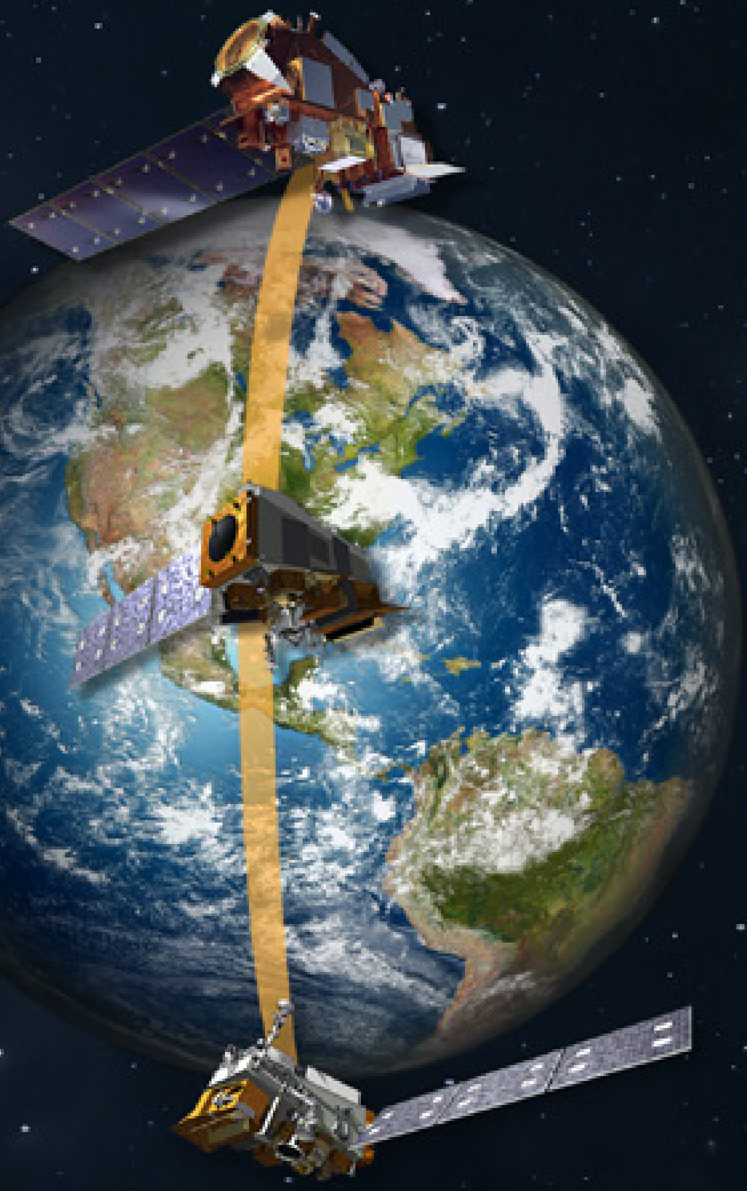
2023

JPSS

ANNUAL SCIENCE DIGEST



EXPLORING THE IMPACT AND APPLICATIONS OF JPSS DATA

FROM THE NOAA NESDIS OFFICE OF LOW EARTH ORBIT (LEO) OBSERVATIONS

IN THIS DIGEST

FEATURED ARTICLES

WEB FEATURES

HIGHLIGHTS

2023 JPSS ANNUAL SCIENCE DIGEST CONTRIBUTORS

Office of LEO Observations Director:
Timothy Walsh

LEO Chief Scientist:
Dr. Satya Kalluri

Lead Author:
Amy Leibrand, *Science and Technology Corporation (STC), contractor (Feature Articles)*

Contributing Writers:
Jenny Marder, *Telophase Corporation, contractor (Web Features)*
Sara Bloom Leeds, *IM Systems Group (IMSG), contractor (Web Features)*
Amanda Keener, *IM Systems Group (IMSG), contractor (Web Features)*
Teresa Johnson, *ASRC Federal System Solutions, contractor (Social Media Highlights)*
Julie Hoover, *ASRC Federal System Solutions, contractor (Highlights from Public Outreach & STEM Engagement)*

Editors:
Bill Sjoberg, *Leveraged Information Technology (LIT), consultant supporting Global Science and Technology, contractor*
Andrew Lomax, *Science and Technology Corporation (STC), contractor*
Dr. Satya Kalluri, *NOAA NESDIS Office of LEO Observations*

Graphic Designer:
Joshua Brady, *GAMA-1 Technologies, contractor*

Strategic Communications and STEM Engagement:
Michelle Birdsall, *ASRC Federal System Solutions, contractor*
Julie Hoover, *ASRC Federal System Solutions, contractor*

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Feature 1 – The Potential of Applying NUCAPS in Predicting Pyrocumulonimbus Clouds

Arunas Kuciauskas, *Meteorologist and Principal Investigator, U.S. Naval Research Laboratory-Marine Meteorology Division*
Andrew Lambert, *Meteorologist, General Dynamics Information Technology*

Feature 2 – Fusing Together Polar and Geostationary Satellite Observations to Improve Severe Weather Forecasts

Dr. William L. Smith Sr., *Senior Scientist, Space Science and Engineering Center, University of Wisconsin-Madison; Professor Emeritus, University of Wisconsin-Madison; Distinguished Professor, Hampton University*

Feature 3 – Perspectives on Satellite Data Training for Operational Meteorology, Weather Research, and JPSS Applications

Jorel Torres, *Research Associate II/JPSS Satellite Liaison, Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University*
Dr. Scott Lindstrom, *Scientist, Cooperative Institute for Meteorological Satellite Studies (CIMSS) at University of Wisconsin-Madison*

Feature 4 - Understanding Methane Emissions With CarbonTracker-CH_4

Dr. Youmi Oh, *Research Scientist, NOAA Global Monitoring Laboratory*
Dr. Lori Bruhwiler, *Physical Scientist, NOAA Global Monitoring Laboratory*

Feature 5 - Revolutionizing Weather Forecasting: How Low Earth Orbit Satellites Have Changed the Game

Dr. Haidao Lin, *Research Scientist, Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University; NOAA Earth System Research Lab/Global Systems Laboratory*

Feature 6 - Monitoring Stratospheric Ozone with the Ozone Mapping and Profiler Suite (OMPS) Limb Profiler

Dr. Natalya Kramarova, *Research Scientist, NASA Goddard Space Flight Center (GSFC) Atmospheric Chemistry and Dynamics Lab*

Feature 7 - Assimilating JPSS Trace Gas Measurements Into an Air Quality Modeling System

Dr. R. Bradley Pierce, *Director, Space Science and Engineering Center (SSEC), University of Wisconsin-Madison*

Feature 8 - Leveraging Low Earth Orbit Observations for Enhanced Tropical Cyclone Forecasting

Monica Bozeman, *JPSS PGRR Tropical Cyclones Initiative Facilitator, NWS Office of Central Processing*
Dr. Mark DeMaria, *Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University*

Feature 9 - Revealing the Night Sky: Using VIIRS Data to Detect and Characterize Natural Gas Flares

Dr. Christopher D. Elvidge, *Senior Research Associate and Director of the Earth Observation Group, Colorado School of Mines*
Dr. Mikhail Zhizhin, *Payne Institute of Public Policy/Earth Observation Group, Colorado School of Mines*

Feature 10 - Enhancing Detection and Monitoring of Sargassum Seaweed Using Low Earth Orbit Observations

Dr. Joaquin A. Trinanes, *Operations Manager, NOAA CoastWatch Caribbean and Gulf of Mexico Regional Node and Atlantic OceanWatch Node, NOAA Atlantic Oceanographic and Meteorological Laboratory*
Víctor Manuel Jiménez Escudero, *Associate Academic Technician C, National Autonomous University of Mexico (UNAM)*

Feature 11 - NOAA NESDIS-OAR Collaboration: Synergies between OAR Observing Capabilities and NESDIS Satellite Missions for Trusted Data and Product Development

Dr. Lihang Zhou, *Data Product Management and Services (DPMS) Deputy and JPSS Product Portfolio Manager, JPSS Ground Segment DPMS, NOAA NESDIS Office of Low Earth Orbit Observations (LEO)*

FROM THE

OFFICE OF LEO OBSERVATIONS DIRECTOR

Timothy Walsh
Director, Office of Low Earth Orbit Observations

This year, I am sharing my Science Digest message with you not as the JPSS Program Director, but as Director of the new Office of Low Earth Orbit (LEO) Observations within NOAA's reorganized National Environmental Satellite, Data, and Information Service (NESDIS). The reorganization defines LEO as managing two major programs: JPSS, our foundational program, which will exist as a program through at least 2038, and our next generation program, the Near Earth Orbit Network (NEON), which will define future LEO architecture beyond JPSS-3 and -4. This year has marked significant advancements for both the JPSS Program and the NEON Program, helping to ensure forecast data continuity for decades to come.

NOAA-21, formerly named JPSS-2, is now fully operational in the JPSS fleet of polar-orbiting satellites, providing critical data to improve the accuracy of weather forecasts and monitor climate change. The JPSS Flight Project completed a successful on-orbit checkout and testing of the NOAA-21 satellite's instruments and systems before handing operations over to NOAA's Office of Satellite and Product Operations (OSPO) on March 30, 2023. OSPO declared NOAA-21 operational on November 8, 2023, in time to celebrate JPSS-2's launch anniversary on November 10.

NOAA-21 is being positioned as the primary satellite in the JPSS constellation with NOAA-20 and Suomi National Polar-orbiting Partnership (Suomi-NPP), where it will continue the vital mission of providing our nation with crucial weather and climate data. Suomi NPP celebrated its twelfth year of operations in October, and NOAA-20 completed its sixth year in orbit in November. The JPSS baseline suite of instruments—the Advanced Technology Microwave Sounder (ATMS), the Cross-track Infrared Sounder (CrIS), the Visible Infrared Imaging Radiometer Suite (VIIRS), and the Ozone Mapping and Profiler Suite (OMPS)—provide life-saving data and valuable products to users as the nation continues to face hurricanes, tornadoes, droughts, floods, fires, heat waves, and other severe weather.

JPSS-3 and -4 development is progressing well. JPSS-3's four instruments have been integrated onto the spacecraft bus, and the satellite is undergoing environmental testing at the spacecraft facility. The JPSS-4 satellite bus is currently next to JPSS-3 in the facility, where it awaits its instruments for integration.

Libera, a NASA research and development instrument, completed its Critical Design Review in 2023. Libera is a follow-on to the Clouds and the Earth's Radiant Energy System (CERES) instrument that currently flies on Suomi NPP and NOAA-20 to measure Earth's outgoing radiative energy. Libera will observe and help maintain the 40-year data record of the solar radiation balance, allowing scientists to understand changes to Earth's climate system, such as whether the planet is heating up or cooling down.

Originally slated for inclusion aboard JPSS-3, Libera will now be part of the JPSS-4 mission. JPSS-4 will launch in 2027 with Libera onboard, while JPSS-3 shifts to a target launch date in 2032. This change in launch sequence minimizes additional testing that would have been needed to integrate Libera onto a nearly completed JPSS-3. Once it is completed, JPSS-3 will enter extended storage and will be tested annually before its new launch date in 2032.

In preparing for the future beyond JPSS, we made significant progress this year with QuickSounder, the first project in the NEON Program. As a pathfinder mission and NOAA's first environmental smallsat, QuickSounder will serve as a prototype for the next generation of environmental satellites and demonstrate NOAA's ability to launch a small satellite within three years. QuickSounder will fly a refurbished Advanced Technology Microwave Sounder (ATMS) Engineering Development Unit, the same ATMS instrument as those flown on the JPSS satellites.

While environmental satellites like JPSS usually take 10 years or longer to develop and launch, QuickSounder is expected to launch in mid-2026, less than 27 months after NOAA and NASA awarded the contract for its development in October 2023. QuickSounder will deliver 95% of collected data within 30 minutes, helping to improve NOAA's weather forecasting ability. It will also provide additional critical microwave sounding observations in an early morning orbit, different from the traditional early afternoon JPSS orbit.

With QuickSounder leading the way, we are defining future LEO architecture for NEON Series-1. In August, we awarded four contracts to conduct NOAA's Sounder for Microwave-Based Applications (SMBA) Phase-A study. The SMBA instrument will be the follow-on to ATMS and serve as the backbone microwave sounder for the NEON Series, with the first Series-1 launch planned in 2030. Microwave sounders will be the first NEON instruments launched because microwave sounder data has the highest-impact on weather forecast models. In defining the future LEO architecture, we envision a disaggregated set of instruments, increased orbital diversity, and faster refresh rates for critical data necessary to optimize numerical weather prediction. We anticipate issuing a Phase A Study request for proposal in FY2025 for a Sounder for Infrared-based Applications (SIRBA) instrument, which will be a follow on to the JPSS CrIS instrument.

The success of our satellite programs, both ongoing and emerging, is a direct result of hard work and extensive collaborations with satellite developers, our NOAA corporate partners, and our national and international stakeholders. 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 key observations to their service areas and stakeholders. Advances in the future of our LEO satellite constellation and our international partnerships expand the capabilities of our data and modeling, which are vitally important for ongoing weather prediction and environmental monitoring as we experience and prepare for extreme weather patterns.

Weather and climate headlines in the news continue to highlight the need for these critical partnerships and programs. One example is the satellite capabilities used during the 2023 Hurricane Season. This hurricane season produced 20 named storms (winds of 39 mph or greater), seven of which were hurricanes (winds of 74 mph or greater) and three intensified to major hurricanes with winds reaching 111 mph or greater. The Office of LEO Observations and 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 (now the LEO 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, LEO program scientist, for his leadership.

Between the successful commissioning of NOAA-21 to our formulation efforts to define the future of LEO observations, 2023 was a tremendous year. We look forward to 2024 as we continue the success of JPSS and shape the future with QuickSounder and NEON.

Tim Walsh
Director, Office of Low Earth Orbit (LEO) Observations
National Environmental Satellite, Data, and Information Service (NESDIS)
National Oceanic and Atmospheric Administration (NOAA)

FROM THE

LEO CHIEF SCIENTIST

Dr. Satya Kalluri
LEO Chief Scientist

With three satellites in orbit (Suomi NPP, NOAA-20, and NOAA-21), the JPSS constellation is robust and resilient! Thanks to the hard work, dedication, and detailed analysis by NOAA scientists at the Center for Satellite Applications and Research (STAR), NASA flight project, and scientists from our Cooperative Institutes, all the key performance parameters from NOAA-21 have been fully validated within a year after launch, and several numerical weather prediction centers, including NOAA's National Weather Service, are now operationally assimilating radiances from NOAA-21 sounders. In recognition of this tremendous achievement, the JPSS science team received the prestigious Robert H. Goddard Memorial Award this year.

In 2023, we witnessed several environmental disasters that broke previous records for their impact and damage, and JPSS data and products have been valuable in providing timely information for detection, modeling, and monitoring the evolution of these events. For example, Visible Infrared Imaging Radiometer Suite (VIIRS) data have been critical for issuing air quality and visibility forecasts for the catastrophic and historic fires in Canada that burnt millions of acres and emitted large amounts of smoke that was transported by global wind circulation across the lower 48 continental U.S. states and the Atlantic Ocean, reaching Europe. Fires such as these create their own meteorology and the article on pyrocumulonimbus clouds (Feature 1, highlighting research conducted at the U.S. Naval Research Laboratory) demonstrates how soundings from the Cross-track Infrared Sounder (CrIS) can be used to diagnose the atmospheric profiles above the fires that lead to severe weather. The High Resolution Rapid Refresh (HRRR) and the Rapid Refresh (RAP) models that are used to issue hourly weather forecasts and predict smoke transport from fires over North America are slated to be replaced by the Rapid Refresh Forecast System (RRFS) in the next few years; these updates are described in Feature 5 that highlights data assimilation work led by Dr. Haidao Lin. Geostationary satellites such as GOES-R and Low Earth Orbit (LEO) satellites like JPSS have their own unique advantages and make distinct contributions to weather prediction with GOES providing rapid imagery over the Western Hemisphere for nowcasting and LEO providing global coverage of soundings and imagery twice a day that drive numerical weather prediction models. However, new techniques to combine observations from both GOES and JPSS are creating new opportunities for short-range forecasting capabilities, as depicted in Feature 2, which details the research of Dr. William Smith. Massive mats of *Sargassum* seaweed washing up onto U.S. beaches also made headlines this year, and Feature 10 provides an overview of how researchers at NOAA CoastWatch and the National Autonomous University of Mexico (UNAM) are using LEO observations to detect, monitor, and predict *Sargassum* inundation events.

The 2023 Atlantic hurricane season was ranked fourth in terms of the most-named storms in a year since 1950, driven by warm sea surface temperature caused by El Niño. Feature 8 describes research being done as part of the JPSS Proving Ground Risk Reduction (PGRR) Tropical Cyclones Initiative with a focus on the value of LEO satellites in tropical cyclone forecasting, including the importance of low latency direct broadcast data in providing timely information to forecasters.

With 2023 finishing as the hottest year on record, there is growing urgency to detect, monitor, and limit the sources of greenhouse gasses, one of the primary factors for the warming trend. There are several articles in this year's JPSS Science Digest that showcase how LEO data are contributing to monitoring and modeling atmospheric chemistry. In our pursuit to develop satellite products to monitor greenhouse gasses, NESDIS collaborates very closely with NOAA Oceanic and Atmospheric Research (OAR), and Feature 11 provides an overview of the collaborative efforts with the OAR Global Monitoring Laboratory (GML), a partnership that has played a crucial role in understanding the atmospheric composition of the stratosphere and troposphere. Feature 4 describes NOAA's methane monitoring tool ("CarbonTracker-CH_4"), developed as part of the NESDIS and GML collaboration, that combines in-situ and aircraft measurements in an atmospheric chemical transport model to infer emission trends of methane, a potent greenhouse gas, and produce analyses. Similarly, Feature 7, highlighting work led by Dr. R. Bradley Pierce, describes efforts to assimilate satellite measurements of trace gasses and aerosols into real-time air quality models to simulate atmospheric chemistry and predict large scale pollution events. The use of VIIRS Day/Night band to detect and monitor emissions from gas flares, an important source of methane, is described in Feature 9, which outlines research being done by the Earth Observation Group at the Colorado School of Mines. The Ozone Mapping and Profiler Suite (OMPS) onboard JPSS satellites is a critical tool to monitor stratospheric ozone that is vital for all life on Earth. Techniques to retrieve ozone are described in Feature 6, which spotlights research led by Dr. Natalya Kramarova.

As you can see from the exciting list of feature articles in this year's Science Digest, JPSS science and applications continue to evolve and excel with new discoveries and enhancements of products and services with over a decade of valuable Earth science data collected by the mission. But the scientific advancements, tools, and techniques are not valuable unless the users and practitioners who deliver vital information to the public are properly trained. Feature 3 describes how the vast network of forecasters and data users are provided training by the LEO program to maximize the impact of observations.

I would like to extend my sincere appreciation to the scientists who contributed to the 2023 JPSS Science Digest by presenting at the widely attended monthly LEO Science Seminars. Authoring the articles in an easily understandable script is no easy task, and I would like to thank Ms. Amy Leibrand for doing an excellent job in writing, along with Mr. Josh Brady for his skill in arranging each article in a visually attractive manner. The dedicated and highly motivated science support staff at the Office of LEO who coordinate the science activities, as well as the communication team that is always exploring opportunities to broaden the programs impact, is much appreciated.

Your JPSS Chief Scientist,

Satya Kalluri
Program Scientist, Office of Low Earth Orbit (LEO) Observations
National Environmental Satellite, Data, and Information Service (NESDIS)
National Oceanic and Atmospheric Administration (NOAA)

FEATURE 1

The Potential of Applying NUCAPS in Predicting Pyrocumulonimbus Clouds

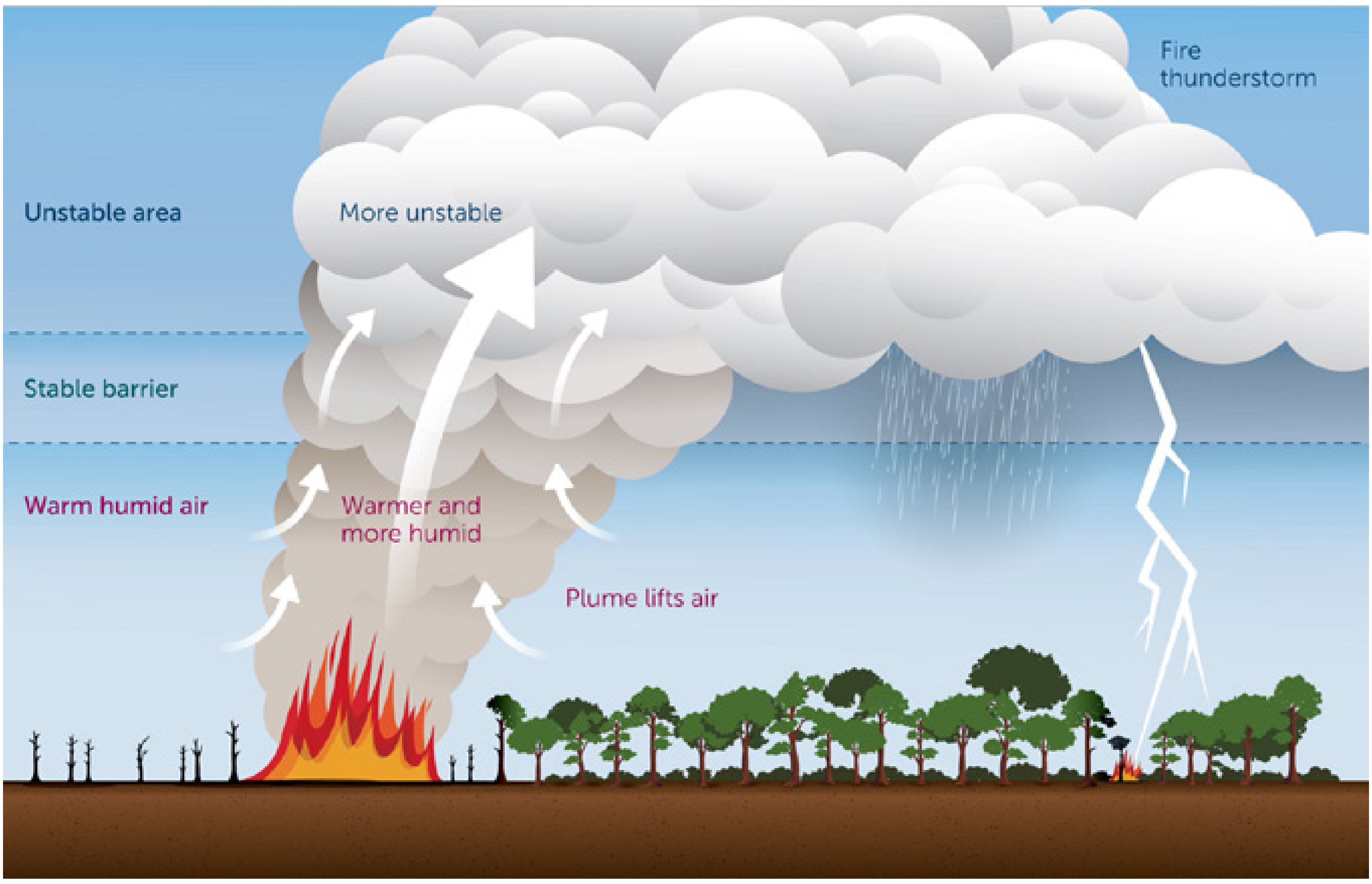
A pyrocumulonimbus cloud or "fire cloud" over the ridgeline rising from the Bootleg Fire in Oregon, July 7, 2021. Credit: InciWeb/inciweb.nwcg.gov.

Weather and wildfires go hand in hand, one often influencing the other. When there is little rain, summer heat dries the environment, turning vegetation into dry fuel that can become dangerously flammable. With suitable atmospheric ingredients, wildfires can create their own weather—monstrous fire-induced thunderstorms capable of producing lightning, hail, strong downdraft winds, and even tornadoes. These unique storms can also ignite new fires, reinforce the intensity of existing fires, and generate massive smoke plumes.

The phenomenon is initiated by heat from large and intense wildfires, when a wide convective smoke column is pushed high into the atmosphere (see below). If the air above the fire is moist and unstable, the smoke plume can condense and grow into a towering pyrocumulonimbus cloud ("pyro" from the Ancient Greek word pyr meaning fire and "cumulonimbus" indicating cloud type). The pyrocumulonimbus cloud, or "pyroCb" for short, remains tethered to the fire, producing dangerous weather and other ground-level hazards.

THE ALARMING IMPACTS

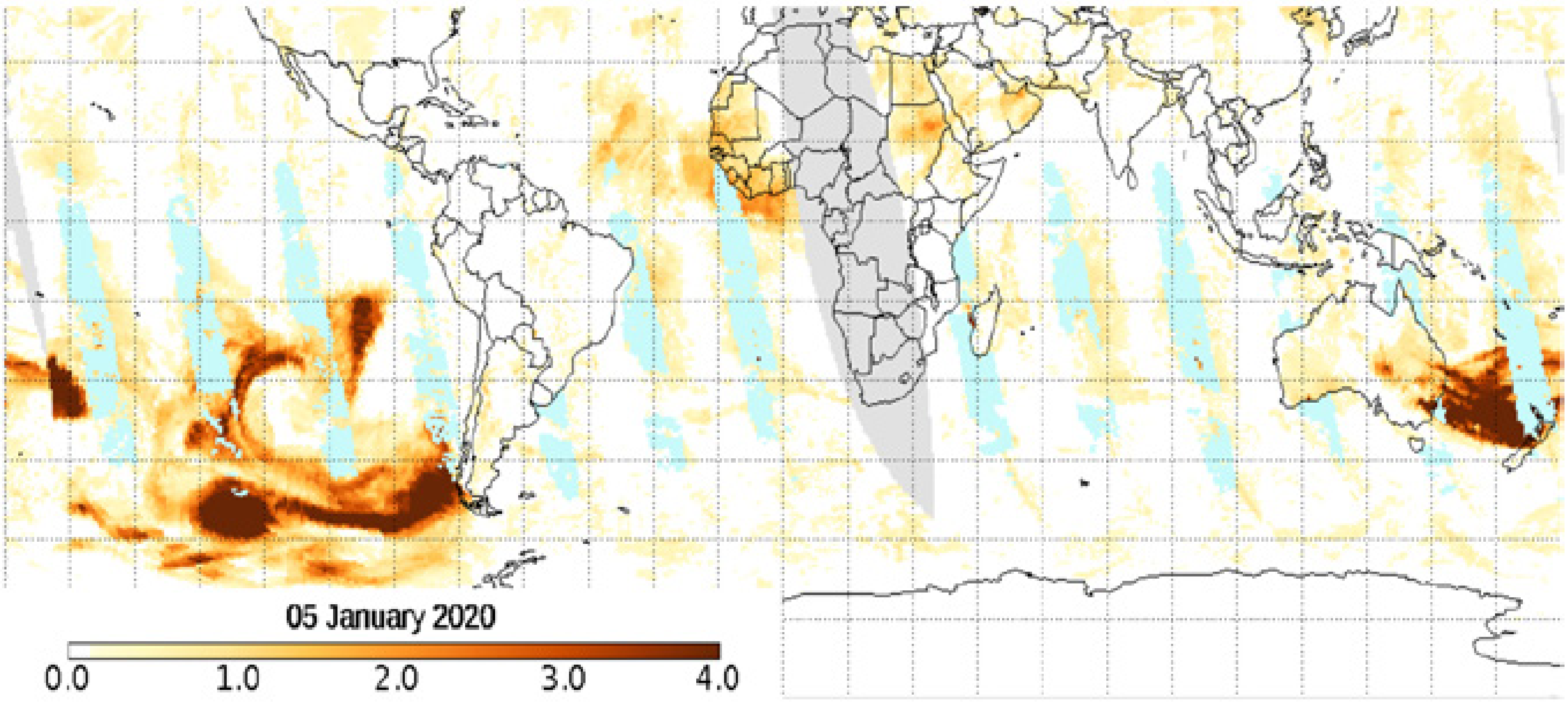
"PyroCbs act as giant chimneys," says Dr. David Peterson, a meteorologist at the U.S. Naval Research Laboratory (NRL) Marine Meteorology Division in Monterey, California, and subject matter expert on pyroCbs. They pull smoke released by the fire upward through the fire-induced thunderstorm core, "releasing the resultant smoke plume at the altitude that thunderstorm tops reach, often at the cruising altitudes of jet aircraft or higher," he explains. Events like these severely impact aviation safety, public health, firefighting, the ecosystem, and climate.



Pyrocumulonimbus clouds are formed when air is drawn into a smoke plume where it becomes warmer and more humid, making it more unstable. Source: Government of Australia/Bureau of Meteorology.

