculture while introducing recipes that use healthy ingredients that can be purchased at a farmers' market or grown in a home garden. These recipes were submitted by JPSS staff and the community and take advantage of the universal language of food, which is a simple way to make a personal connection between JPSS science applications and everyday life. They can be viewed and downloaded at https://www.nesdis.noaa.gov/about/k-12-education/jpss-education/cooking-jpss. Another project that created a personal connection was the Temperature (Ch)Art activity that encouraged people to create art by journaling daily temperatures. These color-by-number sheets, based on the popular temperature quilting/knitting crafts, appeal to kids and adults and endeavor to prompt mindful reflection about climate change. The activity is available at https://www.nesdis.noaa.gov/about/k-12-education/jpss-education/color-temperature-chart. The team also developed the JP Super Seal Activity Book to introduce JPSS and remote sensing concepts to very young children. This paperback follows JP the Super Seal as he flies around the Earth protecting people from fires, disasters, and extreme weather, and can be downloaded at https://www.nesdis.noaa.gov/about/k-12-education/jpss-education/jp-super-seal-activity-book.

Two other unique products were developed for older audiences who are interested in the technological and engineering side of JPSS: the Weather Satellites AR app and the JPSS Paper Spacecraft model. The Weather Satellites AR app, available for Apple products in the App Store and Android platforms in Google Play, lets the user experience the satellite hardware while learning about applications of JPSS data. The paper spacecraft is a pop-out paper model (above) that folds together to create a simplified rendition of the JPSS bus, instruments, and solar panels, helping people to learn about the components of the system (https://www.nesdis.noaa.gov/about/k-12-education/jpss-education/activity-construct-3d-paper-model-of-jpss-2).

Leading up to the JPSS-2 launch, JPSS conducted two community Launch Challenges. The first, aimed at kids, was the Choose Your Own Invention Challenge where young students completed a worksheet that walked them through creating their own weather observation instrument (https://www.nesdis.noaa.gov/about/k-12-education/jpss-education/choose-your-own-invention). The second, open to all ages, was a video compilation of photos collected from the community called the Place You Love Challenge (https://youtu.be/Y_cFrmlIN8c). This initiative highlighted the work that JPSS does to keep people safe while creating a video showcasing landscapes from all over the world.

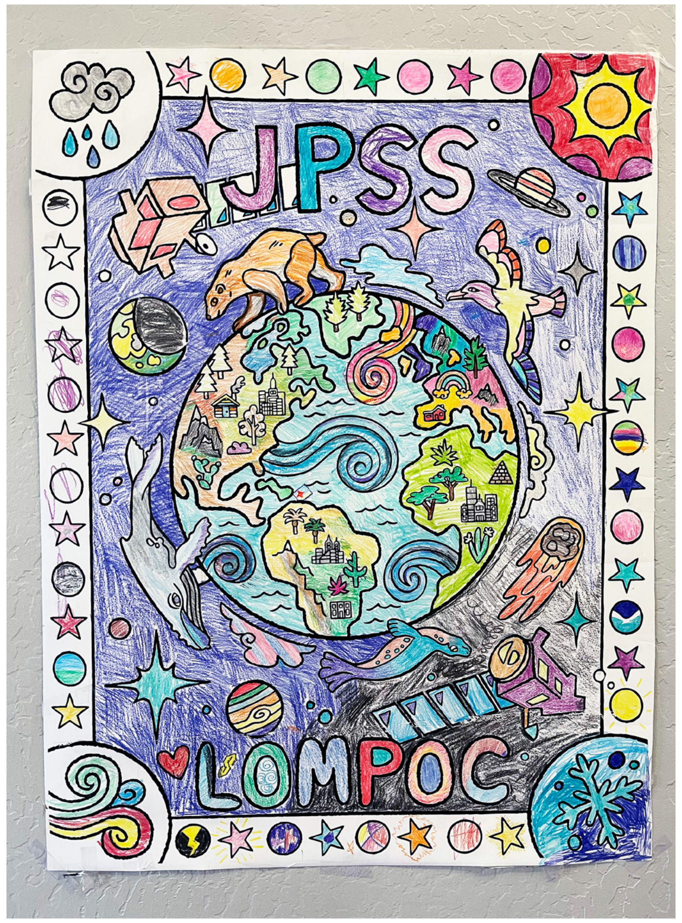
For in-person outreach, the JPSS Communications and STEM Engagement Team started the year with a focus on Earth Day. Three activity videos were developed for the virtual portion of NASA's Earth Day that explain how greenhouse gases work and how to make models of molecules, how learners can make a rain gauge out of household items to track rainfall at home, and about the importance of recycling and soil health while teaching viewers how to make recycled paper with seeds embedded in it. JPSS also partnered with Exploration and Space Communications for a pre-recorded panel discussion for NASA's Virtual Earth Day (https://youtu.be/p6VkoCDQJ_w). This expert panel discussed how satellites gather and transmit data crucial to the conservation and preservation of the Earth. This discussion was an opportunity to demonstrate how data moves from satellites to the users and how JPSS ensures that critical data are always reliably available when it is needed.