PyroCbs can inject smoke 11 miles above the Earth's surface. Absorption of solar radiation by smoke particles can cause the plume to rise even higher—well into the stratosphere—with smoke particles suspended for weeks or months, leading to hazardous flying conditions for pilots and dangerous air quality. In fact, the magnitude of a pyroCb smoke plume can rival that of a volcanic eruption, resulting in far-reaching impacts on regional and global climates, such as changes in stratospheric wind behavior and long-distance smoke transport.

The 2019-2020 Southeast Australia wildfire season produced some of the most intense fires and associated smoke pollution on record. An example of smoke transport from Australia to South America is shown by the JPSS Ozone Mapping and Profiler Suite (OMPS) UV Absorbing Aerosol Index, below—thick, high altitude smoke (dark red) traveling across the Pacific Ocean. The smoke originated from a pyroCb "super outbreak" consisting of more than 30 updrafts between December 29, 2019, and January 4, 2020. "The majority of these pyroCbs injected smoke into the stratosphere," Dr. Peterson notes.



OMPS UV Absorbing Aerosol Index on January 5, 2020, shows the transport of smoke pollution from Australia to South America. Image credit: Fromm, Peterson, and Thapa 2020.

At ground-level, the billowing height and opaqueness of a pyroCb will blanket out the sun, turning daylight into darkness. Hot and chaotic winds from pyroCbs are erratic and can form vertical swirls with wind speeds reaching tornado strength. Additionally, ember showers can ignite new fires downwind, a behavior called fire spotting. "All this is to say that pyroCbs can be both complicated and life-threatening to ground-based firefighting situations," says Arunas Kuciauskas, a research meteorologist at NRL and colleague of Dr. Peterson.

Due to their unpredictable nature, it's hard to predict which wildfires will form into a pyroCb, making firefighting planning all the more difficult. Near real-time tools are needed to provide early warning capabilities for pyroCbs to protect the lives

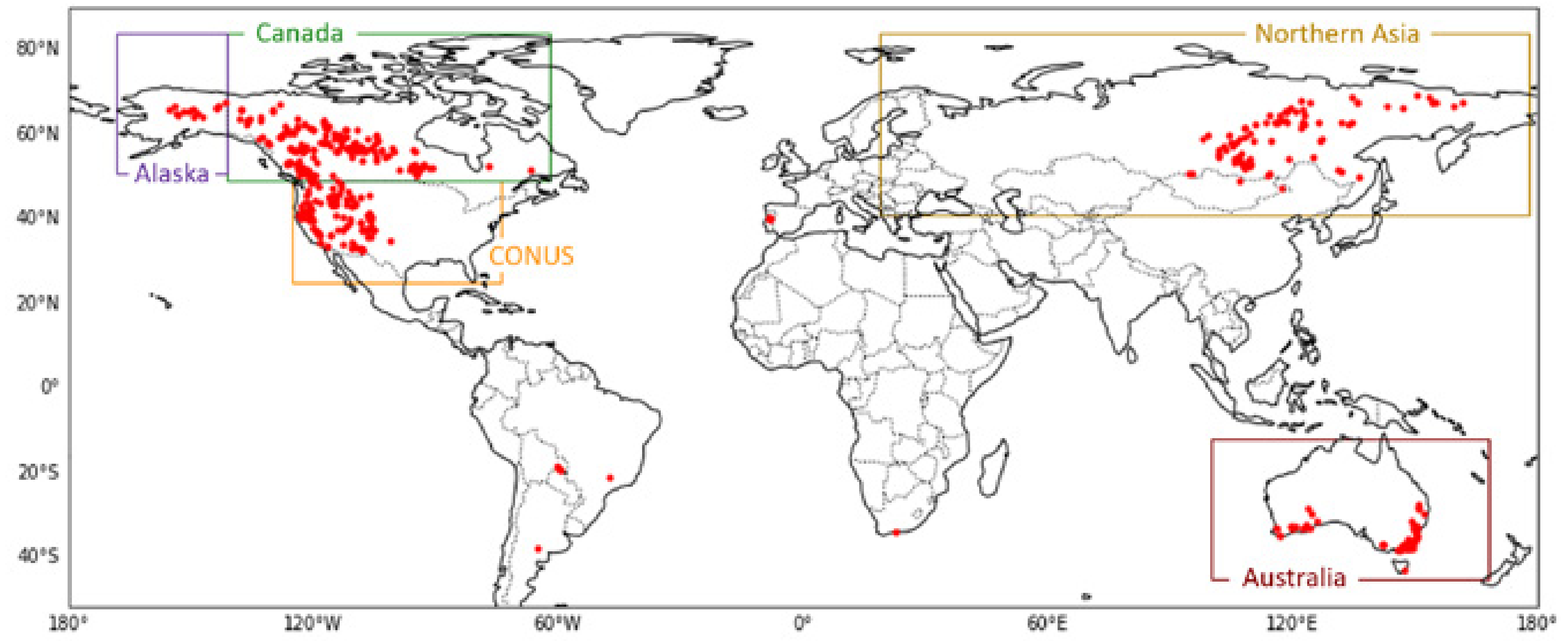
Left: An ember shower during the Grizzly Creek Fire in Colorado. Source: Arvada Fire. Right: Photo of a pyroCb cloud taken over the Pacific Northwest on August 8, 2019, during the FIREX-AQ field campaign from the cockpit of the NASA DC-8 aircraft. Note the dense smoke at the altitude aircraft fly. Credit: U.S. Navy photo by Dr. David Peterson.

of firefighters and the public from unexpected fire outbursts, abrupt wind shifts, and dense smoke. “We feel that pyroCbs, once considered a rare phenomenon, occur quite often and play a major role in generating such unexpected conditions,” Kuciauskas remarks.

To fill this need, Kuciauskas and his colleagues at NRL are developing a prototype pyroCb prediction tool, funded by the Office of Low Earth Orbit Observations (LEO) Proving Ground Risk Reduction (PGRR) Smoke & Fire and Sounding Initiatives. The goal is to predict weather conditions that might lead to pyroCbs 6 to 12 hours ahead of their onset. The tool relies, in part, on input from the NOAA Unique Combined Atmospheric Processing System (NUCAPS) algorithm that combines data from the Cross-track Infrared Sounder (CrIS) and Advanced Technology Microwave Sounder (ATMS) onboard JPSS satellites. NUCAPS provides near real-time profiles of atmospheric temperature and moisture along with stability parameters that are crucial for assessing convective characteristics associated with pyroCbs. “That is our job as researchers,” stresses Kuciauskas, “to mitigate pyroCb impacts using novel approaches with environmental datasets.” At an April LEO Science Seminar, NRL team members Kuciauskas, Peterson, Andrew Lambert, and Lance Wilson discussed the status and applications of the NRL pyroCb prediction tool.

THE GROWING THREAT OF PYROCBS

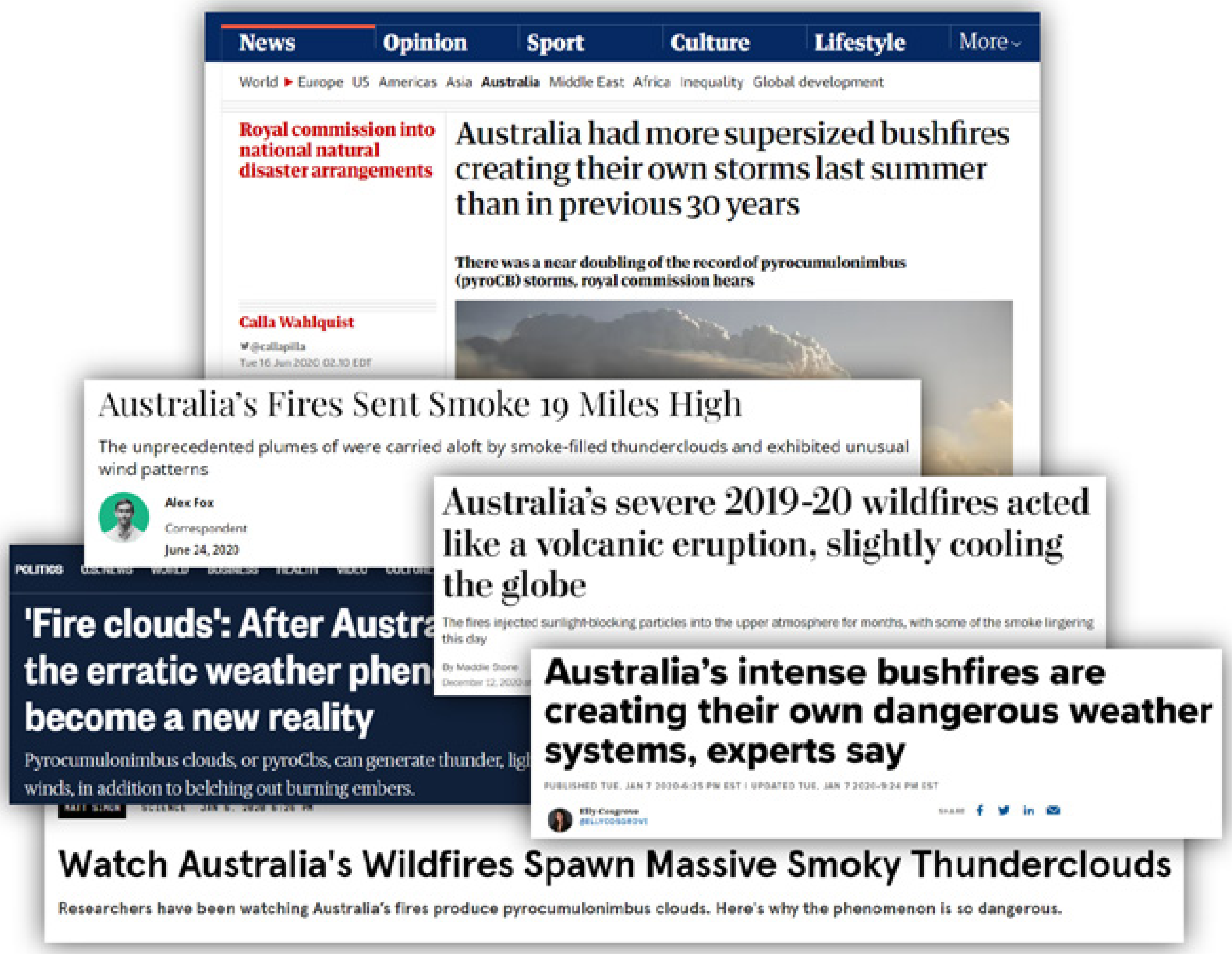
Scientists are still debating whether pyroCb activity will increase because of climate change, since much is unknown about the interaction of pyroCbs within the weather-climate system. Already, more than 700 pyroCbs have been recorded globally since 2013, mostly located in the Western U.S., Alaska, Canada, Australia, and Northern Asia—“regions most conducive for pyroCb development,” says Kuciauskas. Given that atmospheric impacts from the pyroCb phenomenon were discovered by NRL researchers in the late 1990s—in relatively recent times—there is still much to learn.



The distribution of pyroCb events recorded from 2013-2021.

The concept of the pyroCb only recently entered the mainstream. The "super outbreak" of pyroCb activity mentioned above happened during Australia's catastrophic 2019-2020 bushfire season, ominously referred to as "Black Summer." Wildfires scorched nearly 60 million acres and contributed to more than 480 deaths. These events made headlines worldwide, propelling the science-y term "pyroCb" into the public eye. The point: Until recently, pyroCbs were a little known concept even though the phenomenon is not new. Scientists now recognize that, prior to their official discovery, some pyroCb activity was likely misattributed to volcanic eruptions, which can similarly produce large stratospheric smoke plumes.

The newness of the conceptual understanding of pyroCbs feeds into the challenge of predicting these massive fire-induced thunderstorms as scientists are still uncovering the underlying mechanisms by which they form and behave.

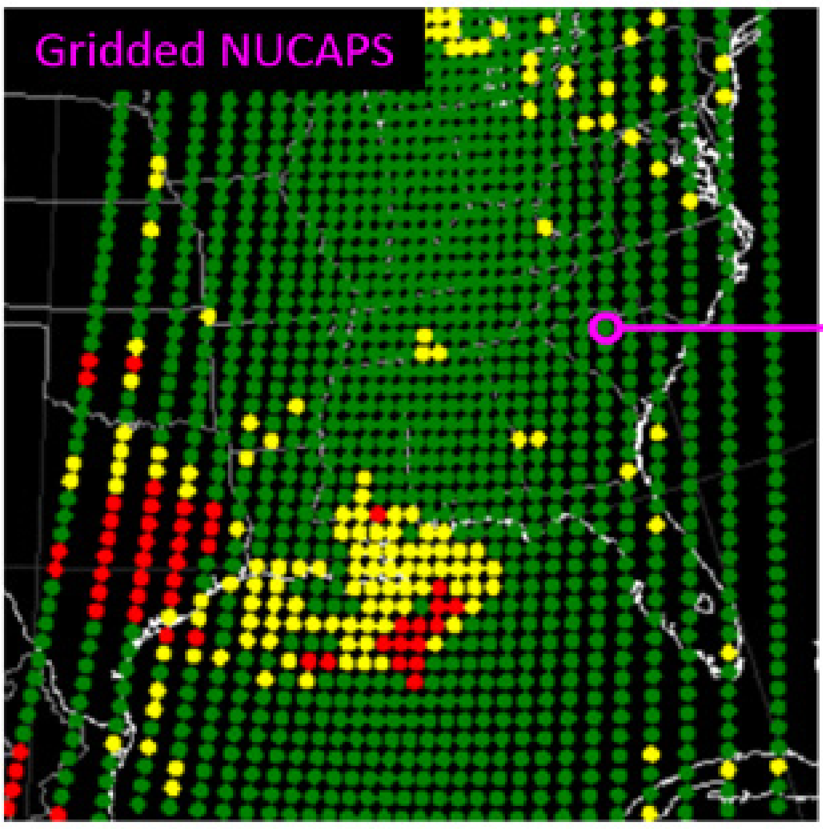


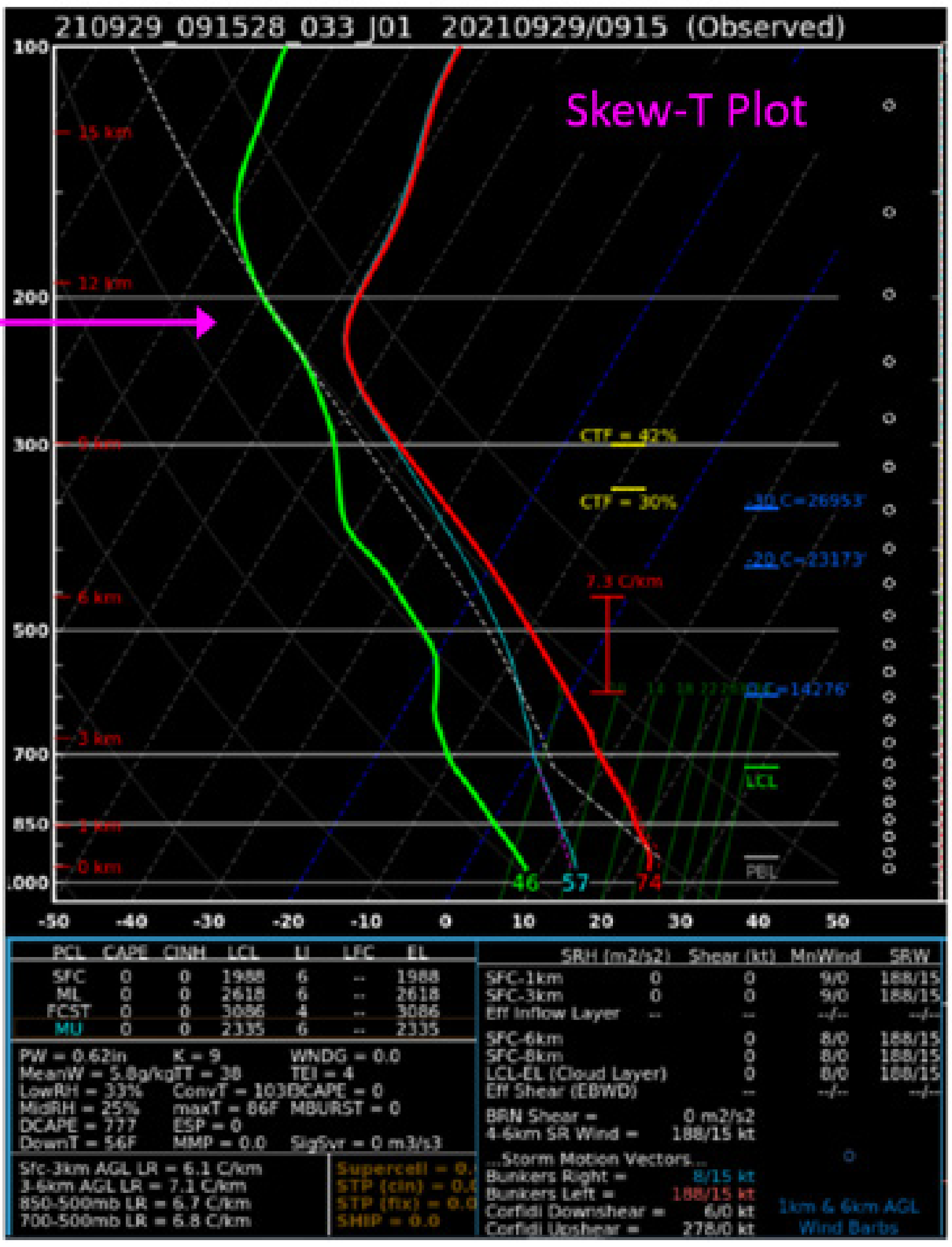
Predicting pyroCb potential is very complicated, requiring examination of terrain characteristics, vegetation type, dryness, local weather, and most importantly, atmospheric thermodynamics. As of today, few operational tools exist to predict pyroCbs, but Kuciauskas and his team at NRL are working to change this.

TRANSFORMING PYROCB PREDICTION WITH SPACE-BASED OBSERVATIONS

"Our goal is to provide risk reduction," Kuciauskas remarks about the prototype pyroCb prediction tool the NRL team is developing. Early warning capability is key for emergency management, which impacts fire operations and public safety alike. The NRL prediction tool takes advantage of atmospheric temperature and moisture profiles retrieved from NUCAPS, an algorithm used to process data from the hyperspectral infrared (IR) and microwave sounding instruments ("sounders") onboard JPSS and MetOp[1] satellites in near real-time.

The Gridded NUCAPS product (gridded for display) provides horizontal and cross-sectional views of temperature, moisture, and other thermodynamic variables that forecasters use to assess atmospheric conditions at different pressure levels/heights (see example below). Additionally, NUCAPS provides thermodynamic profiles onto Skew-T diagrams that allow researchers to estimate the convective nature of an environment, a critical component in the prediction process of pyroCbs. These data and products are accessible to forecasters through various websites and systems, including the Direct Broadcast Network[2] and the Advanced Weather Interactive Processing System (AWIPS), the processing and display system that is the cornerstone of National Weather Service (NWS) operations.





The dots (above) represent the swaths of the satellite overpass. For each dot, a "Skew-T" plot is produced (top right) that describes the conditions in the atmospheric column at that location. From these values, atmospheric stability parameters (bottom right) are derived.

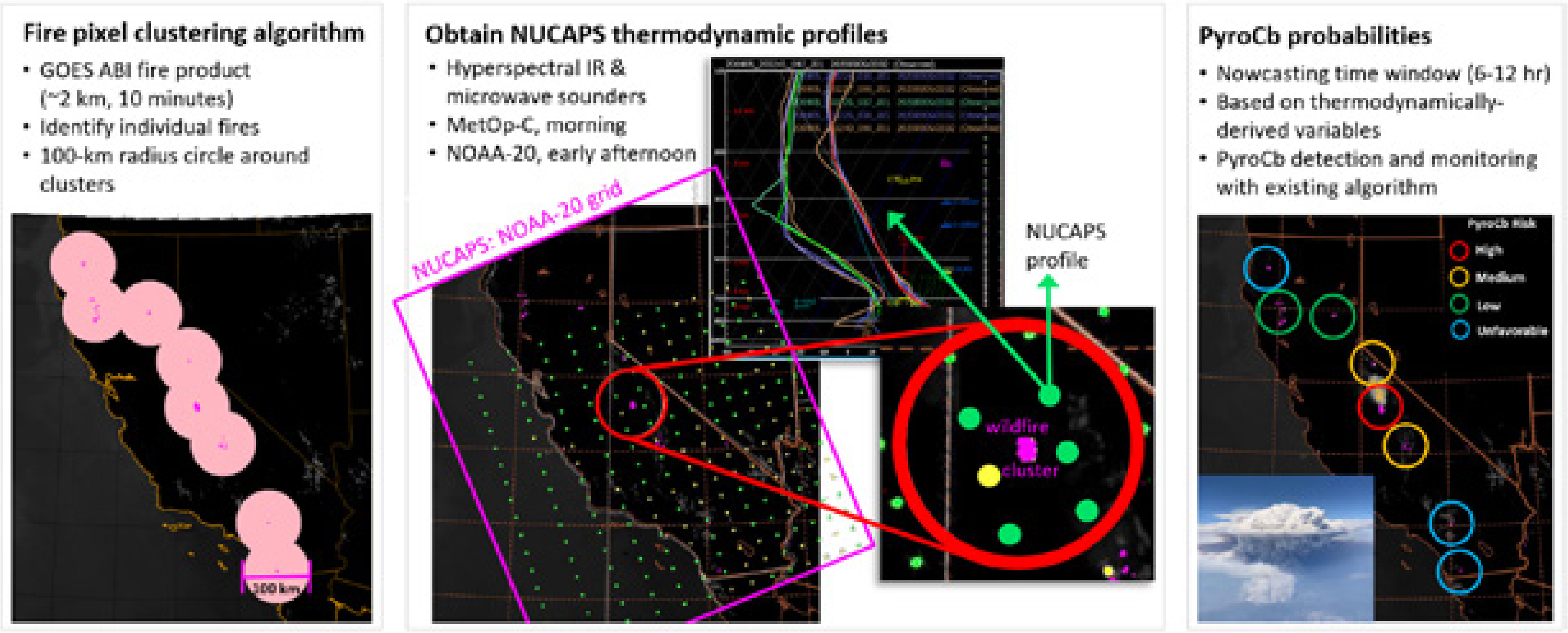
NUCAPS has some limitations. Kuciauskas explains: "To get good data, there needs to be cloud-free, non-precipitating or partly cloudy conditions." Also, since NUCAPS measures a column of the atmosphere (a volumetric measurement), biases vary by atmospheric pressure level. "Uncertainties in NUCAPS measurements of temperature and dew point temperature need to be taken into account when evaluating NUCAPS output throughout the various layers of the atmosphere," Kuciauskas notes. "Also, as uniform cloud cover increases, NUCAPS uncertainty increases." Despite these restrictions, NUCAPS does a good job of measuring through clouds associated with pyroCb phenomena.

NUCAPS Skill in Profiling PyroCbs

NUCAPS has long been used by forecasters to help diagnose atmospheric conditions that produce dangerous thunderstorms. To NRL researchers, the question was whether NUCAPS could also be valuable in profiling conditions that lead to pyroCb formation. Their prediction model was trained using three years of composite NUCAPS profiles from over the Western U.S., Alaska, and Western Canada, to evaluate how well low-level dry, adiabatic conditions (no heat exchange in or out of the system), and mid-level moisture sources are tracked near known wildfire and pyroCb activity. Building on insights from this work led to the development of a prototype that applies a fire pixel clustering technique alongside filtered NUCAPS profiles to identify specific wildfires that are likely to produce a pyroCb. The process (a simplified view is shown on the following page) eventually becomes the product deliverable: a pyroCb prediction tool.

Predicting PyroCbs: A Simplified View

The prediction process starts by identifying individual wildfires using the NOAA 10-minute GOES Advanced Baseline Imager (ABI) Fire Product (dark pink dots in left panel), then defining a 100-km radius circle (shaded pink) around active wildfires clusters, in this case throughout California. Next, NUCAPS profiles are collected from sounders onboard NOAA-20 and MetOp-C satellites from within the 100-km radius and with a starting elevation ≤ 300 meters above the surface, which represents the elevation difference between the wildfire and a potential future pyroCb (middle panel); Skew-T plots are generated from the soundings (see middle panel callout). Informed by these data, 6-hour probabilities of pyroCb formation are calculated and displayed for each wildfire cluster (right panel), with colored circles indicating risk level. Operationally, says Kuciauskas, "this is the product we wish to provide the users."



Meteorological Concepts to Know

Precipitable water (PW) is the measure of the depth of liquid water at the surface that would result after precipitating all the water vapor in a vertical column over a given location, usually extending from the surface to 300 mb.

Potential instability (PI) is the potential ability of an air mass to resist vertical motion. Instability is a prerequisite for severe weather.

Lapse rate (LR) is the rate of change of an atmospheric variable, usually temperature, with height.

Vapor pressure deficit (VPD) is the difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated.

Lifted condensation level (LCL) height is the height at which an air mass become saturated with moisture.

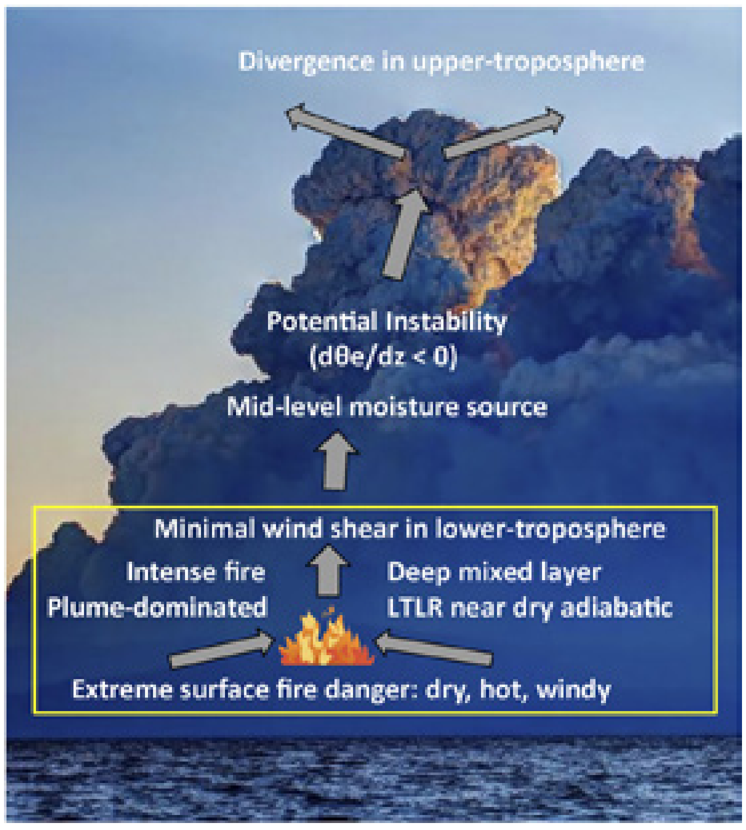
Convective inhibition (CIN) is a measure of the amount of energy needed to initiative convection.

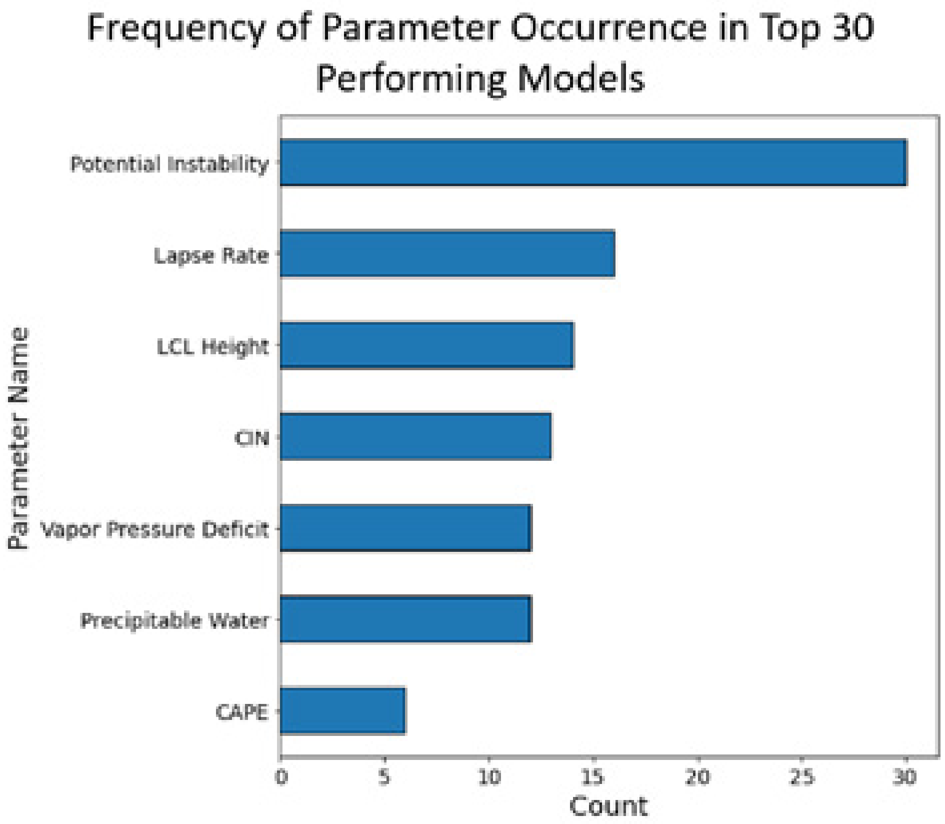
Convective Available Potential Energy (CAPE) is a measure of the amount of energy available for convection.

The tool develops its probabilities from seven moisture and thermodynamic stability parameters that track meteorological conditions that are critical pyroCb ingredients. These parameters, derived from NUCAPS profiles, are precipitable water, potential instability, lapse rate, vapor pressure deficit, lifted condensation level (LCL) height, convective inhibition (CIN), and convective available potential energy (CAPE), defined above (Meteorological Concepts to Know). "This is really an effort to try and build a proxy for feature selection which is used in machine learning," says Lambert. "This is our version, where we're varying the combination of parameters as inputs and monitoring the change in results." The approach enables them to test their model and rank different iterations based on skill scores.

Lambert continues: "We built our model for every possible combination of these seven inputs [parameters] possible. This means we may have used two of them as inputs or all of them as inputs, but we built it for every possible combination and ranked them according to their skill and prediction." The graph at the bottom of the next page shows how frequently each parameter appeared in the top 30 performing models. "If you start at the top," he explains, "potential instability appeared all 30 times, indicating that it is a useful predictor—perhaps the most useful predictor—out of the parameters available for pyroCb prediction." These most useful predictors compare well with the image below depicting the necessary ingredients for pyroCb formation, "which supports confidence in using NUCAPS-derived variables as inputs to a predictive model," Lambert notes.

The path to get to this point was far more involved than described here. The NRL team has spent more than two years using machine learning to collect the most impactful NUCAPS parameters, analyzing NUCAPS and climatology data, and compiling information about past pyroCb events to better understand when and





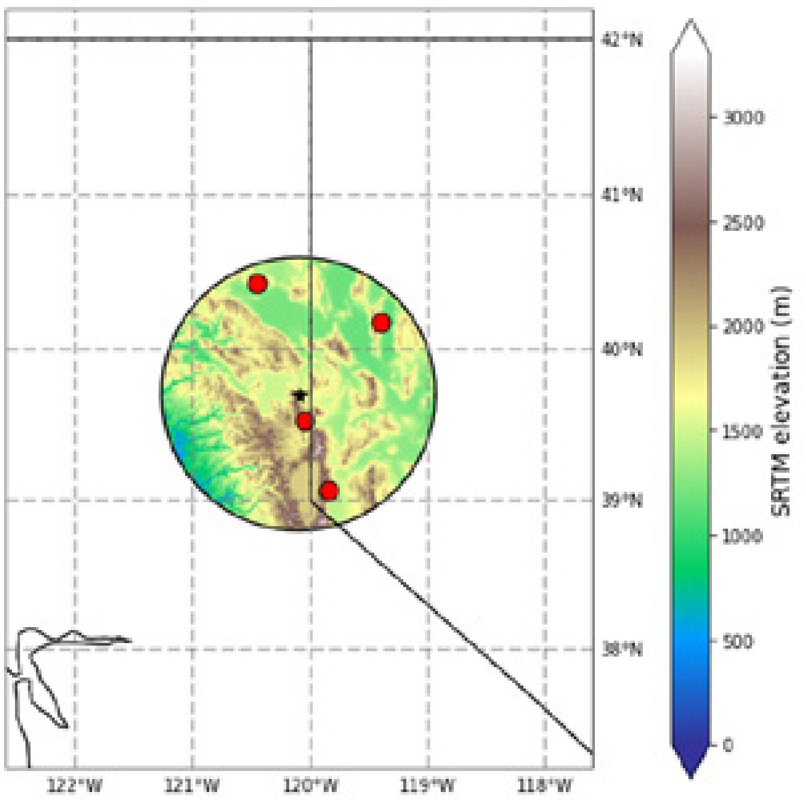
Left: A conceptual model of the necessary ingredients for pyroCb formation. Source: Peterson et al. 2017. Right: Frequency of parameter occurrence in the top 30 performing pyroCb prediction models. Source: U.S. Naval Research Laboratory.

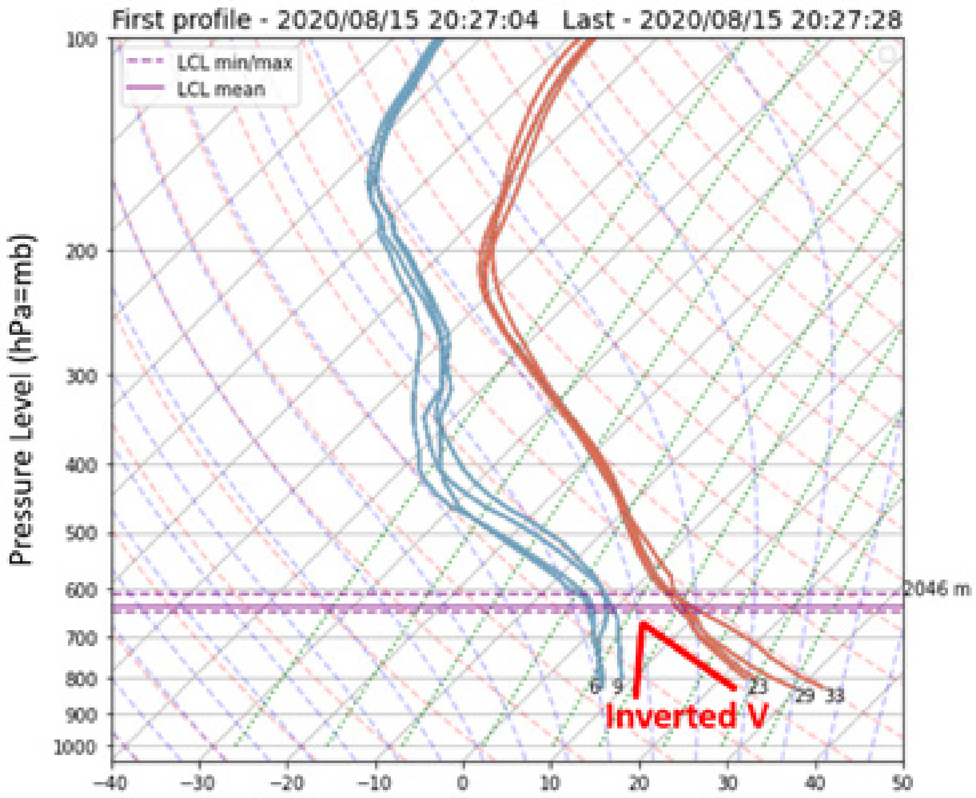
why some intense fires produce pyroCbs and others don't. Their model follows established climatology, and the prototype prediction tool confidently produces a 78% probability of detection with a 16% false alarm rate—a very encouraging result.

Predicting a PyroCb: A Test Case

On August 15, 2020, the Loyalton Fire, which burned more than 47,000 acres over several days across parts of California and Nevada, spawned a monstrous pyroCb that produced an EF-1 tornado and prompted the first ever fire tornado warning by the NWS. Recognition before a pyroCb event is critical, and an Incident Meteorologist (IMET) working that day had seen something similar with the Carr Fire a couple of years prior. This familiarity helped NWS identify conditions favorable for pyroCb development during the Loyalton Fire. With pyroCb activity of this significance, the question was, could the NRL pyroCb tool have predicted it?

Using the Loyalton Fire as a test case, "our model calculated an 80% probability of a pyroCb occurring, so it did very well for this event," verifies Lambert. Looking at the





Left: The location of four NUCAPS profiles (red dots) collected within 100-km of the Loyalton Fire between 20:27:04 UTC and 20:27:28 UTC on August 15, 2023. Right: Skew-T plots for the four NUCAPS profiles (left), along with lifted condensation level (LCL) minimum and maximum at approximately the time of the NUCAPS profiles.

details, the team collected four NUCAPS profiles from within a 100-km radius of the Loyalton Fire and before pyroCb formation (below left), and generated Skew-T plots for each profile (below right). "Note the 'inverted V' indicating dry conditions near the surface and some mid-level moisture and instability," Lambert explains. (The "inverted V" shape is indicative of pyroCb development.)

BRIDGING THE GAP BETWEEN RESEARCH AND END USERS

While NRL researchers continue to test and build the prediction tool, they are also addressing another important matter: getting the tool into the hands of those who matter most, the front-line firefighters. "We are providing weather agencies this model," says Kuciauskas, "but NRL is not an operational center, it is primarily a scientific research lab. As this prototype gains acceptance, we are willing to assist in the operational aspects to NOAA or other fire agencies."

In the meantime, NRL has embarked on a broad outreach campaign targeting NWS IMETs who provide fire support across the U.S. by interpreting weather data and assessing its impact on fire, then communicating it to responders on the ground to help them create an operations strategy. Kuciauskas notes that thanks to the IMET community, there is a "rich and dynamic feedback system between developer and user to capture feedback on the [prediction] product."

Kuciauskas is also engaging with NWS Science Operations Officers, IMETs, air quality forecasters, and agencies like the U.S. Forest Service and National Interagency Fire Center through prototype demonstrations. "Part of our outreach effort includes training on pyroCbs and our experimental website," he explains.

Understanding pyroCbs is of great importance, as the frequency and intensity of wildfires have been increasing in recent decades. With a better grasp of these fire-induced storms, scientists can develop more effective firefighting strategies, provide better early warning to the public, refine weather prediction models, and gain insights into potential climate implications.

Above Left: Morning weather briefing to fire crews at Six Rivers Lightning Fire in Northern California on August 23, 2022. Source: NOAA. Above Right: Firefighters on the ground fight an active forest fire. Source: U.S. Forest Service.

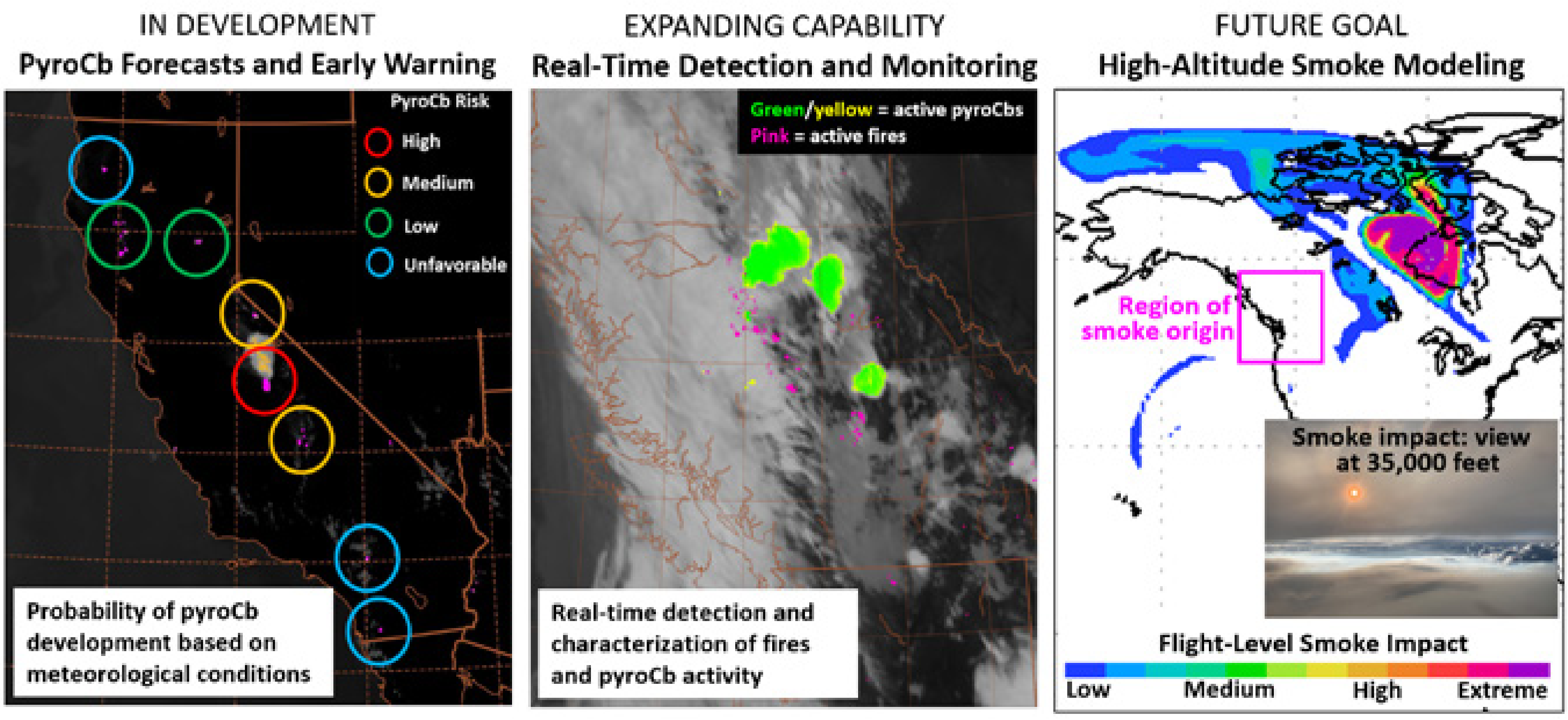
WHAT'S TO COME

Kuciauskas and his team continue to engage with fire and weather communities, with plans to demonstrate the prototype NRL pyroCb prediction tool for NWS, forest agencies, and public health agencies by the end of the 2024 fire season (June - September) or sooner. Development continues to prepare the tool for operational use, and on NOAA's web-based interfaces. NRL is working toward a product with a look and feel similar to those on the NOAA Storm Prediction Center's Mesoscale Analysis web page. "We want users to feel familiar with the product," explains Kuciauskas.

NRL's broad pyroCb research and development goals are illustrated below. One recent development, Kuciauskas says, is "we have developed a satellite display homing in on real-time features of active pyroCbs [middle panel below]—pink indicates the wildfires, and the greens and yellows indicate signatures of the pyroCb. It's a very good quick look in terms of the activity especially related to pyroCbs." A future quest is to develop a model for monitoring smoke produced by pyroCb events (right panel).

NRL's plans are very promising for fire and weather communities. With the recent launch of NOAA-21 in November 2022, the JPSS suite now consists of three satellites that fly over every spot on the planet twice daily and more frequently at higher latitudes. Together with European MetOp satellites, there will be greater coverage in both spatial and temporal coverage. This means more skillful NUCAPS profiles will be available for the NRL pyroCb prediction tool.

Still, questions remain. Within the vicinity of wildfires, "there are many, many unknowns in terms of how the fire characteristics relate to the plume dynamics, which then feeds cloud development and other feedback mechanisms," points out Dr. Peterson. "This isn't resolved well in any modeling applications either," he remarks, noting that field experiments are necessary to answer these types of questions. Bottom line: more work is needed.



Predicting pyroCb events is of great importance for mitigating the significant threat they pose to public safety, air quality, and ecological systems. By accurately forecasting pyroCb events, emergency response agencies can efficiently allocate resources and implement timely evacuations to protect communities at risk. Moreover, early detection of pyroCb formation allows for better coordination in firefighting efforts, preventing the escalation of wildfires into uncontrollable levels. Emphasizing the significance of pyroCb prediction underscores the need for ongoing research at NRL and elsewhere to enhance the ability to forecast and respond to these hazardous fire-driven phenomena. ✦

STORY SOURCE

The information in this article is based, in part, on the April 17, 2023, LEO Science Seminar titled, "Predicting Pyrocumulonimbus (pyroCb) Events Through Remote Sensing Resources in Support of National Weather Service and Firefighting Agencies," presented by Arunas Kuciauskas, Meteorologist and Principal Investigator, U.S. Naval Research Laboratory-Marine Meteorology Division, and Andrew Lambert, Meteorologist, General Dynamics Information Technology, with contributions from Drs. David Petersen and James Campbell, U.S. Naval Research Laboratory-Marine Meteorology Division, and Lance Wilson, General Dynamics Information Technology.

FOOTNOTES

1 MetOp (Meteorological Operational satellite) is a series of polar-orbiting meteorological satellites developed by the European Space Agency.

2 The Direct Broadcast Network is a worldwide network of local receiving stations that allows for real-time acquisition and rapid delivery of polar-orbiting satellite data to the global user community.

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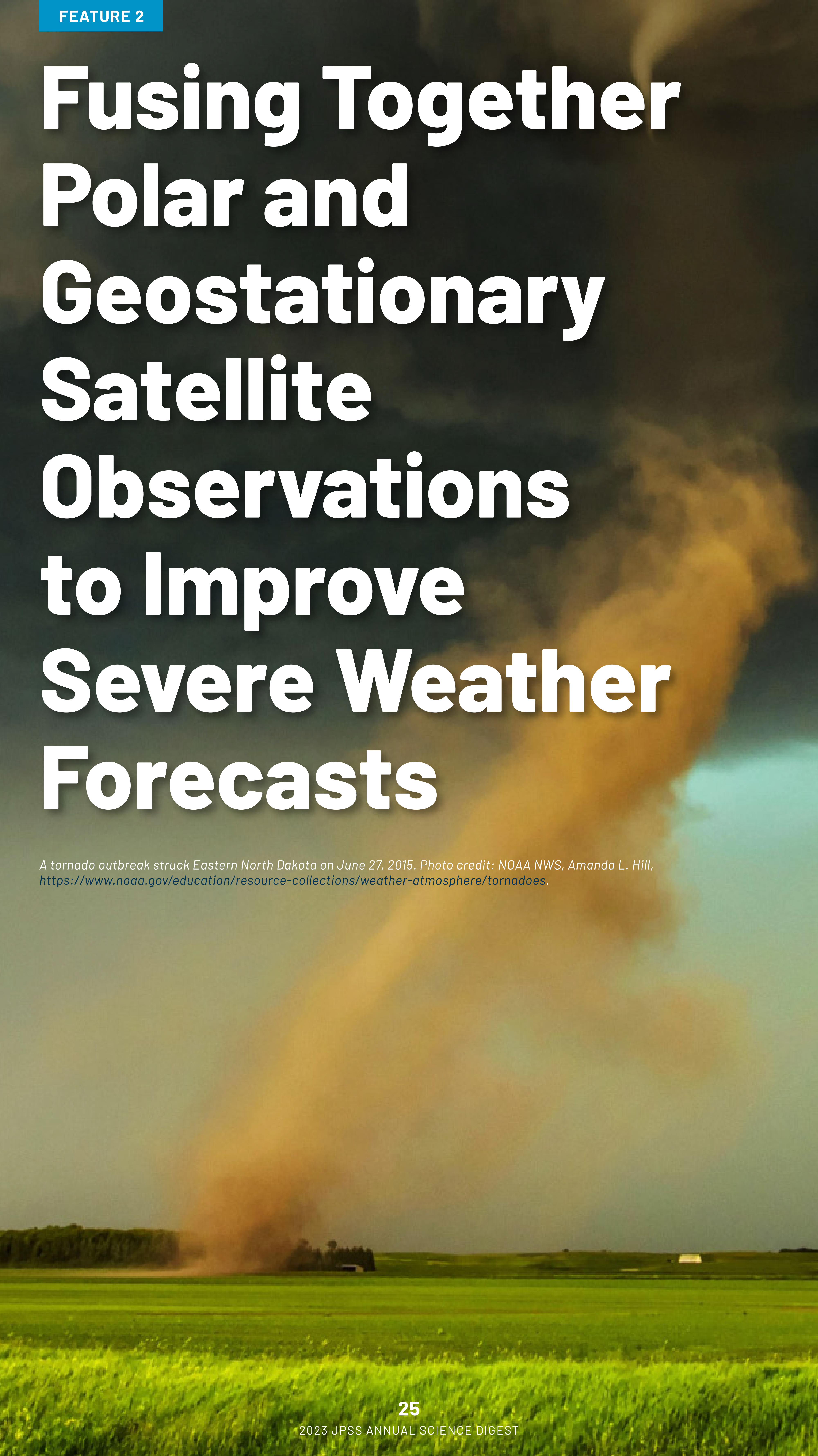
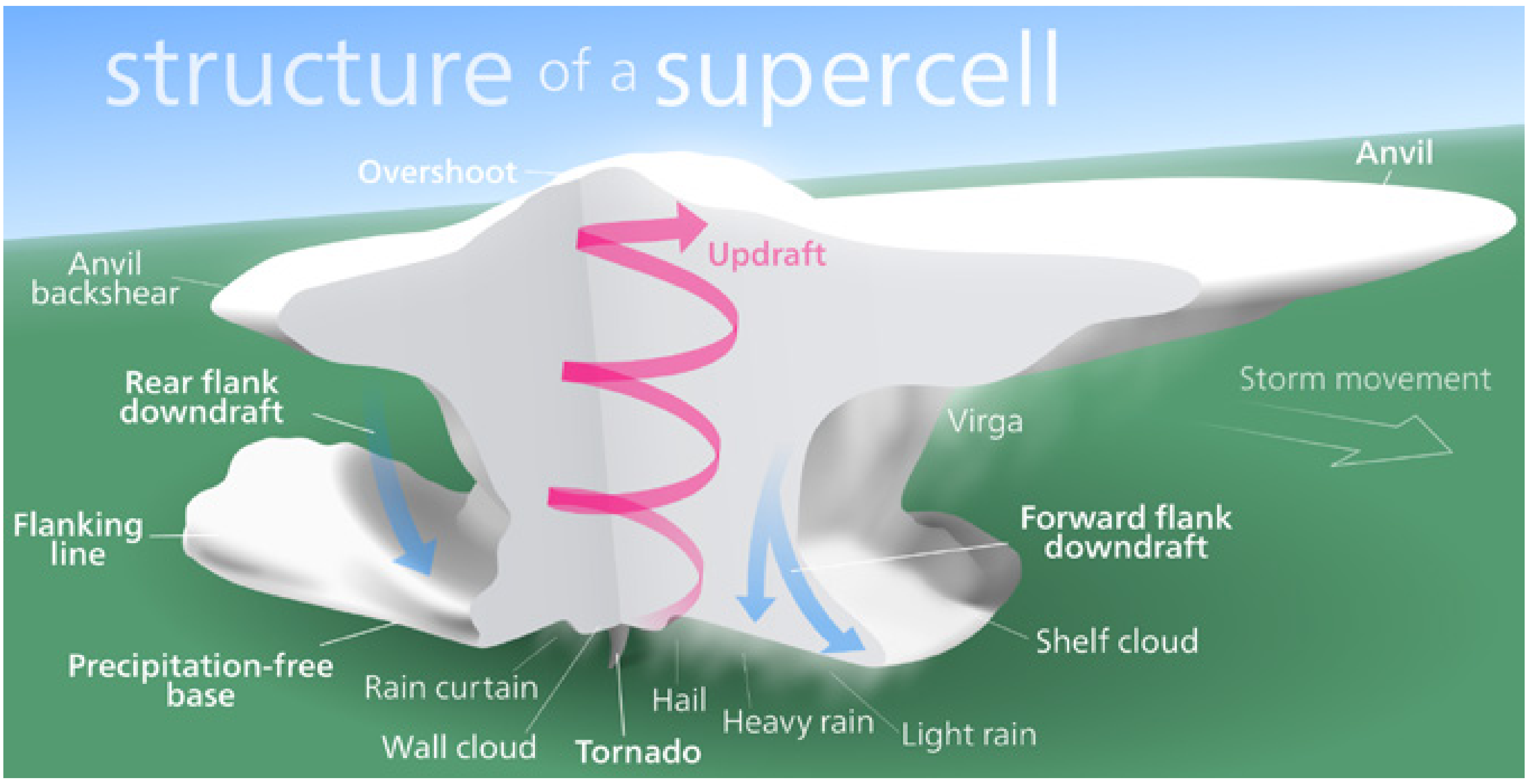
FEATURE 2

Fusing Together Polar and Geostationary Satellite Observations to Improve Severe Weather Forecasts



A tornado outbreak struck Eastern North Dakota on June 27, 2015. Photo credit: NOAA NWS, Amanda L. Hill, https://www.noaa.gov/education/resource-collections/weather-atmosphere/tornadoes.



Typical structure of a supercell (northwest view in the Northern Hemisphere). Source: Wikipedia Creative Commons. Credit: Kelvinsong, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=25259965

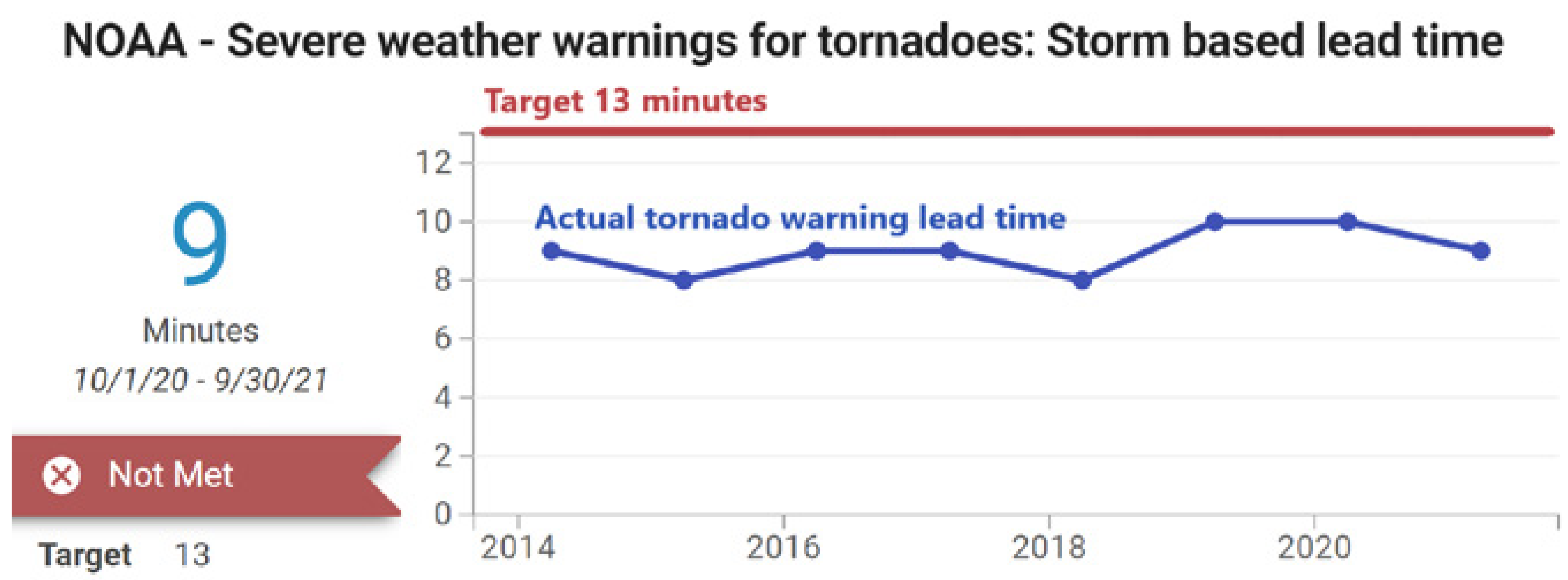
Damaging winds, heavy rain, lightning, tornadoes, and large hail are among the many dangerous events caused by a type of severe thunderstorm called a supercell. On moist, hot days, thunderstorms form when surface heat pushes moisture and other particles up into the atmosphere by a process called convection. In supercells, the updraft—known in meteorology as a mesocyclone—is deep, persistent, and rotating, and violent weather like tornadoes can form within it. While most common in the spring across the Central U.S., supercells can form any time of year and in any state. As the climate continues to change, they are expected to become more frequent, more widespread, and more intense.

Convection

In meteorology, the term "convection" is used to describe vertical transport of heat and moisture in the atmosphere, especially by updrafts and downdrafts in an unstable atmosphere. The terms "convection" and "thunderstorms" often are used interchangeably, although thunderstorms are only one form of convection.