In May, the JPSS Communications and STEM Engagement Team unveiled Orbits Interweave, a kinetic sculpture that was developed in partnership with GOES, at the NASA Goddard Visitor's Center and hosted a kickoff event. This sculpture loosely represents the Sun, Earth, and satellites. The team worked with local rocketry groups to capture a bird's eye view of the new sculpture for a promotional video that highlights the new exhibit (https://youtu.be/BYhIfZQcNk0).

Over the summer, JPSS participated in the BlueStar Families virtual camp by providing a video that guides learners through how to make recycled paper while educating them about JPSS. The organizers wanted to get kids excited about enjoying the outdoors, so the tutorial was filmed in a scenic location at the National Wildlife Center in Maryland. This video and the instructional materials were shared with military families across the United States. The team also worked with the GenHERation group to present two virtual career panels to student groups in North Carolina and New York. The GenHERation panels were a fantastic opportunity to reach large, diverse groups of female students, share career advice, and inspire them to pursue STEM careers in college.

In September, JPSS hosted the first in-person Sunday Experiment since the pandemic began. NASA's Sunday Experiment is a free monthly program offered at the NASA Goddard Visitor Center that features activities geared toward children ages 5 to 10. JPSS experts presented about their careers, demonstrated a clean room "bunny suit," gave an interactive talk about "How to Save the World from Low Earth Orbit," and demonstrated the water cycle with a model that showed the phase changes of water in real-time. Other volunteers led a variety of hands-on activities for kids. The event was a success with 125 adults and 85 children visiting. This and other Sunday Experiments can be found at https://www.nasa.gov/content/goddard/past-months-virtual-sunday-experiment-listing.

The biggest outreach effort of the year was for the JPSS-2 launch in early November. JPSS Communications and STEM Engagement Team members traveled to Lompoc, CA to participate in a multitude of in-person community outreach activities to promote the launch. Events were planned in partnership with Explore Lompoc and community leaders to make sure that everyone benefited from the experience and a wide audience had the opportunity to learn about JPSS. Activities throughout the week leading up to the scheduled launch included hands-on activities in both English and Spanish at the Lompoc Public Library, a lunchtime visit to Lompoc High School and attendance at the Friday night high school football game, an informal panel discussion with JPSS scientists and engineers at a local winery, and an Earth Observation GeoTour through which geocaching enthusiasts learned about JPSS and collected JPSS and Lompoc themed giveaways. The team also participated in the Old Town Halloween trick-or-treating event, led games and STEM activities at the Lompoc Aquatic Center, staffed a booth at a farmers' market where visitors could get JPSS Recipe Cards to pair with their produce, and hosted a "Space Crafts and Craft Brews" event at a local brewery. The busy week concluded with the team visiting Los Berros Elementary students and the Cabrillo High School Aquarium before heading back to JPSS offices in Maryland.



CLICK IMAGE TO ENLARGE.

These are only a small selection of the public outreach and STEM engagement activities developed and carried out by the JPSS Communications and STEM Engagement Team in 2022. Events and activities such as these increase public support and awareness of the applications and importance of JPSS observations. Increasing the public understanding of JPSS and how it benefits the Earth, humans, and the economy can lead to more informed decisions, and inspire a new generation of students to pursue STEM fields.