Source: National Weather Service Glossary

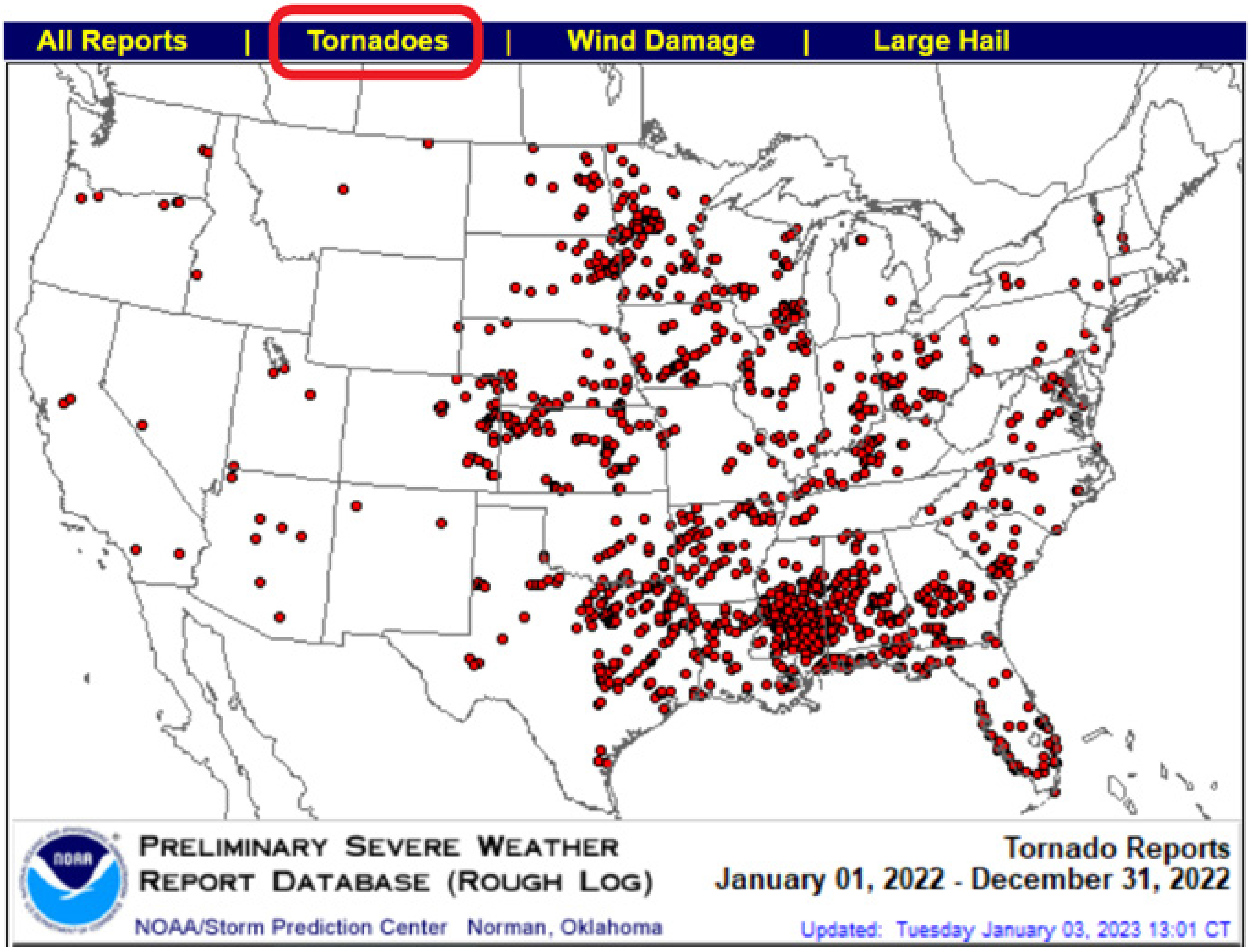
Meteorologists at National Weather Service (NWS) Weather Forecast Offices use radar, ground sensors, radiosondes, satellites, and numerical weather prediction models to assess winds, atmospheric pressure, temperature, and moisture to determine if a supercell thunderstorm is likely to form. But predicting the tornadoes that develop inside them is tricky. While supercells are characterized by an updraft rotation, it can be hard to know whether one will produce a tornado, and even if conditions are right a tornado may never materialize. But when they do, they can appear and disappear quickly, making it a challenge for forecasters to alert the public before disaster strikes. Unlike slow-moving hurricanes that are monitored for days in advance of landfall, the typical warning lead time for a tornado (the time

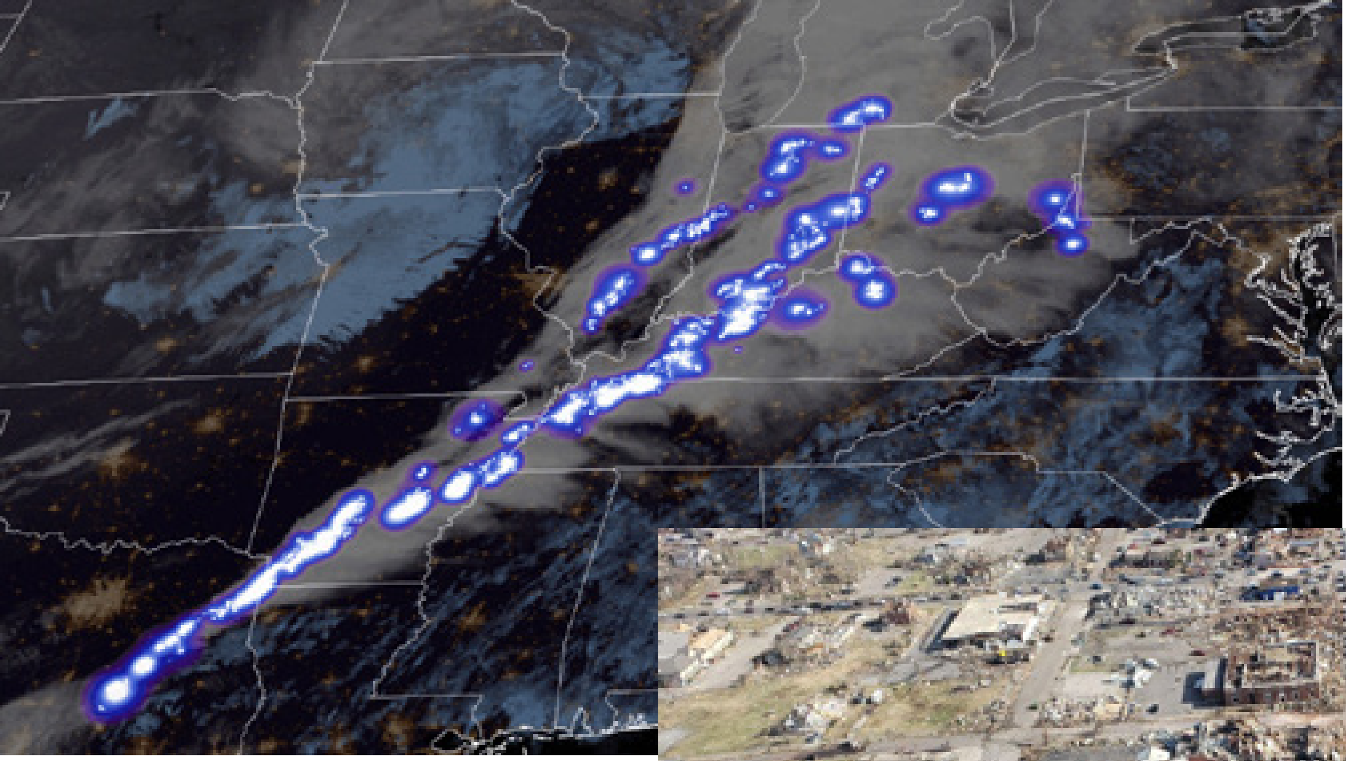


Source: https://performance.commerce.gov/

difference between when a warning is issued and tornado touchdown) is only about 8 to 10 minutes. The public is faced with considering actions during a tornado watch that may be unnecessary if no tornado forms, or delaying their decision and not leaving enough time to safely seek shelter.

In the past 15 years, tornadoes have damaged homes, cars, roads, utilities, crops, factories, and natural resources, and caused more than 1,200 deaths in the U.S. Decreased economic activity from lost production, sales, and incomes, surging gas prices, food and goods shortages, reduced tourism, and widespread power outages are just some of the impacts faced by affected communities. Heavy precipitation, strong winds, and large hail that may accompany tornadoes can magnify the losses. In fact, damages have been identified at about $200 billion[1] from 2008 to 2022 just for U.S. billion-dollar tornadic events.





Left: A view from NOAA's GOES-16 satellite taken at 11:46 pm CST on December 10, 2021, shows the extent of a multi-state tornado outbreak that caused $4.1 billion in damages and cost 93 lives in the Central and Southern U.S. Source: NOAA/CIRA.

Right: An aerial photograph shows the devastation from the December 10, 2021, tornado outbreak in Mayfield, Kentucky. Source: National Weather Service.

Billion-dollar disasters are occurring in the U.S. at an increasing rate—on average, one every 18 days in the past five years compared to one every 82 days in the 1980s—and tornado outbreaks are no exception. The December tornado record was smashed in 2021 with a whopping 232 confirmed touchdowns. The following year, 2022, saw the most tornadoes on record in March with 234, well above the average of 80 for that month. With words like "historic" and "unprecedented" peppering headlines, accurate weather data and advanced warnings are more important than ever.

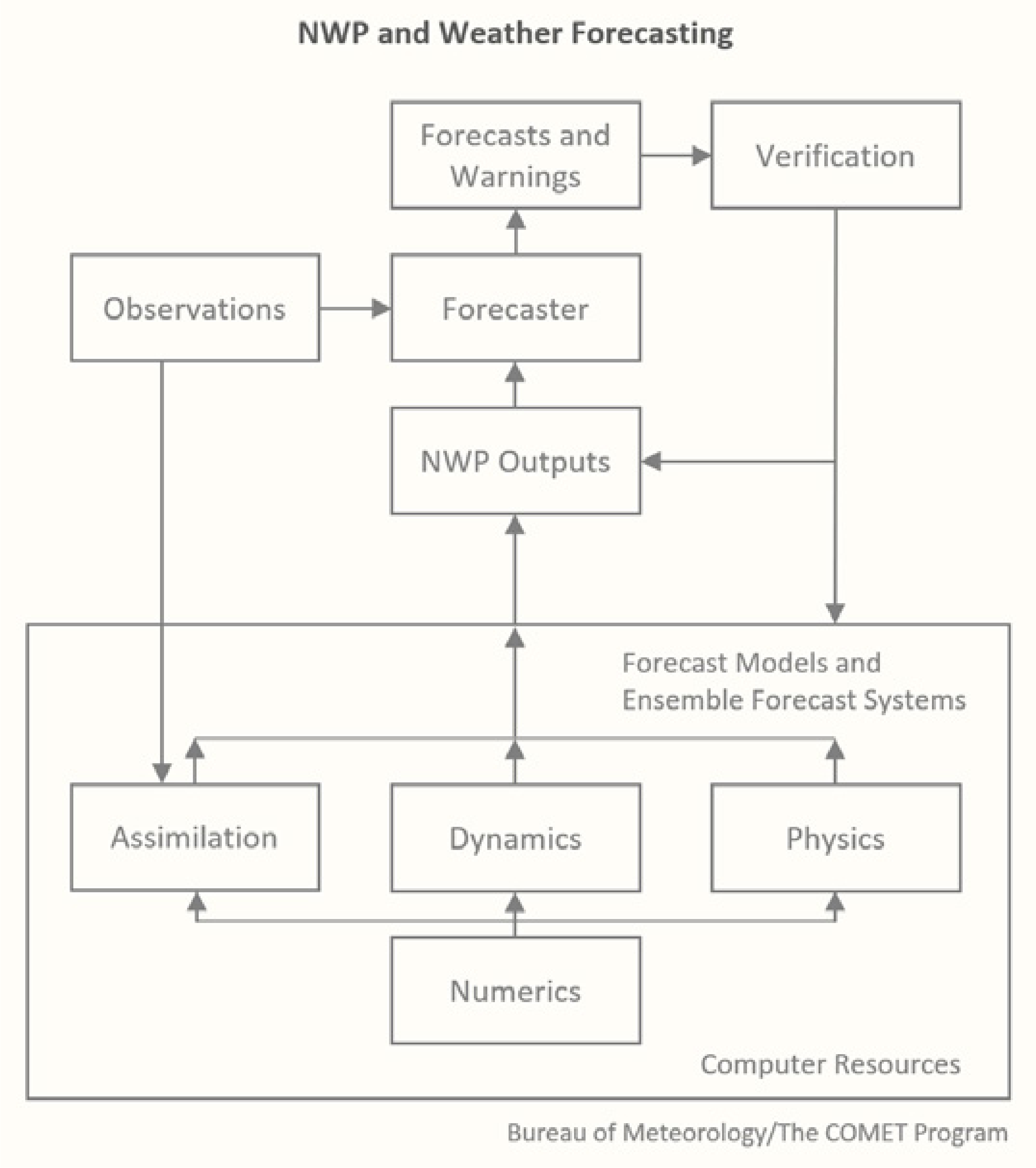
Here is the challenge: Forecasters need higher resolution atmospheric data to better anticipate when a tornado will form so that more timely warnings can be issued to protect lives and property. One potential game changer is a planned hyperspectral infrared (IR) sounding instrument onboard the next generation of NOAA geostationary satellites, the Geostationary Extended Observations (GeoXO) satellite system planned for operation in the early 2030s. This instrument, the GeoXO Sounder, is expected to significantly improve observation of rapidly evolving weather events like supercells by providing near real-time high resolution vertical profiles of atmospheric moisture and temperature and high resolution profiles of wind velocity, a capability not currently available at a high cadence from any single operational U.S. satellite instrument.

To prepare for the use of these data, a team led by Dr. William L. Smith Sr., considered by many to be "the father of satellite atmospheric sounding," developed and validated a product that combines polar and geostationary observations from operational NOAA JPSS and GOES satellites to simulate the data expected from next generation geostationary hyperspectral ("geo-hyperspectral") IR sounders. Dr. Smith, senior scientist at the Cooperative Institute for Meteorological Satellite

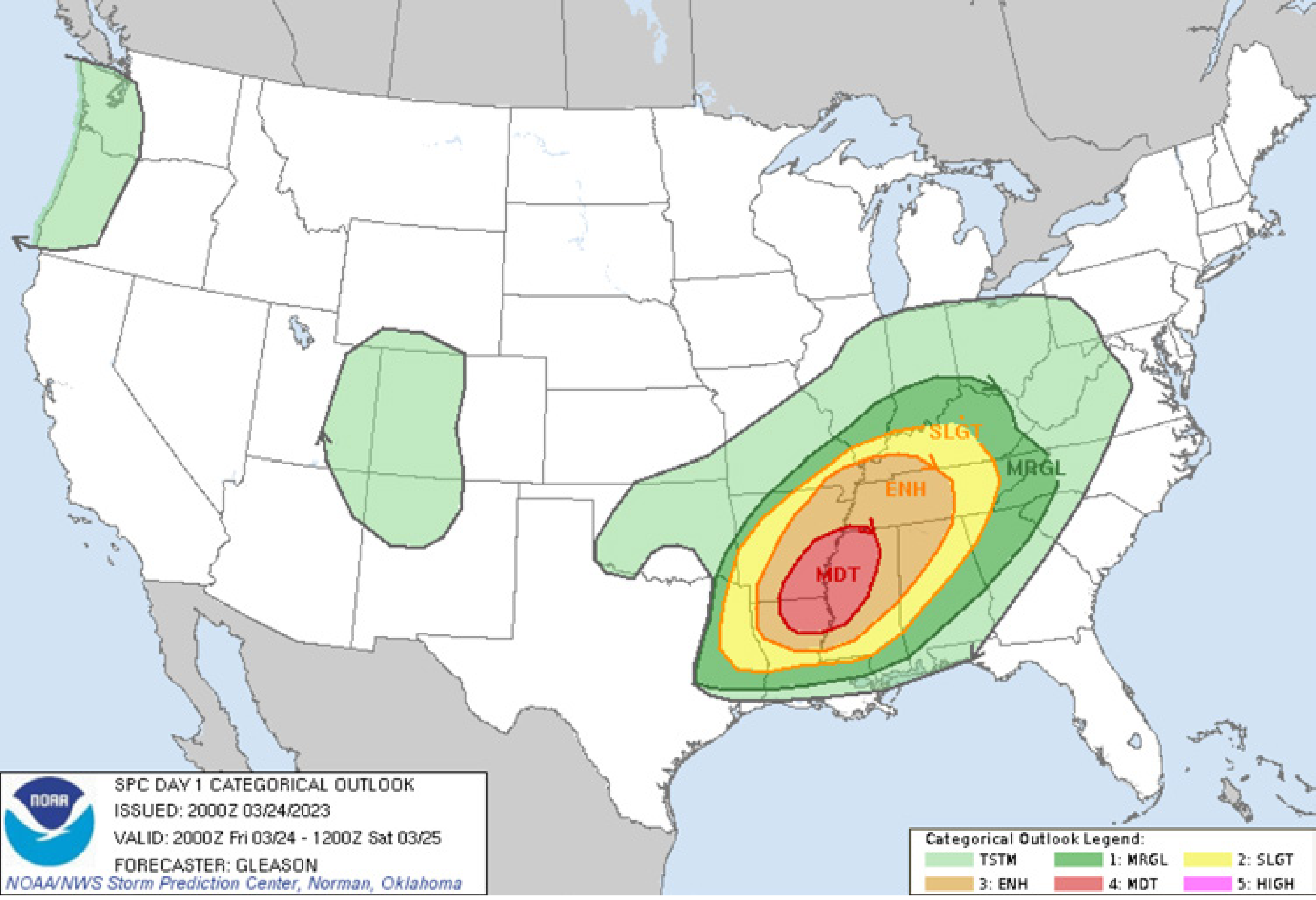
Studies (CIMSS) at the Space Science and Engineering Center/University of Wisconsin-Madison, professor emeritus at University of Wisconsin-Madison, and distinguished professor at Hampton University, provided an overview of this product and it demonstrated benefits for severe weather prediction at the October 2022 LEO Science Seminar.

THE IMPORTANCE OF NUMERICAL WEATHER PREDICTION IN SEVERE WEATHER FORECASTING

Numerical weather prediction (NWP) models are a critical tool for meteorologists to help them decide when conditions might be favorable for severe weather. These powerful and complex computer programs represent the evolution of the atmosphere by using current weather conditions to predict future temperature, precipitation, wind speed and direction, and hundreds of other meteorological elements. As new observations—from satellite, airborne, or ground sensors—become available, these data are assimilated into the model, which then updates its forecast to align with the newly observed conditions. The update (analysis) cycle continues throughout a model's forecast period, which can range from a few hours to a few days or longer.



This flowchart represents a simplified summary of the forecast process and the roles of observations, models, and human forecasters. Source: UCAR MetEd/The COMET Program.

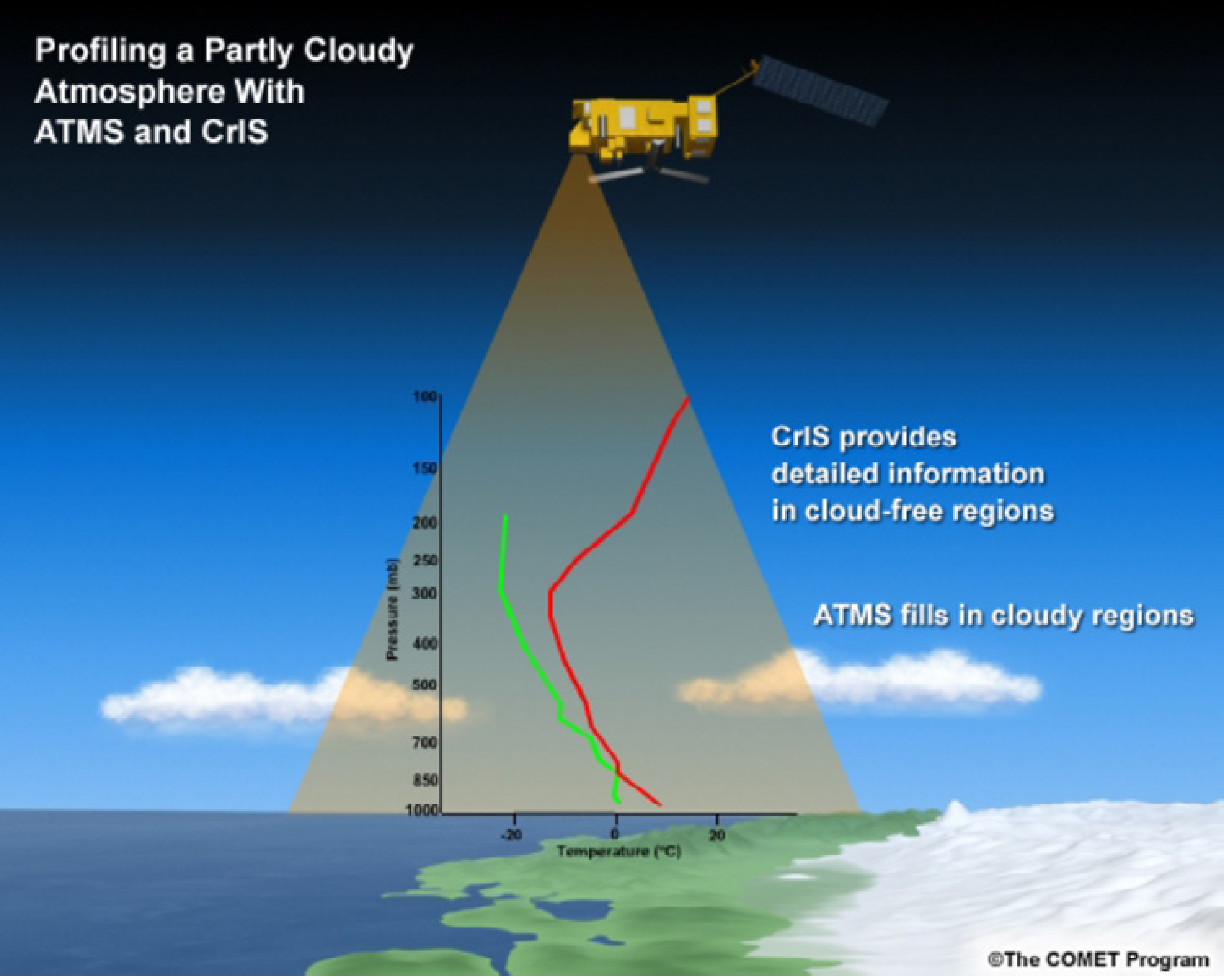


The March 24, 2023, 2000 UTC Day 1 Convective Outlook shows enhanced (orange) to moderate (red) risk of severe weather across the Southern U.S. through March 25, 2023, 1200 UTC. Source: NOAA/NWS Storm Prediction Center.

NWP models also generate critical data to the NOAA/NWS Storm Prediction Center (SPC) in Norman, Oklahoma, to help generate convective outlooks, watches, and mesoscale discussions for the continental U.S. As "the trusted source for the prediction of tornadoes and other high-impact hazardous weather," SPC's forecast products and services provide essential information for the reduction of weather-related losses and protection of life and property. On the next page is an example of an SPC convective outlook product. In this Day 1 Convective Outlook issued on March 24, 2023, enhanced (orange) to moderate (red) risk of severe weather was predicted across the Southern U.S. for March 24-25. This outlook proved true with the region experiencing severe storms and 31 tornadoes in this period.

SATELLITE SOUNDERS AND THEIR CONTRIBUTION TO FORECASTING

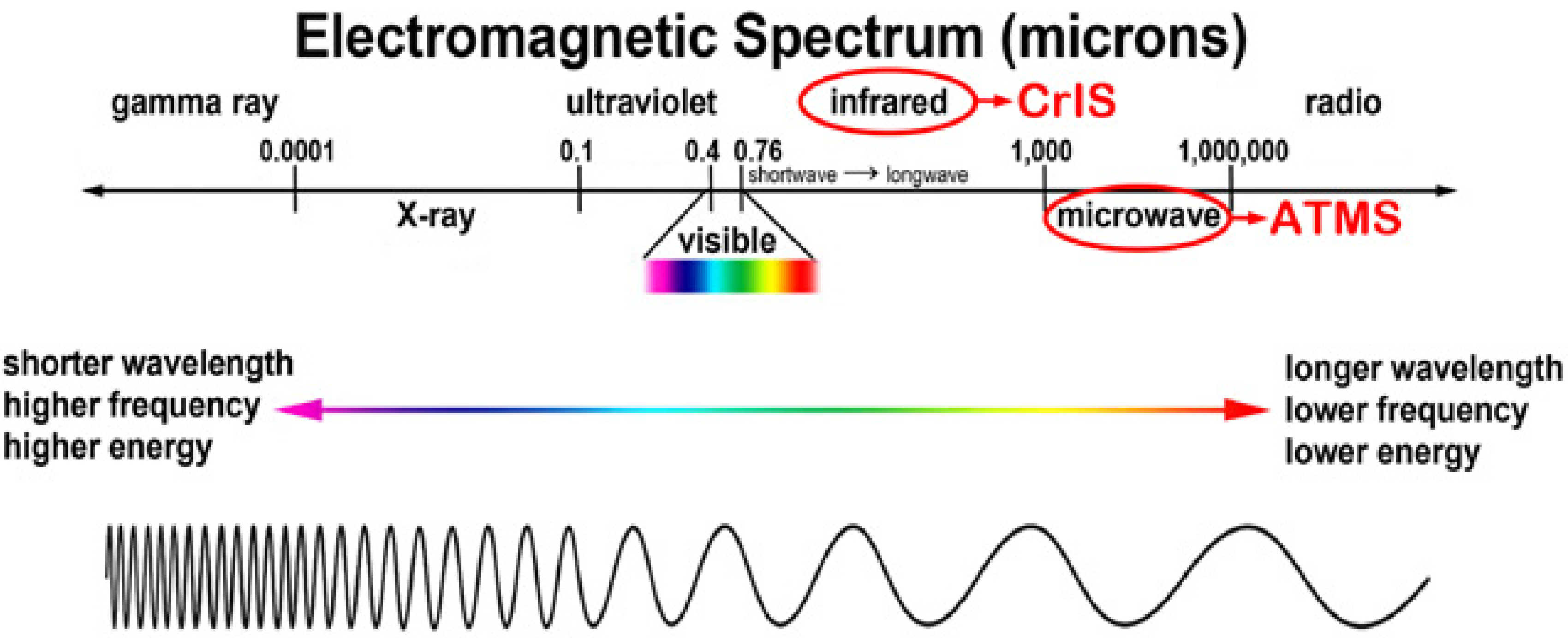
NWP models rely on data from sensors onboard satellites, aircraft, weather balloons, and ships, as well as from surface instruments. One benefit of space-based sensors over the other instruments is that satellites continuously take measurements of the Earth's atmosphere. The JPSS suite of polar-orbiting satellites, also referred to as low-Earth-orbiting (LEO) satellites, fly two sounders that can be used to identify the areas of instability where convection is likely to happen. These two vital sensors are the Cross-track Infrared Sounder (CrIS) and the Advanced Technology Microwave Sounder (ATMS). As their names imply, CrIS measures infrared radiation and ATMS measures microwave radiation. Each provides information about the vertical distribution of atmospheric temperature,



CrIS provides detailed information in cloud-free regions. ATMS fills in cloudy regions. Credit: UCAR/The COMET Program.

moisture, and other parameters. In other words, how conditions change with altitude. These polar-orbiting sounders provide this data at a much higher horizontal resolution than any current or future geostationary sounder, and with multiple JPSS satellites currently in orbit, multiple passes are available to forecasters.

With CrIS, infrared energy is vulnerable to atmospheric absorption, causing a reduction in intensity as the energy propagates toward space and cloud ice particles and water droplets absorb the radiation passing through them. Because of this, infrared energy cannot penetrate optically through clouds, so CrIS does not "see" below them in cloudy weather. Microwaves are a different story—their



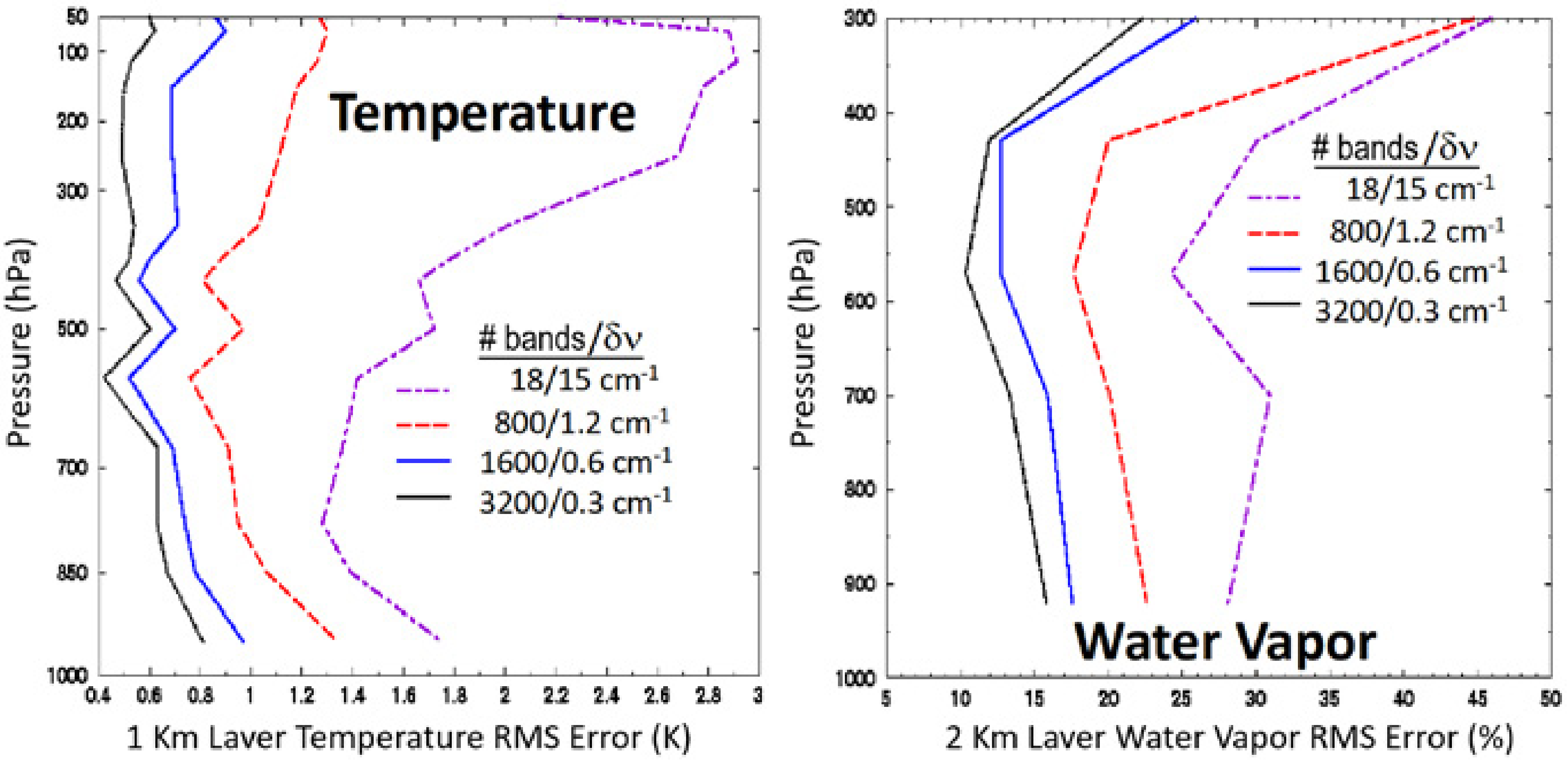
Comparison of wavelength, frequency, and energy for the electromagnetic spectrum. The JPSS CrIS and ATMS instruments measure infrared and microwave wavelengths, respectively. Credit: NASA Imagine the Universe.

longer wavelengths are not susceptible to non-precipitating cloud absorption. Because of this, ATMS can retrieve data in all weather conditions enabling it to measure atmospheric layers missed by CrIS in cloudy conditions. CrIS and ATMS are frequently used together because, Smith explains, "using microwave data along with infrared data fills in the information below the clouds."

Another difference: CrIS is hyperspectral, meaning that it has thousands of spectral bands or channels—the regions within the electromagnetic spectrum where it collects radiant energy—whereas ATMS is multispectral, having just 22 channels. Higher spectral resolution means the sensor "sees" a greater number of layers of the atmosphere, which translates to more detailed vertical profiles and improved accuracy.

"The main source of error in satellite retrievals is the lack of vertical resolution—the 'null space,'" says Smith, "but the vertical resolution and accuracy increase by a factor of two to three going from multispectral to hyperspectral resolution." Below, vertical profiles of temperature and water vapor from four instruments illustrate this concept. While sounding accuracy varies by the atmospheric layer observed (measured as atmospheric pressure, hPa), instruments with the fewest bands have higher prediction errors (indicated by root-mean-square (RMS) error along the horizontal axis). As the number of bands increase from 18 (purple line) to 3,200 (black line), prediction error decreases. Measuring across thousands of bands enhances vertical resolution, which means better sounding accuracy.

The key takeaway message is that hyperspectral IR sounders like CrIS are highly effective at providing accurate and detailed vertical profiles of temperature and moisture (as well as horizontal winds and trace gases) at multiple layers of the atmosphere. These data, when assimilated into NWP models, significantly improve model forecast skill. The problem, when talking about rapidly changing supercell



Sounding root-mean-square (RMS) error as a function of spectral resolution and associated number of spectral radiance bands. Source: Smith Sr. et al. 2009.

storms, is that the current generation of operational hyperspectral IR sounders[2] fly on polar-orbiting satellites. The issue: revisit time.

Polar Orbit and Geostationary Orbit: What's the Difference?

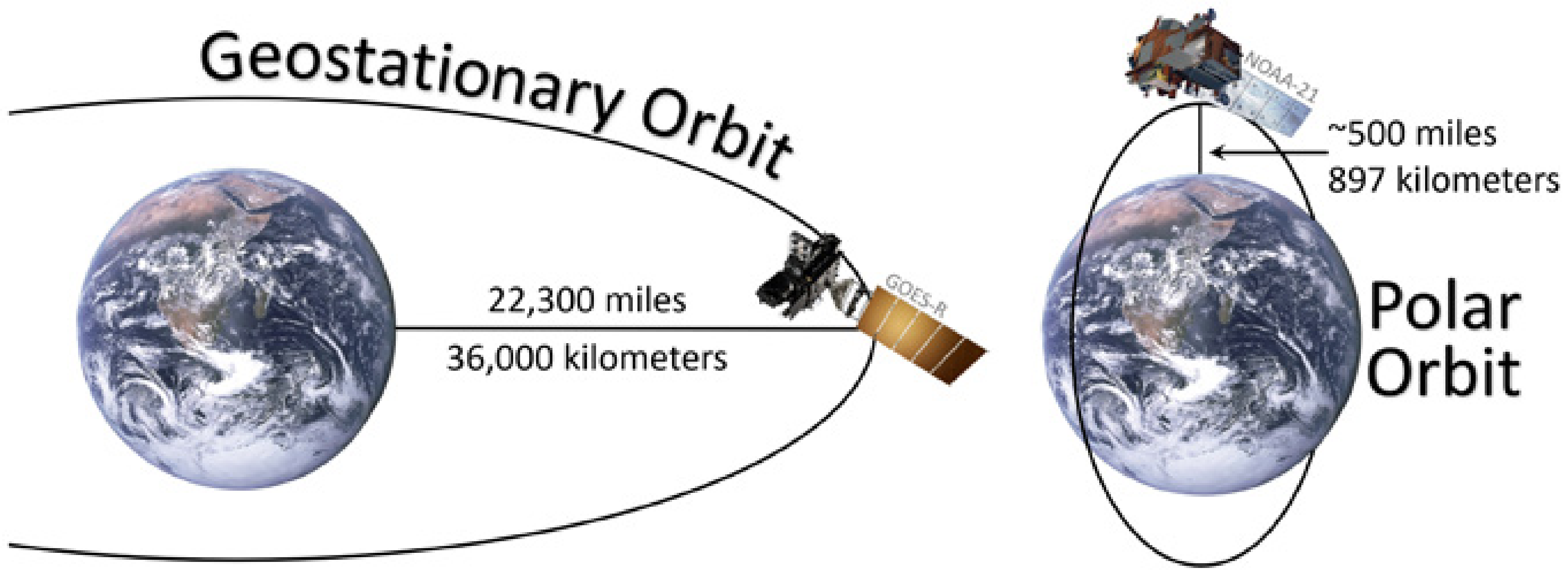
Polar-orbiting sounders like CrIS and ATMS provide some of the most important observations used in NWP models to predict convective weather several days in advance. But on their own they are less valuable for monitoring supercells because of their temporal resolution—the time it takes for a satellite to revisit the same spot on Earth (complete an orbit). For instruments in polar orbit, revisit times range from several hours to several days. CrIS, for instance, circles the Earth pole-to-pole providing high resolution vertical profiles of the atmosphere on a global scale—an advantage over geostationary satellites—but at a revisit rate of just 12 hours, which is not fast enough to track rapidly evolving tornadic thunderstorms. Sometimes this limitation can be mitigated using observations from multiple polar-orbiting satellites, but there is no guarantee that multiple observations will be available when needed.

Geostationary satellites, on the other hand, are in an orbit where they are synchronized with the Earth's rotation keeping them situated above the same spot. Their fixed position allows them to observe weather and other events on much shorter timescales making them critical for observing volatile storms. Take for example NOAA's Geostationary Operational Environmental Satellite (GOES) series that can provide full disc coverage every 15 minutes, continental U.S. (CONUS) images every 5 minutes, and mesoscale coverage (horizontal scales ranging from a few to several hundred kilometers) within 30 to 60 seconds, which is handy for looking at an area where storm activity is present. However, while the ABI has exceptional temporal coverage, it has only 16 spectral bands and low vertical resolution, unlike CrIS with its thousands of bands and high vertical resolution. The ABI's current value is tracking severe weather conditions as they form, move, and dissipate, which is critical to the warning lead times for tornadoes.

A Snapshot Versus Continuous Monitoring

Polar-orbiting instruments provide a snapshot of an area on Earth every few hours to every few days, whereas geostationary instruments can monitor an area continuously in near real-time because they match the rate at which Earth is rotating.

Consider the JPSS CrIS sounder (polar-orbiting)—it makes one measurement over an observation area every 12 hours. In that same period, GOES-R ABI (geostationary) can take hundreds of images of the same area for a more complete picture of an evolving weather event. Each of these sensors has its own strengths and applications that are complementary when used together.



Source: Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin-Madison (https://cimss.ssec.wisc.edu/sage/remote_sensing/lesson1/concepts.html).

Next generation geo-hyperspectral sounders intend to combine the advantages of geostationary orbit with hyperspectral measurements, applying the lessons learned from today's polar-orbiting sounders. With this new technology, forecasters can expect a leap forward in their ability to respond to severe weather events. In the meantime, Smith and his team have shown that rapid refresh, low latency, high fidelity data is attainable with currently operational polar and geostationary satellites. The trick is fusing together data to simulate a "geo-hyperspectral" perspective that gives forecasters better information on the location and onset time of convective storms. Using polar and geostationary data together allows forecasters to identify areas of potential severe weather (from polar-orbiting sensors) and give the public information on severe storms and tornadoes as they move (from geostationary sensors).

DATA FUSION TO IMPROVE CONVECTIVE WEATHER FORECASTING

The Benefits of Combined Polar and Geostationary Observations

What is data fusion? Simply put, data fusion is when information from multiple sources is combined. Its purpose in Earth observation for forecasting is to provide complimentary views, fill gaps, and improve the understanding of a weather event or environmental condition. One big advantage of data fusion is that merging the data from different sensors onboard different satellites in different orbits can compensate for the limitations of individual sensors while amplifying their strengths.

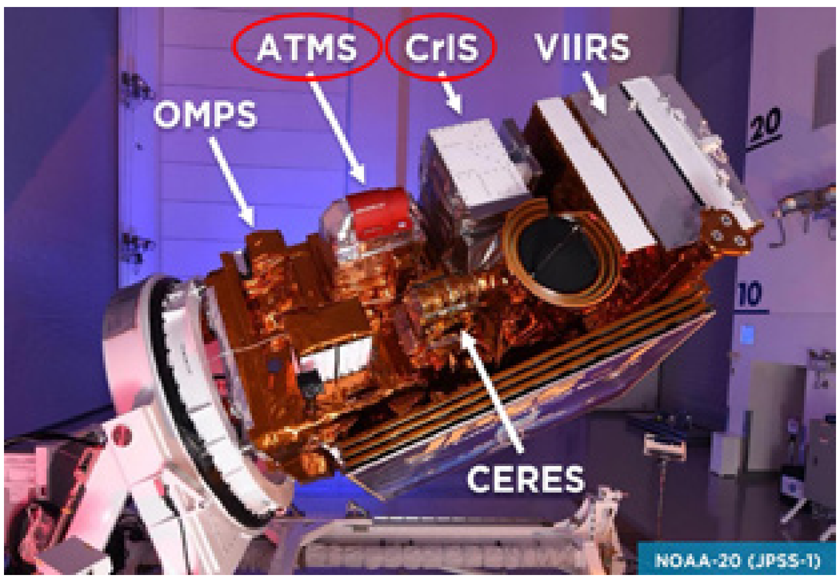
When combined, polar and geostationary observations can produce hyperspectral-like sounding products that show near real-time atmospheric variations at the small scale needed to predict and monitor the formation of severe storms. This fusion of observational power provides additional insight into the behavior of the atmosphere that is important for defining severe weather watch areas and improving tornado warning lead-times to save lives and reduce shelter in place time. Smith's team applied a data fusion approach, combining sounding and imager data from several polar-orbiting and geostationary instruments to leverage the benefits of each. "Our objective," Smith says, "was to produce high resolution water vapor and temperature profiles to improve convective weather forecasts."

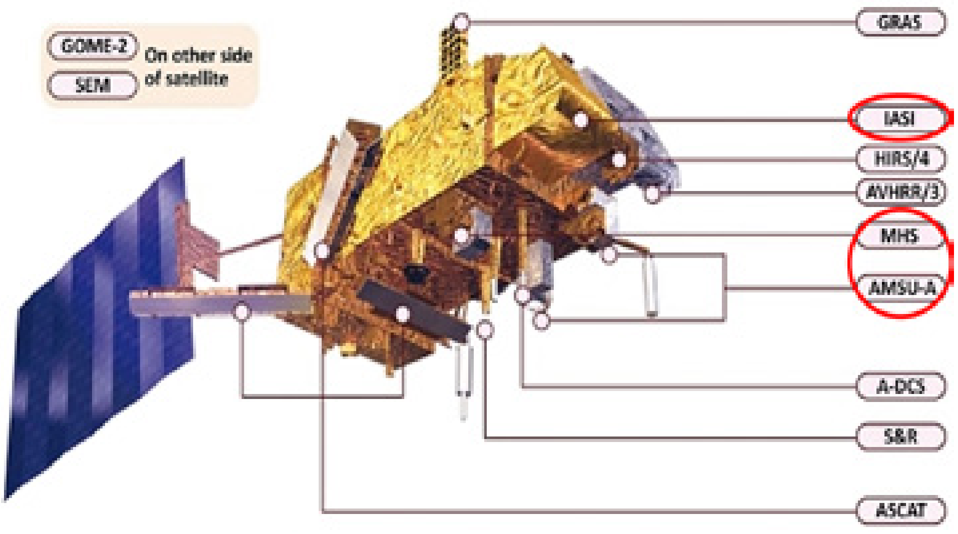
Producing High Resolution Soundings Through Data Fusion

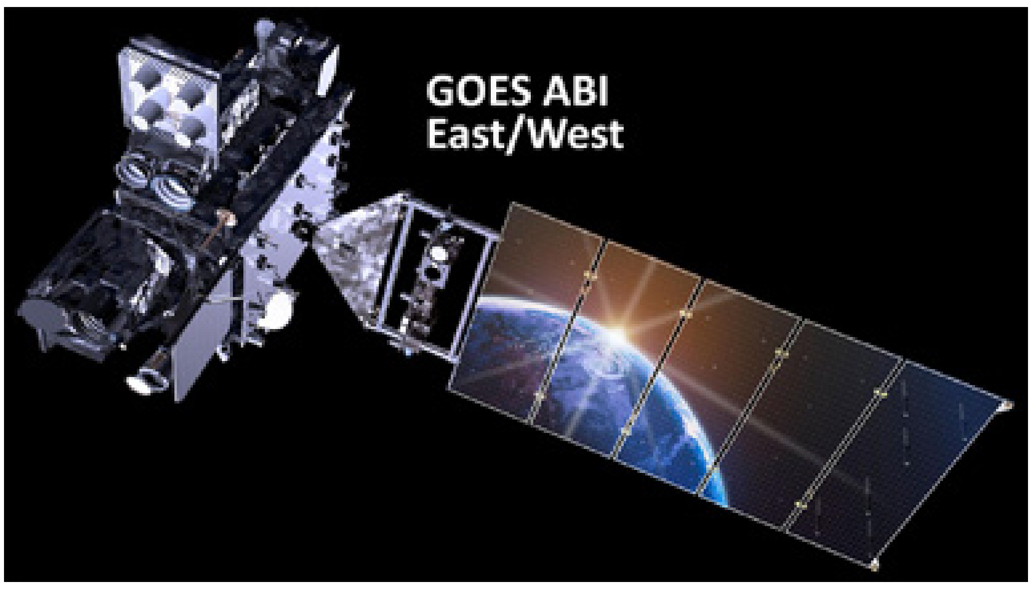
Integrating polar and geostationary satellite observations "gives us the high spatial and temporal resolution needed to detect small scale features missed by models, and also nearly continuous data to assimilate in numerical models, which improves the dynamics of the forecast," Smith explains. His team's data fusion technique combined observations from seven instruments to produce high spatial (2-km) and high temporal (30-minute) resolution soundings that take advantage of the unique benefits of each instrument. But getting there was complicated.

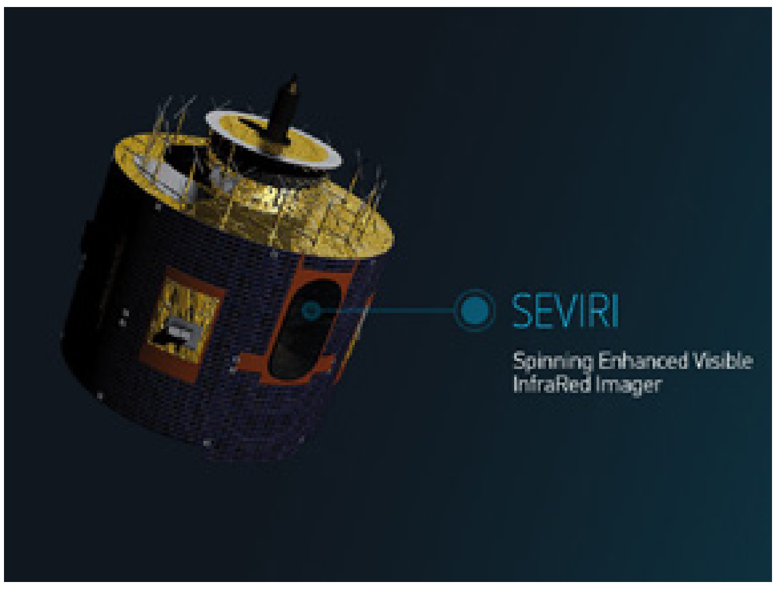
Satellite Instruments Used For Data Fusion

Sensor	Function	Benefit	Satellite Series	Orbit
CrIS	Hyperspectral IR sounder	High vertical resolution	NOAA NESDIS JPSS	Polar
ATMS	Microwave sounder	Penetrates clouds	NOAA NESDIS JPSS	Polar
IASI	Hyperspectral IR sounder	High vertical resolution	EUMETSAT[3] MetOp	Polar
AMSU-A	Microwave sounder	Penetrates clouds	EUMETSAT MetOp	Polar
MHS	Microwave humidity sounder	Penetrates clouds	EUMETSAT MetOp	Polar
ABI	Imager (VIS, IR, NIR)	High horizontal & temporal resolution	NOAA NESDIS GOES	Geostationary
SEVIRI	Imager (VIS, IR, NIR)	High horizontal & temporal resolution	EUMETSAT Meteosat	Geostationary









Clockwise from top left: ATMS and CrIS sounders onboard JPSS polar-orbiting satellites; IASI, MHS, and AMSU-A sounders onboard EUMETSAT's MetOp polar-orbiting satellites; SEVIRI onboard EUMETSAT's Meteosat geostationary satellites; and ABI onboard NOAA GOES geostationary satellites.

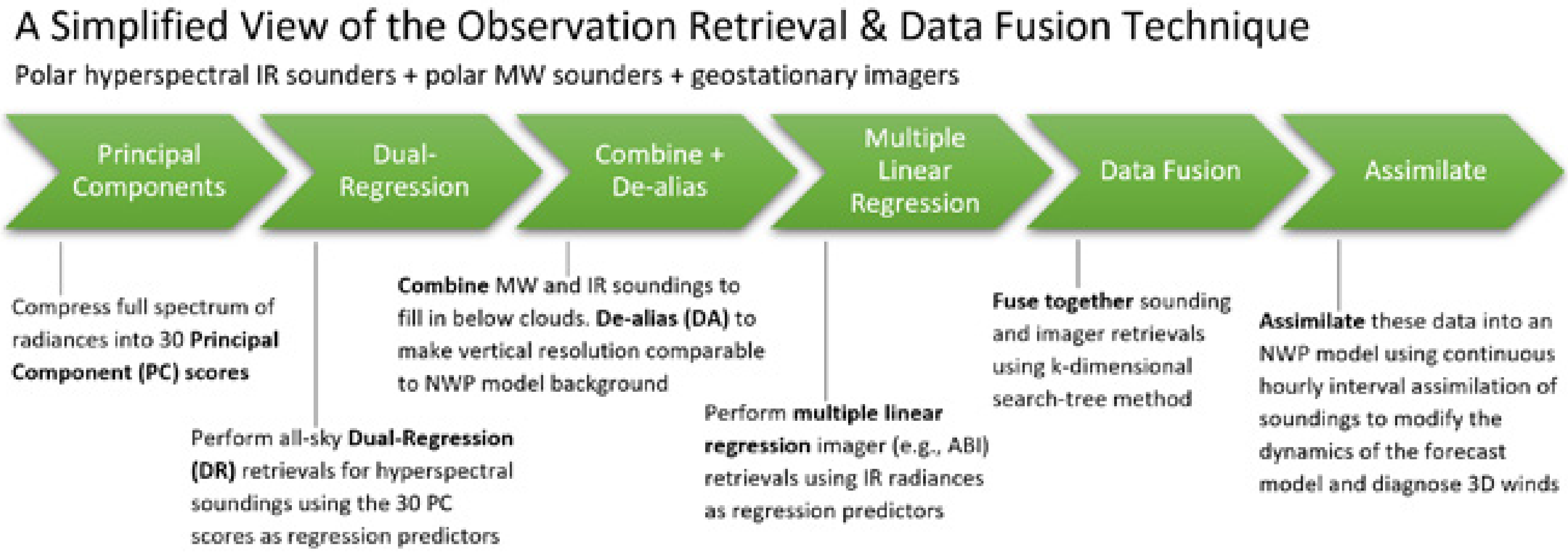
The Observation Retrieval and Data Fusion Technique

"The importance of using all these data," says Smith, "is to achieve the resolution needed for numerical weather prediction." A very important realization the team had, he points out, was that "in order to get the hyperspectral vertical resolution advantage, all spectral measurements at full spectral resolution need to be used to gain the full information content of CrIS and IASI data." Full spatial resolution is equally important for diagnosing errors.

Data System Characteristics

- Full spectral resolution and full spatial resolution
- Clear polar hyperspectral IR soundings above cloud
- Microwave soundings below cloud
- 3-km resolution NWP model
- Continuous humidity data assimilation to diagnose winds and dynamics

The team performed a series of steps to retrieve observations, enhance vertical resolution, fuse together polar and geostationary data to improve spatial and temporal resolution, and assimilate these data into an NWP model. A simplified view of the technique is shown below.



Understanding the Concepts

Principal Component (PC) scores: Principal Component (PC) scores are one output of the Principal Component Analysis (PCA) algorithm for simplifying datasets. When using the regression method in forecasting, some predictors may be related to each other. PCA transforms these predictors into a smaller set of forecasting factors. In Smith's work, the full spectrum of radiance observations was compressed into 30 PC scores, which were then used as regression predictors for producing all-sky Dual-Regression (DR) retrievals.

Dual-Regression (DR): The Dual-Regression (DR) algorithm is a fast method for retrieving atmospheric profiles and surface and cloud properties from satellite hyperspectral sounders. Because hyperspectral radiance measurements are obtained across thousands of spectral bands, computationally fast methods like DR are needed.

Multiple Linear Regression (MLR): Multiple Linear Regression (LR) is a regression model that estimates the relationship between multiple independent variables and dependent variables. MLR estimates are used to describe data and to explain the relationship. MLR is the most basic and commonly used predictive analysis.

De-aliasing: De-aliasing is a correction used to eliminate errors from aliasing, an effect that causes different signals to become indistinguishable when sampled.

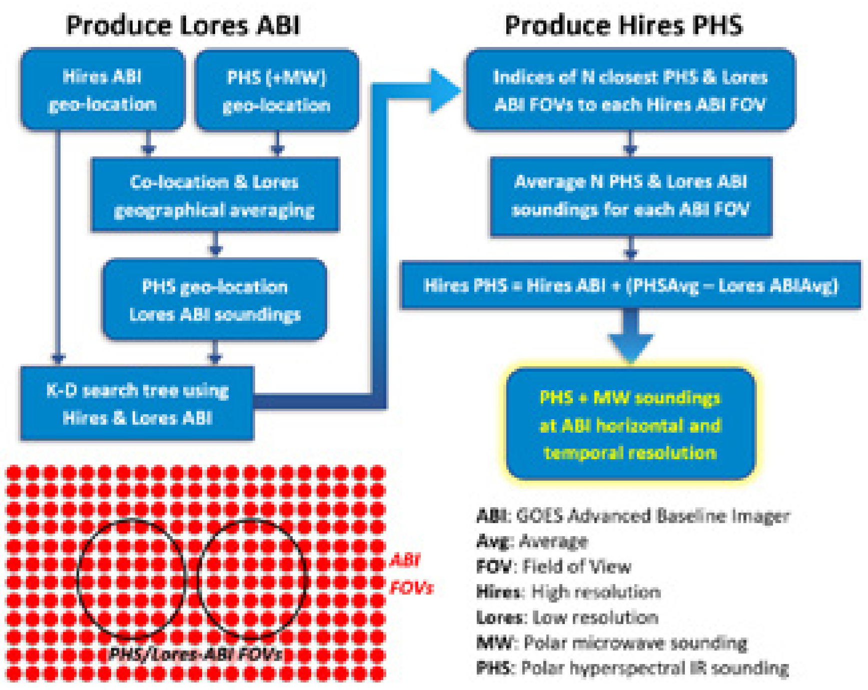
DRDA: This acronym refers to the de-aliased (vertically enhanced) dual regression retrievals from satellite-derived atmospheric soundings.

Enhancing Vertical Resolution

Enhancing vertical resolution requires eliminating errors from retrieved sounding profiles using a process called de-aliasing. "Basically," Smith explains, "we use a regression technique to derive an initial profile and de-alias it—we used the model background in this case—to enhance the vertical sensitivity of the retrieval and fill in the 'null space' to get our final sounding result" for fusion later in the process. De-aliasing makes the vertical resolution of the profiles consistent with that of the forecast model. "We do this so that the model will accept the sounding retrievals when we assimilate them," Smith clarifies.

Enhancing Spatial and Temporal Resolutions

To achieve high spatial and temporal resolution, data fusion is key. "It's a very important technique for putting together our polar hyperspectral data with the imager data to make high resolution profiles," Smith emphasizes. "The idea here is to pair the hyperspectral infrared soundings and multispectral microwave soundings and so on with the imager data, which has high temporal resolution, to create a training dataset." The training dataset is used to predict polar hyperspectral soundings at the locations and times of every full resolution geostationary imager data point, essentially



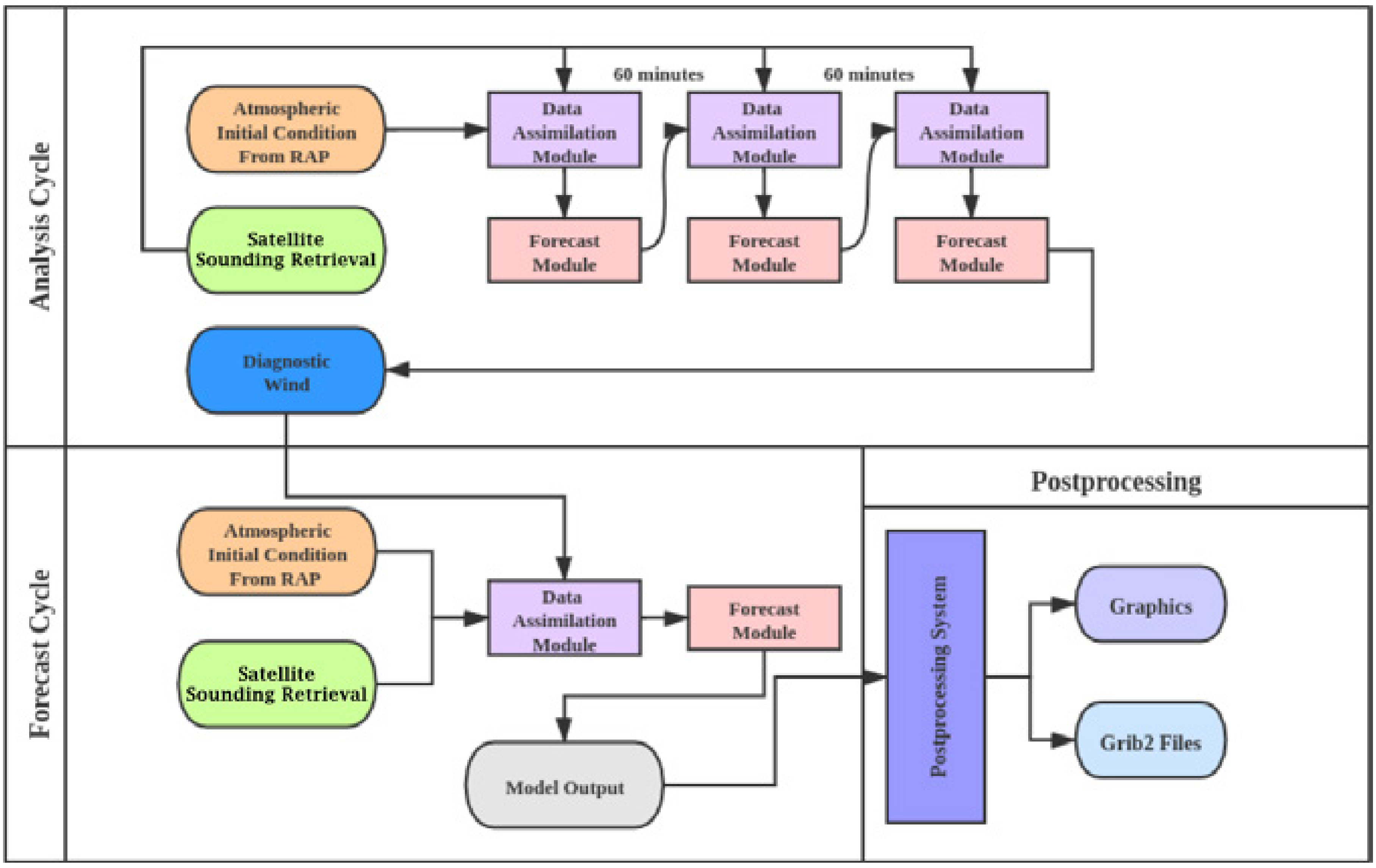
Schematic diagram showing the process for combining low-vertical-resolution ABI clear-sky regression retrievals with high-vertical-resolution DRDA all-sky retrievals. A satellite footprint diagram is also shown. Source: Smith Sr. et al 2020.

generating a geo-hyperspectral sounder-like perspective: 2-km scale atmospheric temperature and moisture soundings with a rapid refresh rate of about 30-minutes. An example schematic of this complex technique is shown above.

Assimilation Into a Numerical Weather Prediction Model

For more than three years, the 2-km resolution profiles generated by the data fusion technique have been continuously assimilated on an hourly basis into an NWP model—a Weather Research and Forecasting (WRF) model that is comparable to NOAA's Rapid Refresh (RAP) forecast model. Assimilation of the high resolution soundings into an NWP model has an important objective: "We need to continuously assimilate the satellite sounding data in order to modify the model's dynamic processes to conform to the spatial and temporal changes that we're assimilating," Smith explains. "In other words, the model has to change its dynamics so that it's consistent with the high resolution profiles that we are assimilating."

Altogether, the high resolution satellite sounding and numerical weather forecast system has four parts: data assimilation, analysis, forecast, and post-processing. Data assimilation (DA) is a technique by which numerical model data and observations are combined to obtain an analysis that best represents the state of the atmospheric phenomena of interest. In the analysis cycle, data assimilation produces wind profiles for initializing the forecast cycle (initialization is the process of establishing the starting conditions—atmospheric temperature, humidity, and wind velocity—upon which a model builds future forecasts). The forecast cycle produces model output. Post-processing is the final stage to produce usable forecast products. The system workflow is shown below.



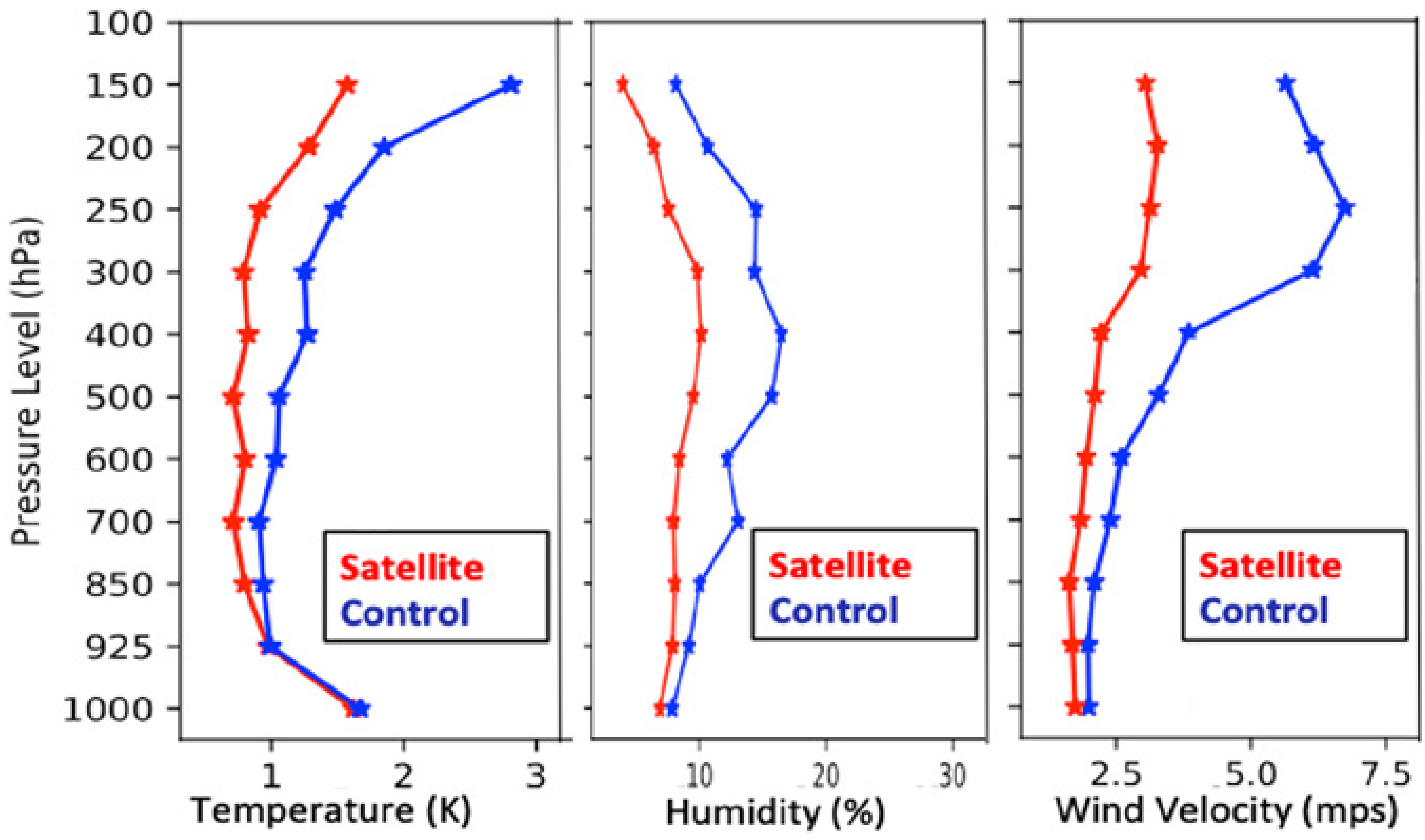
System workflow for the high resolution satellite sounding and numerical weather forecast system.

The Impact of High Resolution Satellite Soundings on Modeled Forecasts

The impact of high resolution satellite soundings on a 6-hour 8-km NWP model is shown in the figure below. Significant improvements are seen in forecasts for temperature, humidity, and wind velocity for the model initialized with sounding data (red) versus without (blue). This indicates that the high resolution soundings improved initial model conditions. The quality of initial conditions is crucial to the accuracy of future forecasts. In other words, garbage in, garbage out. Improvements like these are important because they lead to improvements in forecasts of precipitation, atmospheric instability, wind shear, and other severe weather indicators like the Significant Tornado Parameter.

Demonstrating Usefulness in an Operational Setting

Evaluations of the satellite sounding and numerical weather forecast system have shown that assimilating high resolution satellite profiles into NWP models can considerably improve forecast skill for atmospheric state parameters like temperature, humidity, and wind velocity. But there are other demonstrated improvements, as well. With support from the Office of Low Earth Orbit Observations (LEO) Proving Ground Risk Reduction (PGRR) program, Hampton University, and NASA Langley, the system has operated continuously for more than three years, providing validation statistics that show improvements in 0- to 18-hour precipitation and severe convective weather forecasts for North America. For instance, dramatic improvements have been seen in precipitation forecasts for the type of heavy, localized precipitation that causes deadly flash flooding.



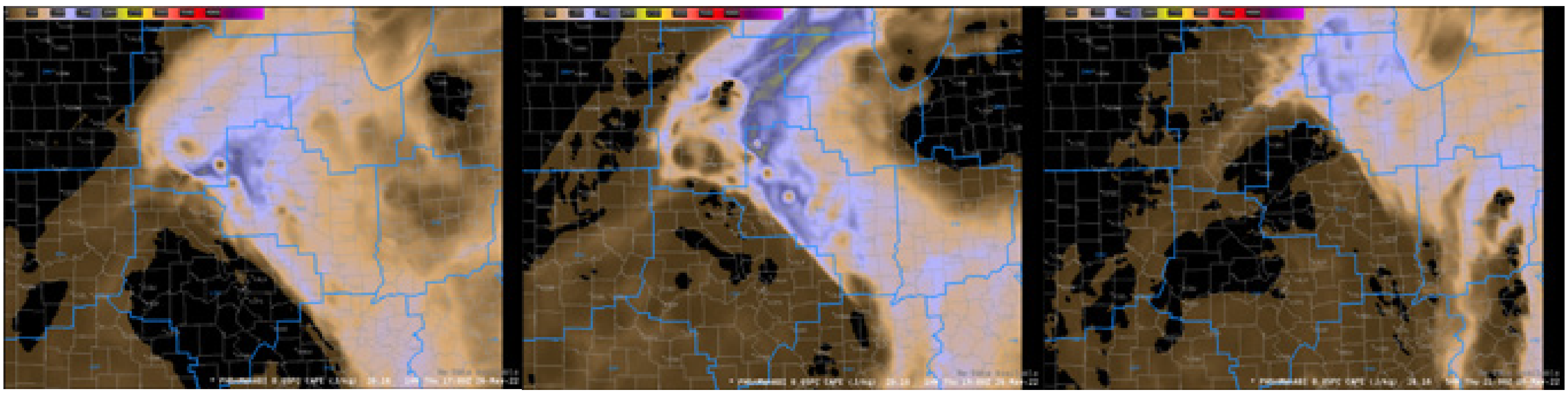
Standard deviations between radiosondes and 6-hour 8-km resolution NWP model forecasts for temperature, humidity, and wind velocity initialized with high resolution satellite soundings ("Satellite," red) and without ("Control," blue) for February and March 2021.

NOAA HWT

As part of the NOAA Hazardous Weather Testbed (HWT), researchers and forecasters work side-by-side to evaluate emerging research concepts and tools in simulated operational settings. Participants assess the viability of new models, techniques, and products in a real-time environment, ensuring an effective, two-way path between research and operations.

Results in the operational setting are impressive, too. For example, forecasters at the 2022 NOAA Hazardous Weather Testbed (HWT) demonstrated the operational usefulness of high resolution soundings and the forecast products they generate. Over several days, they found that the satellite sounding and numerical weather forecast system consistently and accurately identified instability corridors along where convection developed and captured areas where tornadoes formed.

Operational forecasters at the Wakefield, Virginia and Milwaukee/Sullivan, Wisconsin Weather Forecast Offices have also evaluated the system's products, which are available from Hampton University, University of Wisconsin, and the NOAA Advanced Weather Interactive Processing System (AWIPS), the display and analysis system that is the cornerstone of NWS operations. Through these assessments "we've been able to show that the satellite data improves tornado and convective weather forecasts significantly," remarks Smith.



MUCAPE (which stands for "Most Unstable Convective Available Potential Energy" and is a measure of instability in the troposphere) from the satellite sounding and numerical weather forecast system shows features lifting northeastward across Illinois, as observed on May 26, 2022, at 17:00 UTC (left), 19:00 UTC (middle), and 21:00 UTC (right) at the 2022 Hazardous Weather Testbed. Source: Lindstrom, May 2022.

> **It [the satellite sounding and numerical weather forecast system] was a nice 'confirmation' tool of the Tornado Warning. The units of the STP [Significant Tornado Parameter] were nearly 10 at the time of the strong couplet north of Clifton, Wisconsin, and it was in the right location at the time of warning.**
>
> Kevin Thiel, *2022 NOAA Hazardous Weather Testbed*

Improving Tornado Prediction: Example Evaluations of the Satellite Sounding and Numerical Weather Forecast System

March 3, 2020: Middle Tennessee

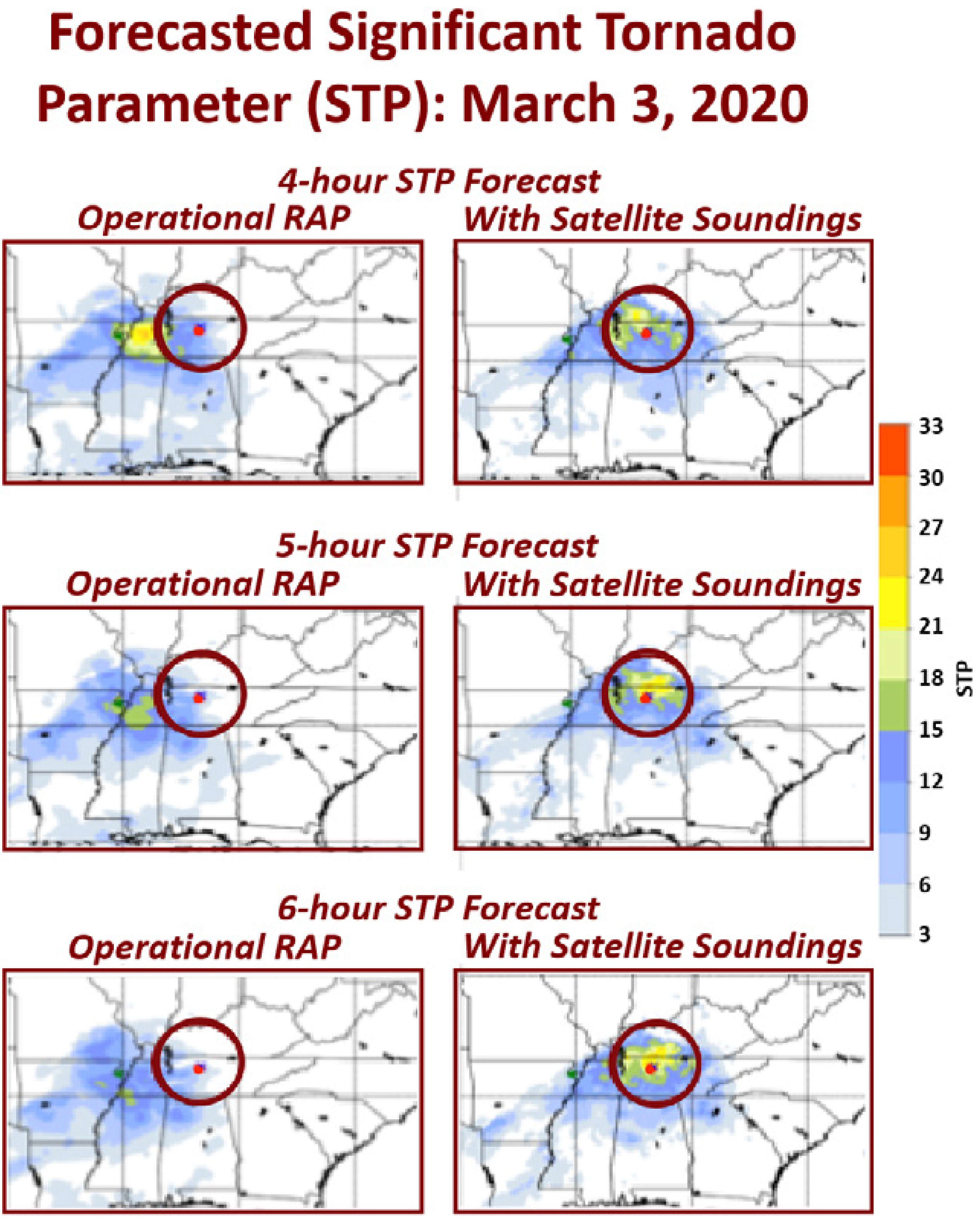
In the early morning hours of March 3, 2020, an outbreak of deadly tornadoes hit Middle Tennessee killing 25 people, injuring hundreds, and leaving 70,000 without power. The most destructive tornado carried on for 60 miles, ripping through the Nashville metro area at wind speeds topping 165 miles per hour. The outbreak became the sixth costliest tornado event in U.S. history with damages totaling $1.6 billion.

One reason the outbreak was so devastating was that it occurred in the middle of the night when most people were asleep and unaware of conditions outside. Another factor was having very little warning—about 5 to 6 minutes for downtown Nashville residents, while some areas received almost no warning at all. What happened? Simply put, weather radar and forecast models failed to provide accurate information fast enough to keep up with the rapidly evolving storm. Supercells are complex and unpredictable beasts, after all.

Heavy damage in East Nashville, Tennessee after tornadoes ripped through the region on March 3, 2020. Image credit: NOAA NWS.

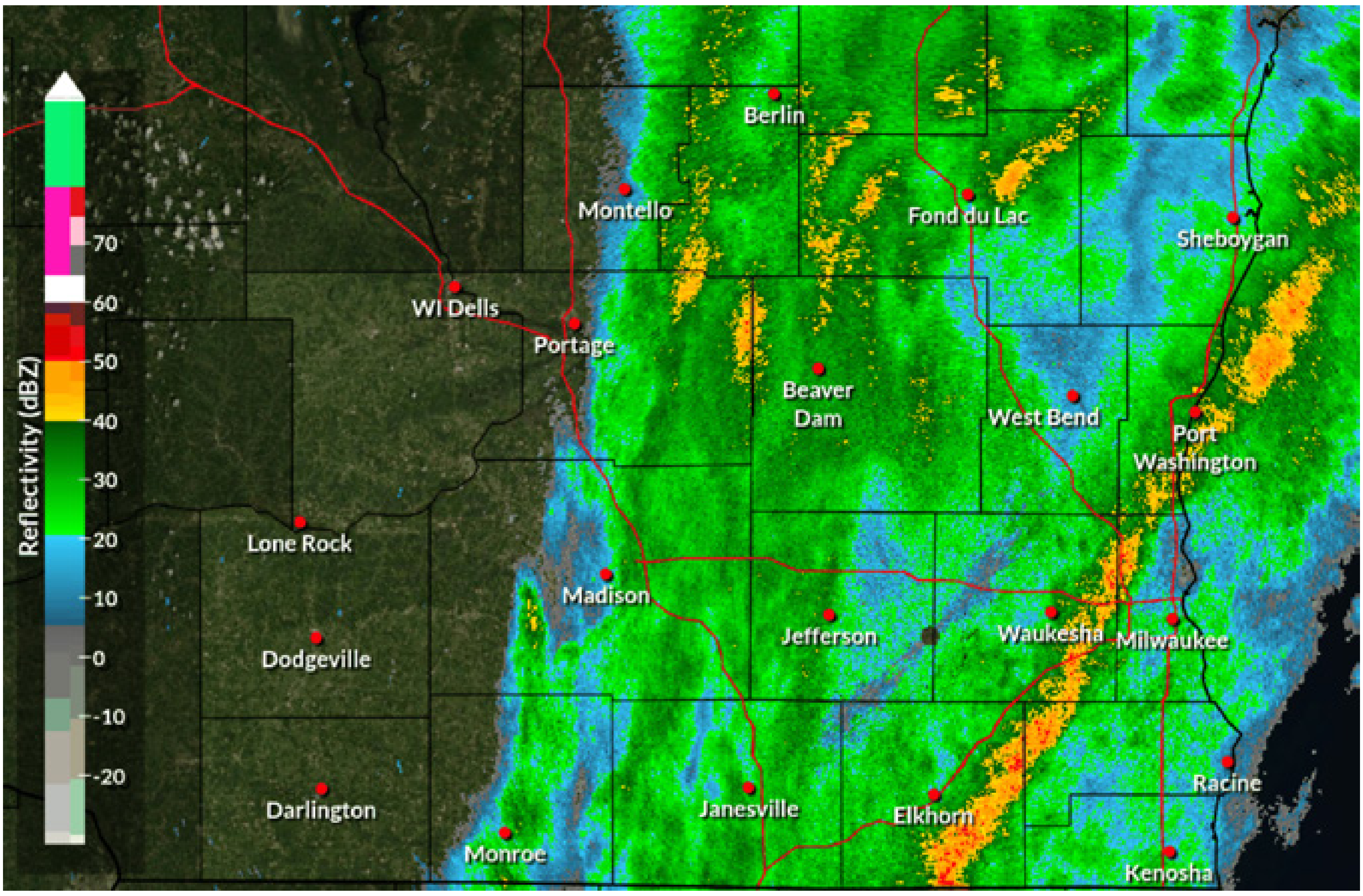
A combination of key indicators, environmental conditions, and information from human storm spotters is needed before the NWS will issue a tornado warning. To help forecasters decide if conditions are right, they often use a severe weather forecast index called the Significant Tornado Parameter (STP or SigTor). The STP calculates whether atmospheric conditions—instability, wind shear, and moisture derived from NWP models—favor tornado development; the higher the STP value, the greater the likelihood of a tornado. But for Nashville, STP forecasts for March 3rd from the operational Rapid Refresh (RAP) model (figure below, left side) placed the highest STP values far west of the city, nowhere near the location of the tornado touchdown (red dot). (RAP is an NWP model used by the NWS to provide short-term hourly weather forecasts.)

The STP tells a different story when the forecast is initialized with high resolution data from the satellite sounding and numerical weather forecast system (figure below, right column). "The satellite forecasts show much better how the tornado will develop over four, five, and six hours compared to the operational [RAP] forecast that had a position too far to the west," Smith says.



These figures show the 4-, 5-, and 6-hour STP forecasts initialized with high resolution satellite soundings ("With Satellite Soundings") and the operational RAP model for the Tennessee region on March 3, 2020. Higher STP values (yellow/orange) indicate an increased likelihood of tornado development. The red dot (circled) is the location of the Nashville tornado.

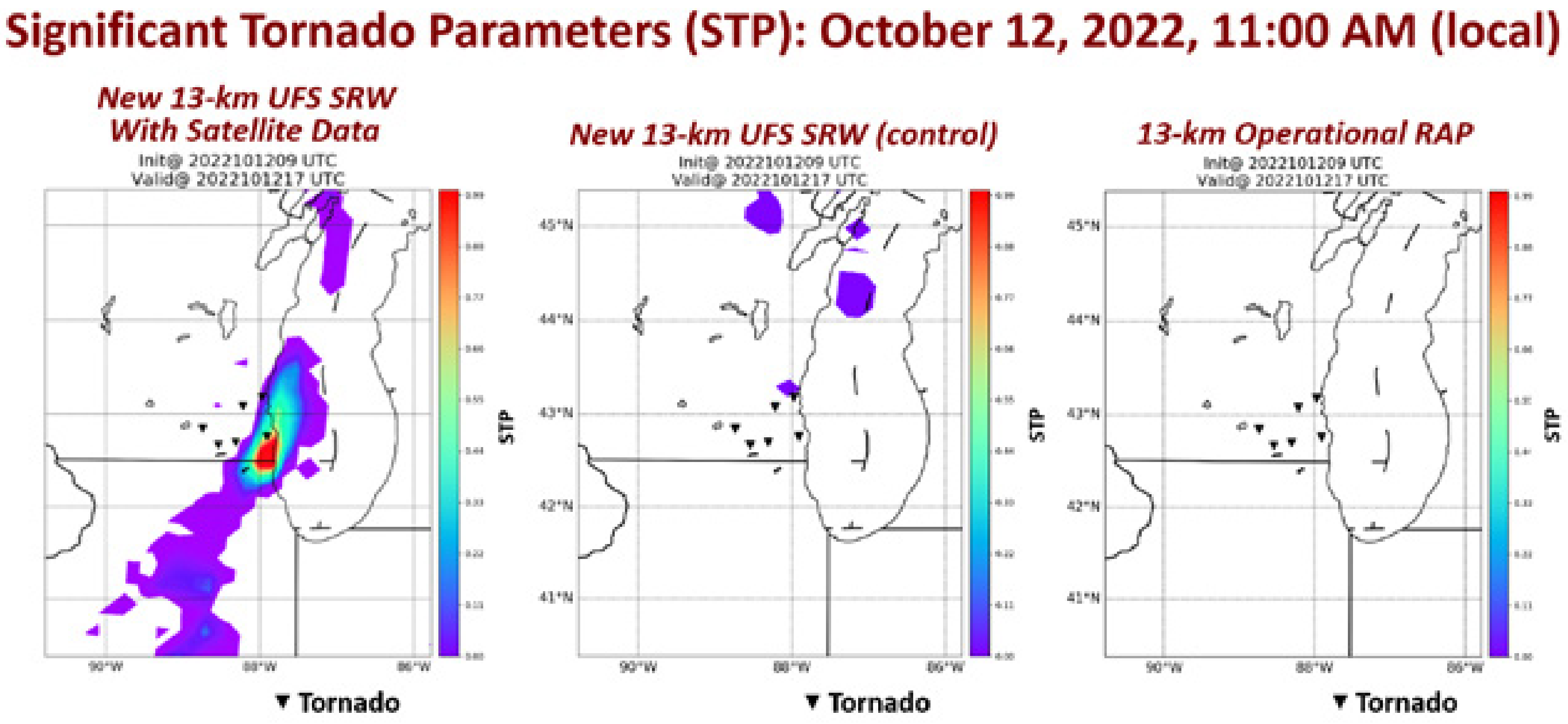
October 12, 2022: Southeast Wisconsin



Radar showing storms moving through Southeast Wisconsin on October 12, 2022. Source: NWS Milwaukee/Sullivan, WI Weather Forecast Office.

It was a similar story in Southeast Wisconsin on October 12, 2022—a line of strong thunderstorms produced seven small tornadoes in the area between 11:13 AM and 12:20 PM local time. The outbreak was Wisconsin's largest on record for October, a month when tornadoes are a rare occurrence. While the tornadoes were short-lived and relatively weak, they left behind many downed trees and about 21,000 Wisconsinites without power.

The figures below compare STP values at 11:00 AM (local) from the operational RAP model (right), NOAA's new 13-km Unified Forecast System Short Range Weather (UFS SRW) model (middle), and the UFS SRW initialized with high resolution data from the satellite sounding and numerical weather forecast system (left). The UFS SRW with satellite data did well at predicting the formation of tornadoes (indicated by black triangles), evident by the high STP values in green, orange, and red in the area.



"Even the short range forecast with the control [UFS SRW], which didn't include the satellite data, predicted some evidence that there was going to be significant convection in that area, although it didn't pinpoint the locale of the tornadoes" like the UFS SRW with satellite data did, says Smith. "Against the operational RAP, the RAP, which did not benefit from the satellite sounding data, didn't show anything."

A LOOK TOWARD THE FUTURE

The above examples provide a glimpse into the value of geo-hyperspectral-like observations and an early look into the next generation geo-hyperspectral sounders that are anticipated to greatly improve the timeliness and accuracy of severe weather warnings. "The life and property savings implied by the LEO/GEO [polar/geostationary] fusion sounding data forecast impact results strongly justify implementing the next generation of satellite sounding sensors as rapidly as is practically possible," Smith proclaims. But with next generation sounders years away from operation, the high-resolution satellite sounding and numerical weather forecast system offers an opportunity to leverage today's operational satellites to improve severe convective weather forecasts and the timeliness of high wind, tornado, flash flood, and hail warnings without having to wait a decade.

For now, the system is an experimental product providing satellite-enhanced high resolution nowcasting, hourly, and short-term forecast products to the NWS and research community for validation before becoming operational. Smith remains hopeful about the future of the system's operational status, noting, "we have great sensors in orbit and good data is coming from them and if we use it all we'll get significant improvements." Until then, the satellite sounding and numerical weather forecast system continues to undergo readiness activities to support a research-to-operations transition, operating around the clock to produce more data for analysis, validation, and demonstration.✦

STORY SOURCE

The information in this article is based, in part, on the October 17, 2022, LEO Science Seminar titled "Applications of Combined Polar and Geostationary High-resolution Sounding Observations" presented by Dr. William L. Smith Sr., a senior scientist at the Space Science and Engineering Center at the University of Wisconsin-Madison, professor emeritus at University of Wisconsin-Madison, and distinguished professor at Hampton University, with contributions from Elisabeth Weisz, University of Wisconsin-Madison (data fusion), and Qi Zhang and Anthony DiNorscia, Hampton University (WRF model and profile retrieval, respectively).

FOOTNOTES

1 CPI-adjusted.

2 Specific to instruments that provide U.S. coverage.

3 The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is an intergovernmental organization that serves as the European operational satellite agency for monitoring weather, climate, and the environment from space. In 2013, NOAA and EUMETSAT signed a long-term cooperative agreement, ensuring continued space-based weather, water, and climate monitoring.

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FEATURE 3

Perspectives on Satellite Data Training for Operational Meteorology, Weather Research, and JPSS Applications

Attendees of a short course hosted by the American Meteorological Society (AMS). Credit: AMS.

Meteorologists and researchers alike use satellite data and derived products to study the Earth's surface, atmosphere, cryosphere, and oceans. Operational forecasters use them to improve situational awareness about severe weather and life-threatening events like hurricanes, wildfires, and unsafe air quality that cause billions of dollars in damage and cost thousands of lives each year. Researchers and others use satellite observations for climate change modeling, surveillance of illegal fishing vessels, tracking dust across continents, monitoring harmful algal blooms, estimating economic growth, and countless other purposes. In fact, satellite data are used across nearly every sector of the U.S. economy from transportation to construction, commerce to energy, tourism to public health, and many more, touching the lives of all Americans in some manner.

Given the importance and prevalence of Earth observations to the U.S. economy, human health, and the environment, satellite data users must stay informed about the latest applications and newest products. Early career data users may need a basic understanding of products and their applications, while others may change job roles or locations and need to become familiar with how satellite data apply to new mission requirements. Equally challenging, users must stay informed about how data can be accessed and keep pace with data delivery in an era in which JPSS satellites alone deliver more than seven terabytes of data each day. As more and more Earth observation satellites are launched and data volume grows exponentially, it is more important than ever to provide operational forecasters, researchers, decision-makers, and other data users with comprehensive and accessible training resources to ensure their decisions are informed by the best, most appropriate satellite data available.

THE BENEFITS OF SATELLITE DATA TRAINING

For operational forecasters, training is an ongoing part of their profession. New research, new datasets, new products, and new tools are always being evaluated for use in the operational setting. According to the National Weather Service (NWS), the purpose of training is to "effectively and efficiently maximize a forecaster's understanding of the current and future state of the atmosphere and allow them to issue the best possible warning and forecast in order to meet the mission of [NWS], Saving Lives and Property."

Beyond forecasting, satellite data training offers numerous benefits ranging from increasing accessibility to products to learning a new skill or methodology. Moreover, satellite sensors are continuously evolving, and scientists are making tremendous technical advancements, like using machine learning to better understand data and improve predictive tools. To make the most of these opportunities, end users need training to understand and apply the latest data and products in the operational environment.

Training also drives innovation. Training, at its core, is the exchange of knowledge and ideas and encourages openness to new concepts. The training environment can stimulate new ideas or creativity through interactive discussion, learning exercises, debating existing approaches, and exposure to emerging concepts, all of which can be a source of inspiration. Likewise, training can act as a bridge between product developers and end users, facilitating a feedback loop or collaboration that spurs new and updated algorithms, data visualizations, datasets, products, and new ways to access data. Through innovation, training turns satellite observations into knowledge and information that benefits society.

10 Benefits of Satellite Data Training

1. Increase knowledge about latest applications
2. Understand what products/tools are available
3. Learn new methodologies and skills
4. Remove barriers to product/tool adoption
5. Improve software proficiency
6. Provide feedback to product developers
7. Keep up with the state-of-the-art
8. Bridge gap between research and operations
9. Prepare for the next generation of satellites
10. Foster professional development

DIFFERENT METHODS FOR DIFFERENT NEEDS

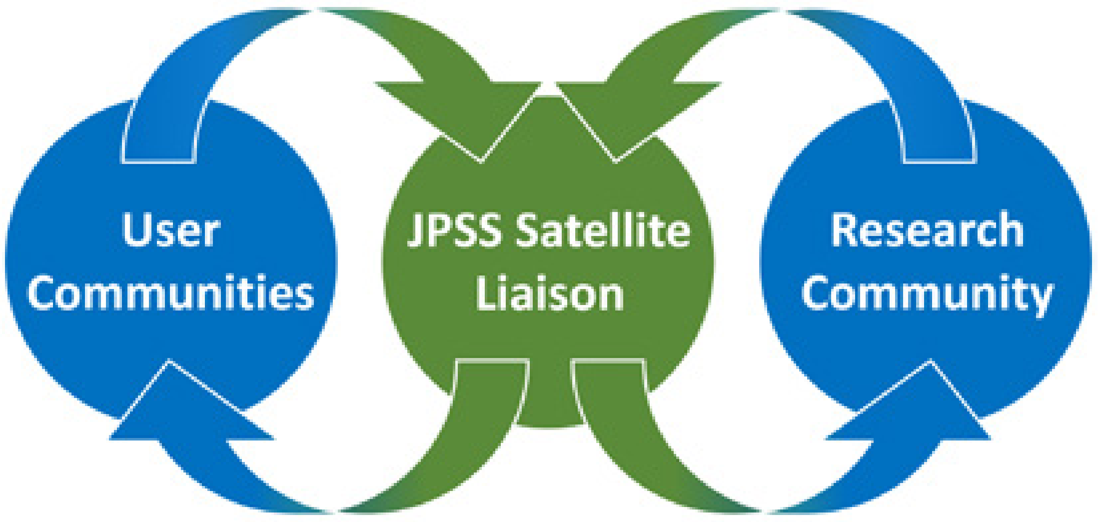
Satellite data training takes on different forms. The type of training used depends on many factors, such as available resources, trainee needs and background, and trainee location, culture, and virtual or in-person settings. Depending on the desired goals, training may be designed to reach a broad or narrow audience. For instance, an open access self-paced online learning course is more suited to a global audience than a fee-based in-person workshop with limited venue space. Each has their pros and cons—in-person workshops allow for personalized interaction with an instructor but may involve travel and registration-related expenses, while open access self-paced online courses are cost-effective and convenient but may offer little to no individual support. Training material length is another consideration—a 20-minute in-depth video takes more resources to create than a brief 1-2 page "quick guide," and each serves a specific purpose. Building a training with a specified audience, goals, and potential challenges in mind goes a long way in developing effective learning resources. Some common examples of satellite data training methods are shown in the figure below.

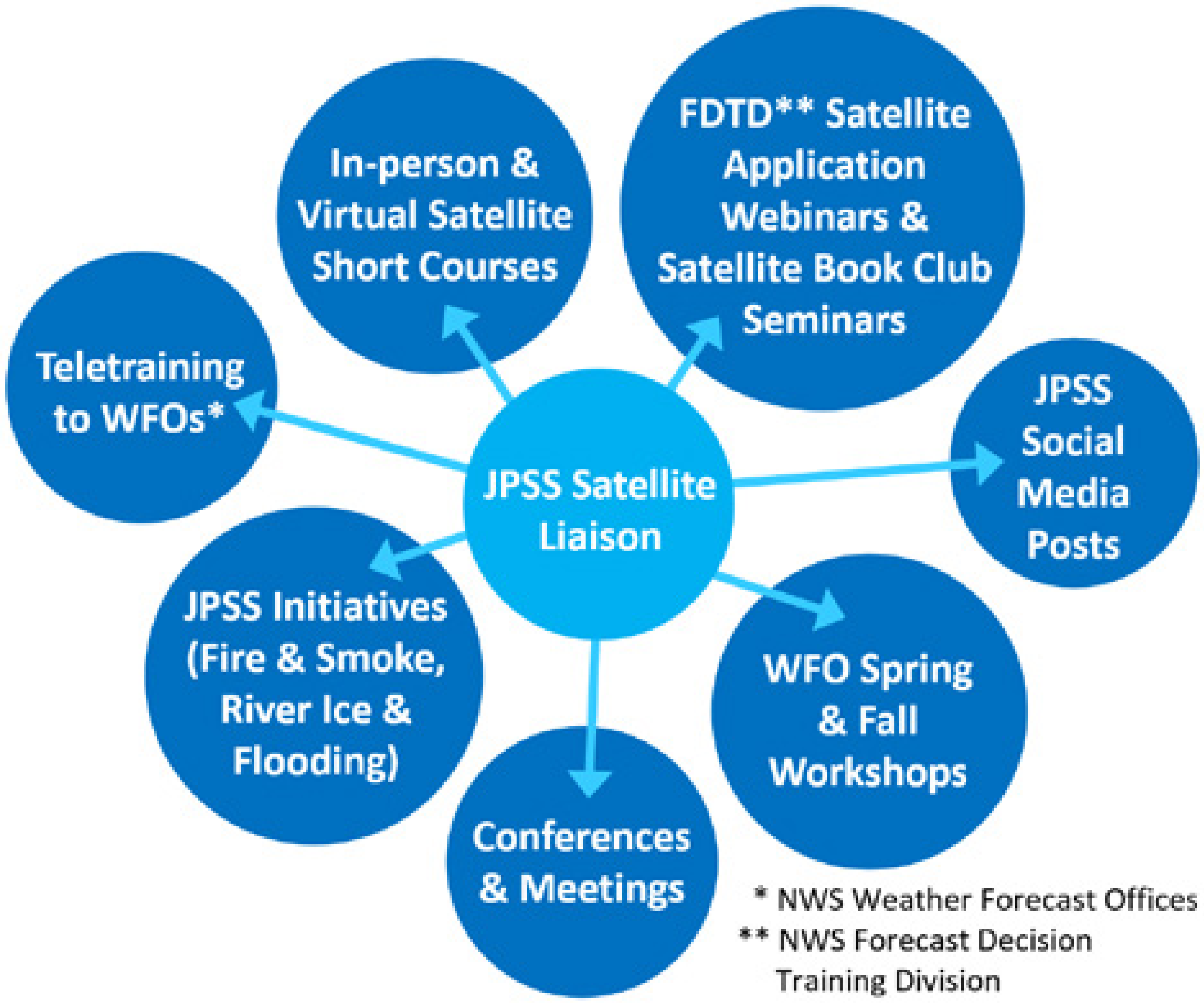
Each of these methods requires a unique approach to make them valuable to the trainee. The Office of Low Earth Orbit Observations (LEO) looks within[1], to the user community, and to external organizations to develop and facilitate trainings like these specific to low Earth orbit data and products. Some of LEO's most valuable training resources are the trainers themselves—people like Jorel Torres, a JPSS Satellite Liaison at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, and Dr. Scott Lindstrom, a scientist at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at University of Wisconsin-Madison. Both Torres and Lindstrom have years of experience in planning and conducting trainings and creating resource materials for forecasters and researchers, and each shared their perspective at the November 2022 and February 2023 LEO Science Seminars, respectively.

THE PERSPECTIVE OF A JPSS SATELLITE LIAISON

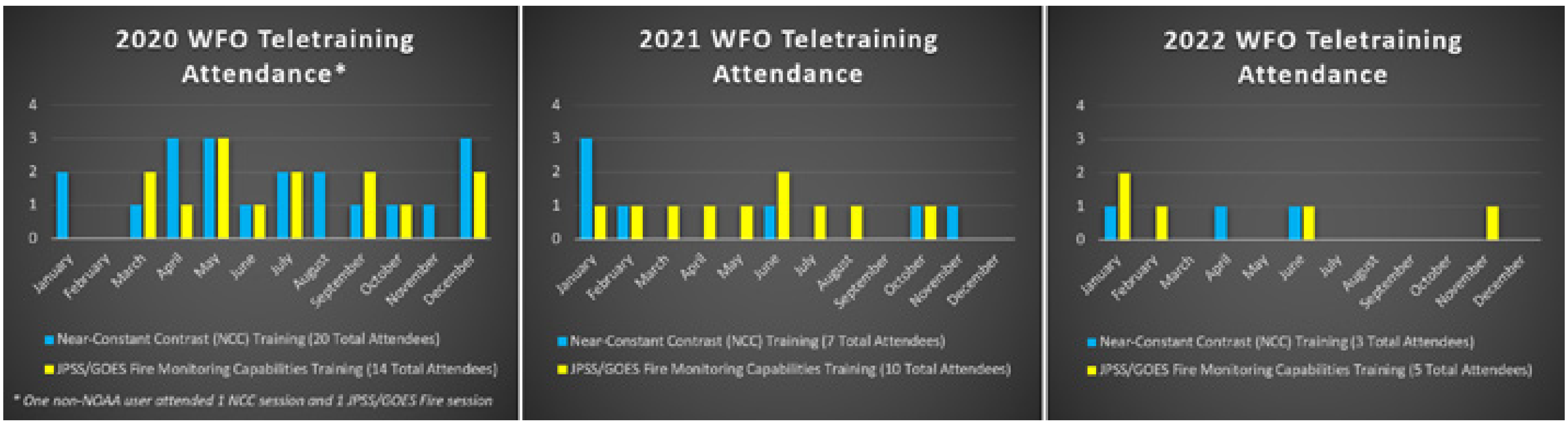
"In my role as JPSS Satellite Liaison," Torres explains, "I disseminate JPSS information and materials between user and research communities, where I focus mainly on JPSS applications, datasets, the development of satellite training materials, and the collection of user feedback." He connects with data users through different forums ranging from social media to in-person workshops. On a typical day he interacts with forecasters from NWS Weather Forecast Offices and researchers, often sharing information about operational and experimental JPSS products. Taking user feedback back to the research communities is important to improve product capabilities, and with a steady flow of leading-edge products being made available to Weather Forecast Offices, Torres is there to walk forecasters through the learning process.

His favorite part of the job? Working with different people that have different perspectives and objectives. "I get to learn from researchers about all of the new capabilities of the satellites they're working with, and I help forecasters understand how they can use those capabilities to improve weather forecasts," Torres says. He also travels to meteorological conferences and meetings to facilitate workshops and present on JPSS capabilities—more opportunities to meet LEO data users.





Online, Torres leads twice-weekly teletraining sessions for NWS forecasters that focus on using polar-orbiting satellite products in AWIPS (short for the Advanced Weather Interactive Processing System, an interactive computer system that integrates meteorological and hydrological data with satellite and radar imagery). These are the Intro to Near-Constant Contrast (NCC) that introduces a nighttime visible imagery product derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band, and JPSS/GOES Fire Monitoring Capabilities that demonstrates using JPSS and GOES[2] fire data together to leverage their individual strengths. In 2020 and 2021, Torres saw "a noticeable uptick in attendance as more of the user community was working from home due to the [COVID-19] pandemic" (see attendance statistics, below). In fact, he has noticed many changes over the years with how training takes place. For instance, short teletraining sessions—15 to 20 minutes—are preferred because Weather Forecast Offices are incredibly busy. "Shorter, targeted lessons that are designed to help users on the operational floor" are most beneficial, remarks Torres. Also, hands-on interactive workshops are appreciated—"we're trying to avoid 'death by PowerPoint'," he says.

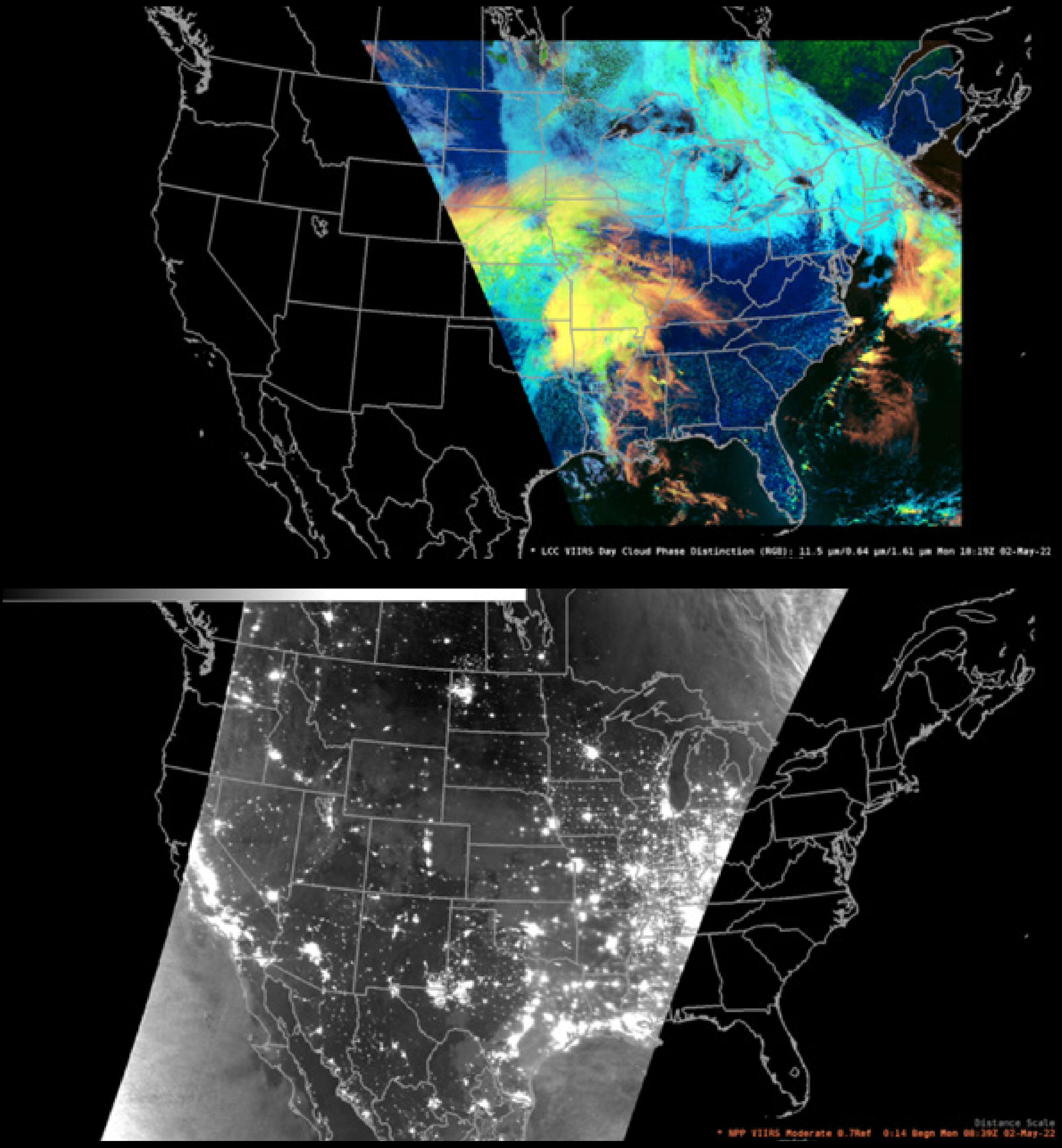


Weather Forecast Office (WFO) teletraining attendance for 2020 (left), 2021 (middle), and 2022 (right) for Near-Constant Contrast (NCC) (blue) and JPSS/GOES Fire Monitoring Capabilities teletraining sessions (yellow).

What Data Are the Right Data?

While Torres' training activities focus mainly on JPSS products, it is important for data users to think about whether JPSS data are right for their application. "Unlike data from geostationary satellites, with JPSS data we have to consider the temporal resolution. We also want to think about data latency, or essentially the time difference between the satellite overpass over a particular area and when that dataset is available for users." Each JPSS satellite circles the Earth pole-to-pole, crossing the equator 14 times per day to provide full global coverage twice daily. While a weather event may be

Torres speaking to NWS forecasters at the Weather Forecast Office (WFO), Cheyenne, WY. Image courtesy of Jorel Torres. https://scijinks.gov/satellite-liaison/



Top: VIIRS Day Cloud Phase Distinction (RGB) from Suomi-NPP passing over the continental U.S. on May 2, 2022, at ~18 UTC.
Bottom: VIIRS nighttime lights over the continental U.S. on May 2, 2022, at ~0840 UTC.

visible on multiple passes thanks to JPSS's wide swath (between 2200 km and 3060 km wide), for fast moving events like thunderstorms the high temporal resolution of a geostationary satellite might be more suitable for real-time tracking. Torres notes, "we want to encourage our users to use both polar [low Earth orbit] and geostationary datasets in operation and to do so comfortably, as well as understand the pros and cons of each."

As far as data latency, for NWS users accessing JPSS data in AWIPS, data can be acquired in as little as 30 minutes after satellite overpass through the Direct Broadcast Network—a worldwide network of local receiving stations that allows for real-time acquisition and rapid delivery of JPSS and other polar-orbiting satellite data to the global user community. "Latency depends on how the data is accessed, and can vary by product," Torres clarifies, noting that it is important to be specific during training when presenting different datasets or products.

Another aspect of training to consider is data accessibility. Satellite data products are the result of complex algorithms and without specialized knowledge, like that of a NWS forecaster, model output can be hard to work with. Luckily for non-NWS users, Torres says, "many online options are available to view near real-time imagery from polar orbiters like JPSS," giving users a convenient and easily understandable way to access and view complex data. These include many data visualization tools and cover a wide range of applications, such as fire monitoring, atmospheric profiling, hydrology, aviation, ocean color, and tracking aerosols, among others. A few of these resources are listed below; a more complete list is available on the CIRA website.

NOAA NESDIS JPSS EDRs — www.star.nesdis.noaa.gov/jpss/Teams.php
JPSS Environmental Data Records (EDRs) covering a wide array of environmental parameters and phenomena pertaining to the ocean, atmosphere, vegetation, fire, and land surface.

CIRA Polar SLIDER — https://col.st/bP40s
A satellite loop interactive data explorer providing global VIIRS data in near-real time, including cloud products, multispectral RGB composites and imagery, and individual VIIRS bands.

CIMSS VIIRS Imagery Viewer — https://cimss.ssec.wisc.edu/viirs/imagery-viewer/
VIIRS scenes that provide imagery products related to active fires, cloud-top pressure, cloud-top height, cloud emissivity, and other parameters for all VIIRS bands on NOAA-20 and SNPP.

GINA (Alaska Imagery) — http://hippy.gina.alaska.edu/distro/nrt/
Direct Broadcast imagery from VIIRS specific to Alaska related to snowmelt, snow depth, snow cover, rain rate, ice concentration, volcanic emissions, and other parameters.

JSTAR Mapper — www.star.nesdis.noaa.gov/jpss/mapper/
Global imagery from JPSS fire, vegetation, cryosphere, ocean, ozone, and aerosol products, as well as NUCAPS soundings and trace gases data and VIIRS imagery.

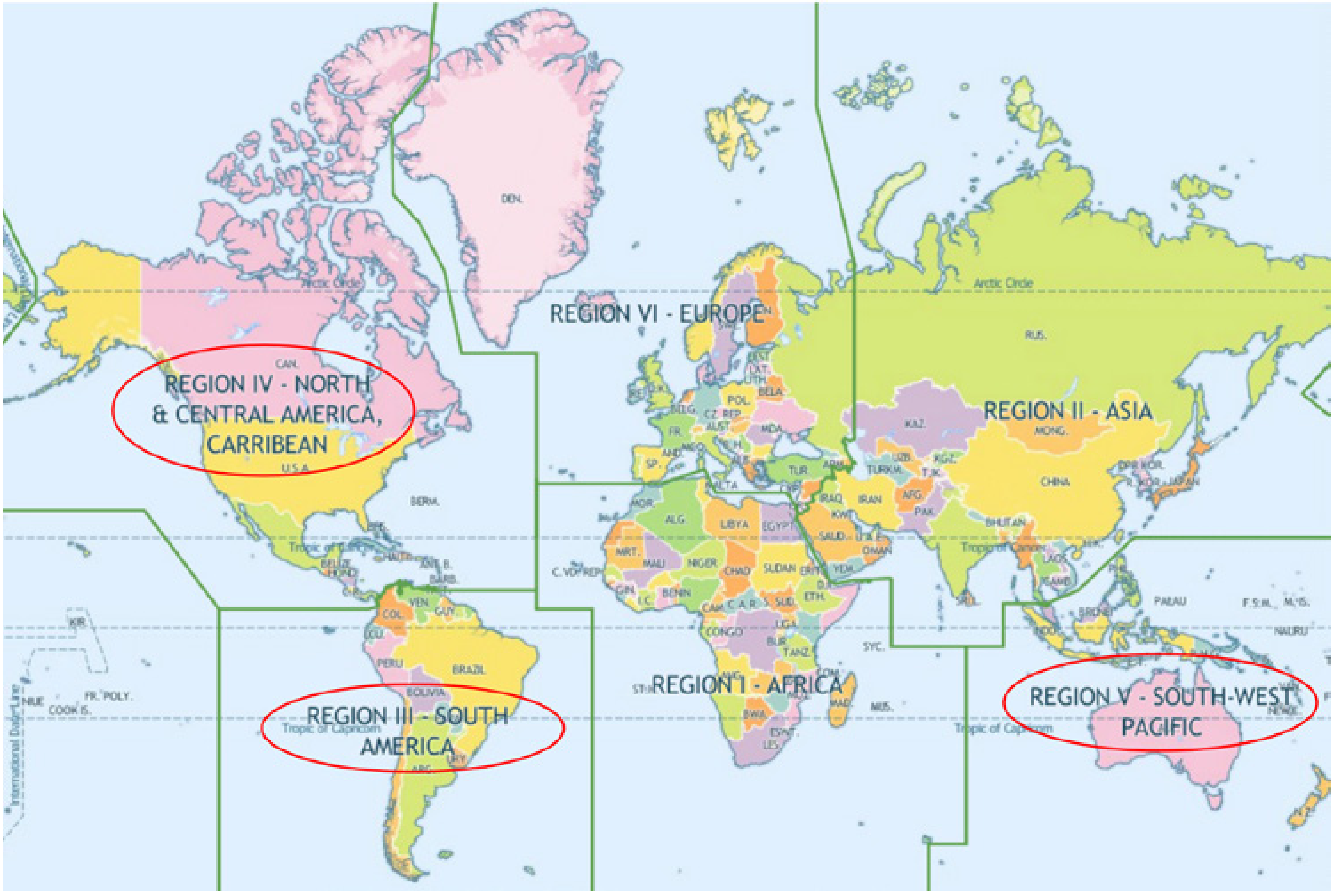
SSEC RealEarth™ — https://realearth.ssec.wisc.edu/
Imagery from a variety of satellites and their derived products, including JPSS fire, flood, and ice products, NUCAPS soundings, and VIIRS Direct Broadcast data over the U.S. and Puerto Rico.

NASA SPoRT Viewer — https://weather.ndc.nasa.gov/sport/viewer/
Gridded NUCAPS soundings for various areas around the world, including the U.S. and U.S. Territories, VIIRS imagery for the North Atlantic, and data from many other sources.

A GLOBAL PERSPECTIVE ON TRAINING

Lindstrom has a different perspective on satellite data training than Torres given that his recent experience has been mostly global. "A lot of where I've done training in the last couple of years has been in the tropics," Lindstrom elaborates, stating that he works with users throughout the South/West Pacific, Americas, and the Caribbean (World Meteorological Organization Regions III, IV, and V). His training style spans in-person workshops, webinars, videos, Quick Guide handouts, and blog posts about weather events and satellite imagery, and to make the most impact Lindstrom tailors his training materials to the specific concerns of the trainees' region.

Taking a holistic approach to training, Lindstrom regards preparation and follow up as important as the training itself. "If something goes catastrophically wrong (during training), which it occasionally does," he says, "it's good to be prepared." Lindstrom

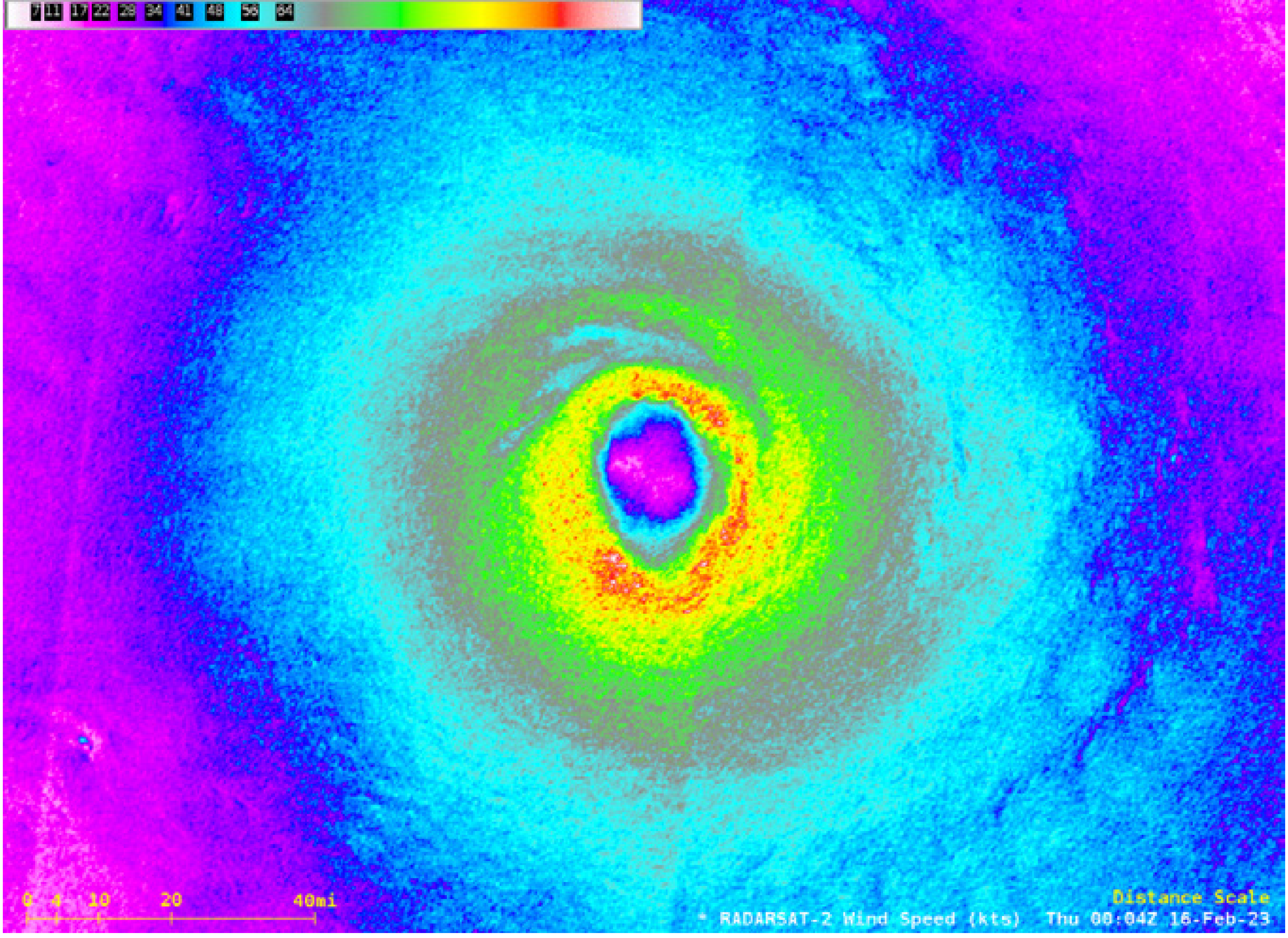


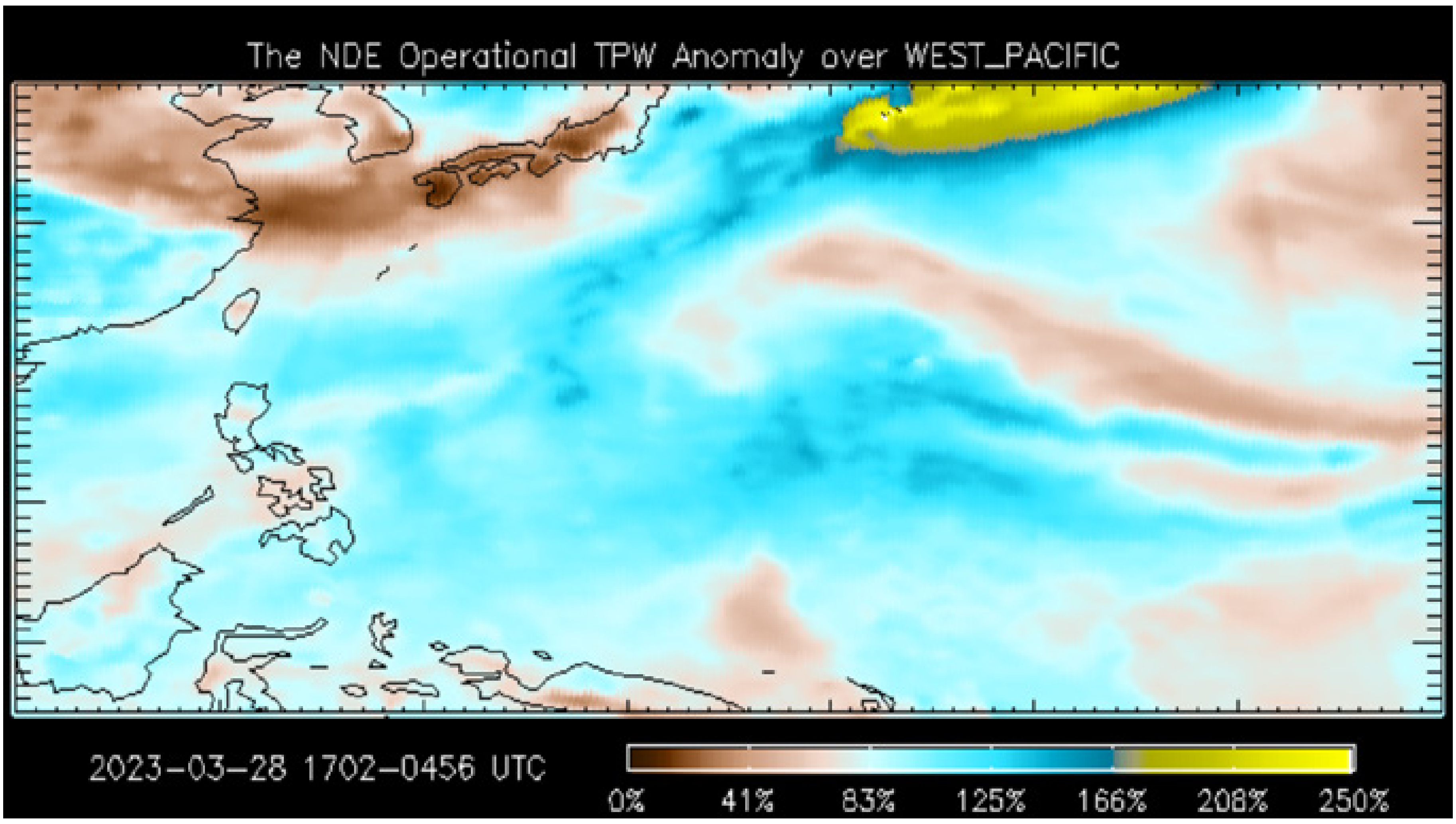
also points out that follow up is especially important for new topics. Without it, trainees tend to forget what they learned. "When you're introducing someone to something new you have to introduce it to them multiple times. I try to do this with follow up emails or a webinar after I've led a training."

Like Torres, Lindstrom is constantly learning. "Learning to find data that can be used, learning how to train within the confines of a different culture, learning the weather of the region—all of this must occur for a trainer to establish connections with the forecaster so that a good working relationship can develop, one that allows ongoing give and take of information between the meteorologists being trained and the trainer, because training must be ongoing and not just a one and done event." For Lindstrom, there are many factors to consider when putting together a satellite data training and many potential challenges to overcome.

Considerations and Challenges

One of the first questions Lindstrom asks himself when preparing for a training is, What kind of information needs to be shared? Over the years he has learned that trainees are most interested in learning how to apply satellite data to events that affect them. In the tropics—where Lindstrom trains the most—this means talking about tropical cyclones. But significant weather events like these happen infrequently. Trainers should also talk about everyday weather because, Lindstrom says, "you want people using satellite imagery every day so that they're familiar

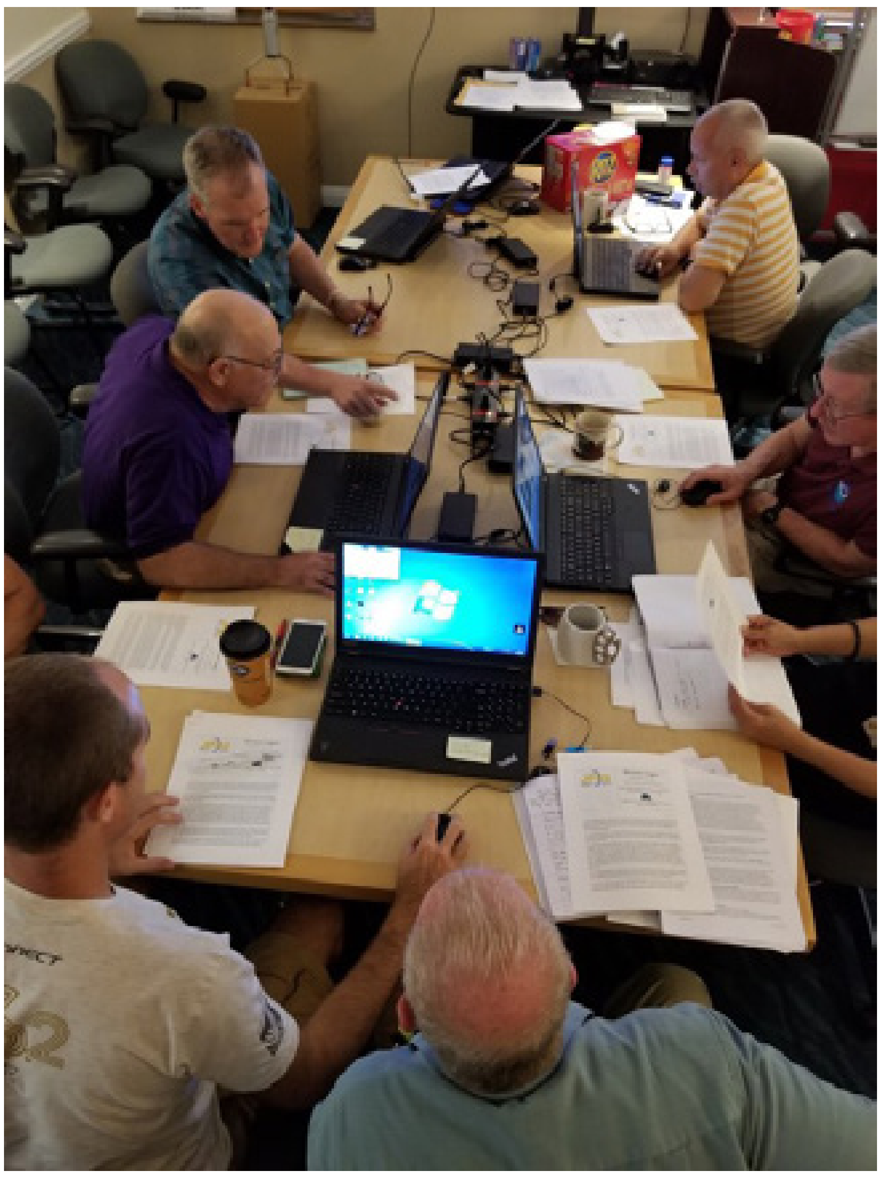




Top: An infrequent weather event. Cyclone Freddy in the Indian Ocean on February 16, 2023, from RADARSAT-2 SAR data depicting wind speed. Source: CIMSS. Bottom: "Everyday" weather. Percent of Total Precipitable Water (TPW) over the West Pacific region on March 28, 2023, from the NESDIS Operational Blended TWP product. Source: NOAA OSPO.

with it" and prepared for when an impactful event is approaching. "The difficulty is, sometimes the data is pretty boring," he remarks. Keeping the audience engaged can be a challenge—one approach is to start with a good image. "A good image can capture your eye and tell a compelling story," says Lindstrom, prompting a trainee to want to learn more.

For international trainers like Lindstrom, a trainee's fluency in English is a potential barrier to effective communication and comprehension. In his experience, "it's a huge roadblock as to how much information you can transfer to your students because they have to receive what you're saying and then translate it into something they understand." Providing trainees with lecture material beforehand can help them prepare but doing so leaves trainers with less flexibility during the live lesson.



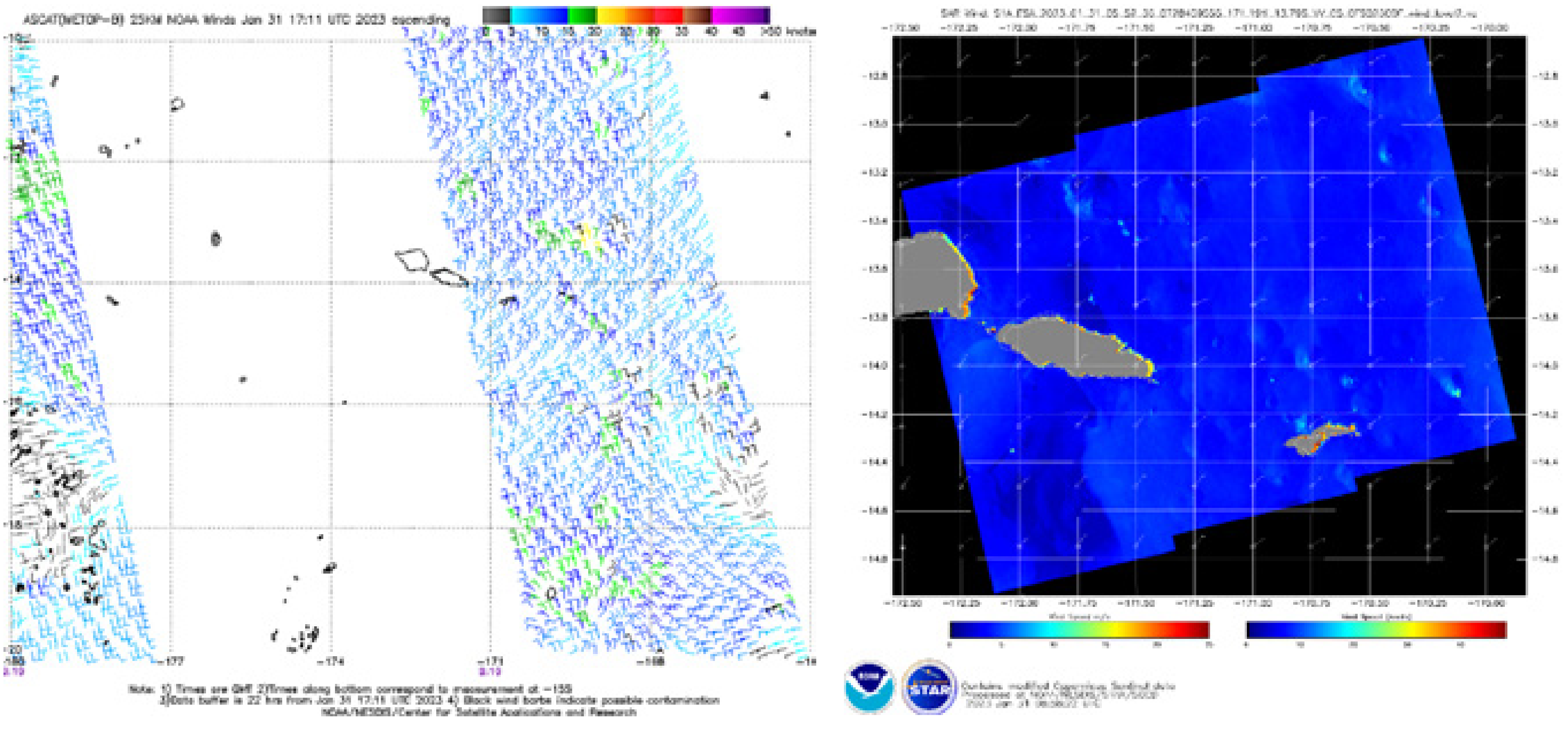
Guam Direct Broadcast Polar Orbiter Applications Workshop, National Weather Service Forecast Office, Tiyan, Guam, April 2018.

Culture can also limit productive learning. Lindstrom explains, "some cultures frown on questioning an expert or an elder, which makes it hard to gauge understanding, especially in a remote framework!" Creative solutions help in these situations, like using a question and answer app designed for anonymous feedback.

Challenges like these are amplified in a remote setting. Internet access and speed, distractions, and lack of engagement are some of the things Lindstrom dealt with as training moved online during the COVID-19 pandemic. While he has ways to address such challenges, he prefers in-person training. In-person sessions enable more accountability and support and allow Lindstrom to get a better sense of how well trainees are absorbing the information.

No Single Solution

"An important aspect of any training," asserts Lindstrom, "is to understand that no product is a silver bullet. I always tell people that if you're looking for one product to tell you everything, you will be disappointed. No product does it all." Like Torres, Lindstrom encourages trainees to look at several satellite data products to get a more complete picture or to confirm what they find.



Wind data from January 31, 2023, from Metop-B ASCAT (left) and Sentinel-1 SAR (right).

Scale (spatial resolution and geographic coverage) is also important. "You need to know which products to use for which kind of situation," he explains. "Talking about scale helps your students think about the scale that they need for different events and what kind of product provides information at that scale." Case in point: The Metop-B Advanced Scatterometer (ASCAT) and Sentinel-1 Synthetic Aperture Radar (SAR) instruments both provide wind information but at different resolutions (below). SAR data has a high spatial resolution (down to five meters), but it covers a small geographic region. ASCAT provides global coverage, but has a 25-km spatial resolution, much lower than SAR. A challenge for any trainer is to illustrate when one product should be used instead of another, or how products may enhance each other when combined. "A good trainer has to be a good meteorologist and be able to quickly understand and interpret a scene," says Lindstrom. "This comes with experience and with looking at a lot of data."

ONLINE TRAINING RESOURCES FOR A BROADER AUDIENCE

Live training sessions, whether in-person or virtual, are an active learning approach that provide a means for trainees to take part in discussions and receive immediate feedback from the instructor. Different, but just as valuable, are online training resources available to anyone with access to the internet—materials like product reference guides, recorded webinars, video tutorials, and blogs. One such organization that offers online resources is the Virtual Institute for Satellite Integration Training (VISIT), a collaborative program administered by CIRA, CIMSS, and NOAA staff. Their Quick Guides (1-2 page handouts) and Quick Briefs (short videos) that concisely summarize product purpose, impact, and specifications "are powerful tools because the information responds to the operational use and applications of the products," says Torres. VISIT also has a Satellite Help Desk where forecasters can ask satellite-related questions and search through already answered questions. All these resources are available for free through the VISIT program.

Training materials for satellite data products developed by CIMSS "are all funded through GOES-R and JPSS" programs, says Lindstrom. These include Quick Guides, videos, presentations, satellite imagery, and blogs available on the CIMSS website. The CIMSS Satellite Blog is of particular interest to forecasters. It is a searchable site that explains how satellite imagery and products are used to monitor meteorological events across a broad range of topics from air quality to winter weather, including a category called "What the Heck is This?" that talks about unusual events. CIMSS also hosts several other blogs about specific weather phenomena (like fog) or satellite instruments (like the JPSS Ozone Mapping and Profiler Suite (OMPS)) that provide a more focused view of select topics.

Satellite Hydrology and Meteorology (SHyMet) courses offered by CIRA in collaboration with CIMSS and others are designed to prepare operational forecasters for the latest polar and geostationary satellite data, products, and forecasting techniques. The brief self-paced training videos cover a range of subject matter from basic principles of satellite imaging and sounding to advanced topics like the identification of atmospheric and surface phenomena. Going a step further, the WMO-CGMS[3] Virtual Laboratory for Training and Education in Satellite Meteorology (VLab) takes online training global through a network of virtual training centers focused on satellite applications in meteorology. Through these Regional Meteorological Training Centres, CIRA, CIMSS, and NOAA (including NWS and NESDIS) provide training support to countries in Central and South America and the Caribbean.

A LOOK AHEAD

With the next generation of polar orbiting and geostationary satellites from NOAA planned for operation in the 2030s, operational and research communities will have more information than ever to solve complex problems. New users of satellite data will need instruction in how to acquire, make sense of, and apply new data and products, and there will be a continuing need for new training resources as satellite sensors evolve and products advance beyond state-of-the-art. Meeting these needs requires experienced trainers like Torres and Lindstrom, each of whom has shown great success in translating complex topics into understandable concepts that others can readily apply to meet their mission requirements. Trainers like them are LEO's most important training resource and continuing to offer tailored curricula as well as online materials is critical for ensuring that forecasters and researchers are prepared for a new era of satellite data and products. ✦

STORY SOURCE

The information in this article is based, in part, on the November 30, 2022, LEO Science Seminar "The Joint Polar Satellite System (JPSS): Applications, Data Access, Liaison Interactions with Users, and Training" presented by Jorel Torres, Research Associate II/JPSS Satellite Liaison, Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, and on the February 22, 2023, LEO Science Seminar "Training Forecasters to Use Satellite Data Worldwide" presented by Dr. Scott Lindstrom, Scientist, Cooperative Institute for Meteorological Satellite Studies (CIMSS) at University of Wisconsin-Madison.

FOOTNOTES

1 The Office of Low Earth Orbit Observations (LEO) offers many JPSS-specific training resources on the NOAA NESDIS website: www.nesdis.noaa.gov/jpss-training.

2 GOES is NOAA's Geostationary Operational Environmental Satellites

3 World Meteorological Organization (WMO)—Coordination Group for Meteorological Satellites (CGMS) is the group that globally coordinates meteorological satellite systems.

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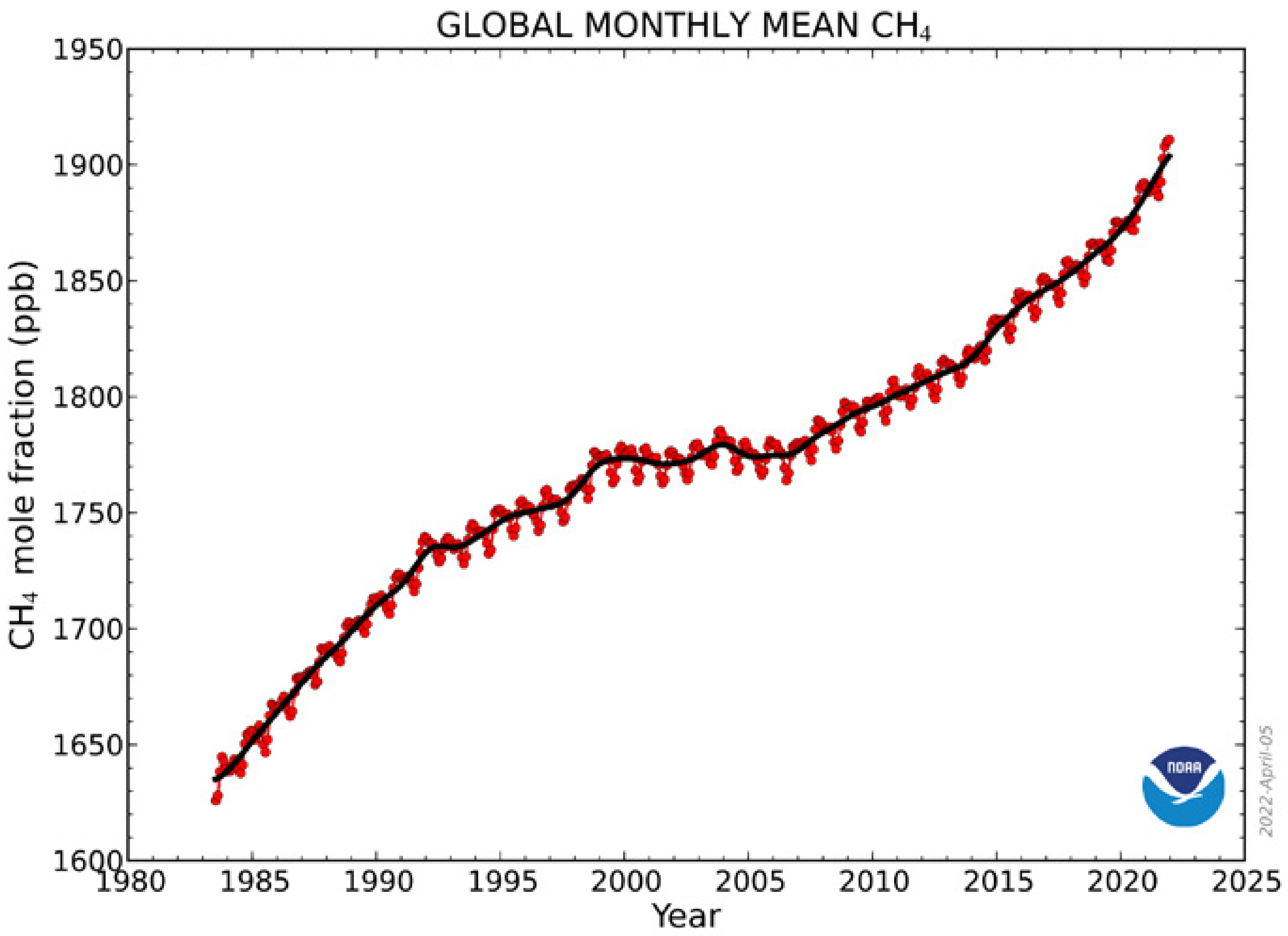
FEATURE 4

Understanding Methane Emissions With CarbonTracker-CH_4

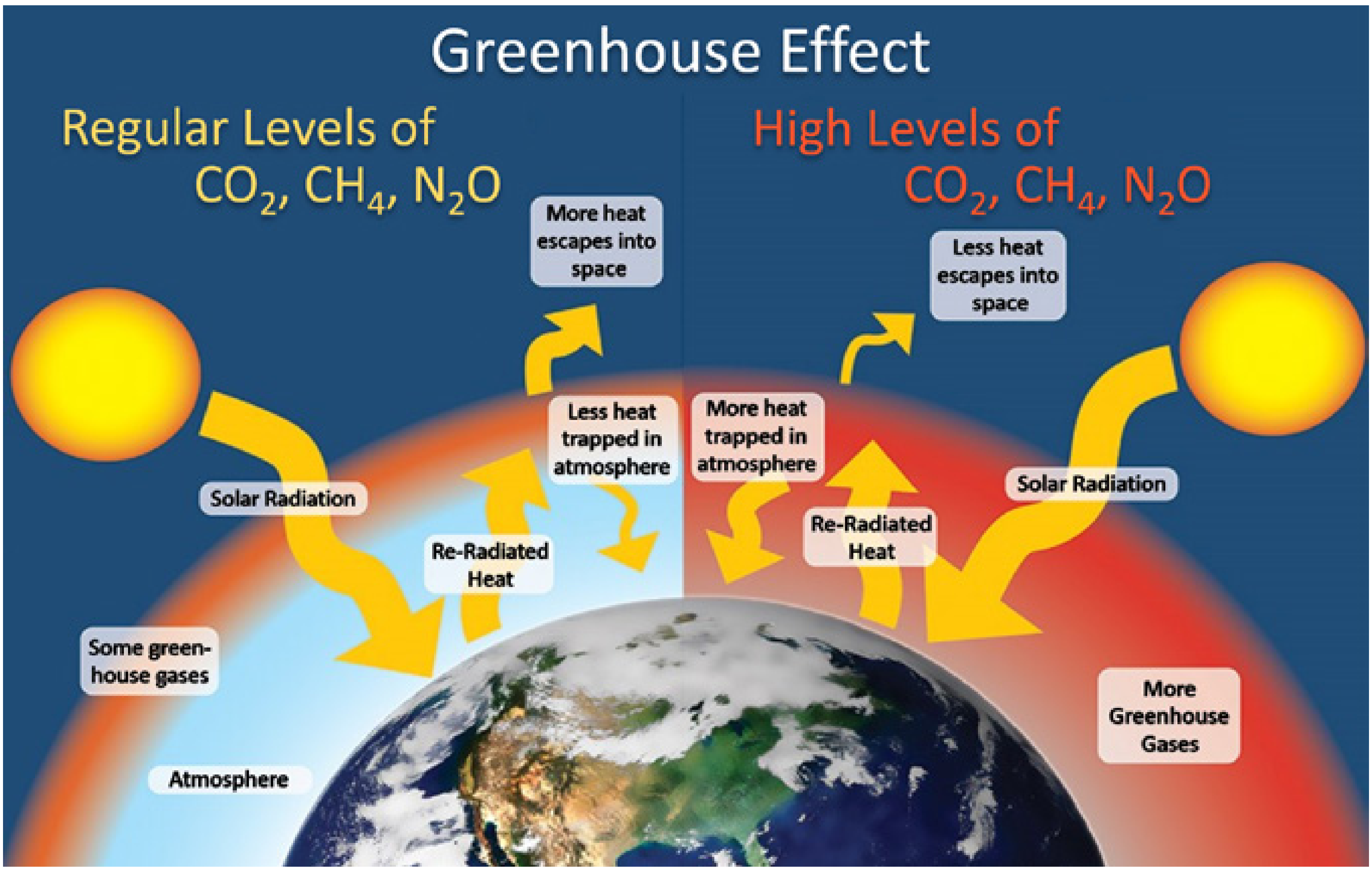
Jatiluwih rice terraces in Indonesia. Rice production is a significant contributor to global methane emissions due to the anaerobic decomposition process. (Image credit: Flickr user Enrico Strocchi, Creative Commons CC BY-SA 2.0 DEED, image cropped).



Methane trend: This graph shows globally-averaged, monthly mean atmospheric methane abundance determined from marine surface sites since 1983. Values for the last year are preliminary. Source: NOAA Global Monitoring Laboratory.

The last few years have seen atmospheric methane (CH_4) surge to an average of nearly 1,900 parts per billion (ppb), more than two and a half times pre-industrial levels. The largest increase on record occurred in 2021, beating the previous record set just one year prior, with 2022 right behind as the fourth-largest annual increase in four decades. These unprecedented numbers are worrisome. “After carbon dioxide, methane is the second most important greenhouse gas contributing to human-induced climate change,” says Dr. Youmi Oh, a research scientist at NOAA’s Global Monitoring Laboratory. “And unlike the pretty steady increase of CO_2 [carbon dioxide] and N_2O [nitrous oxide], atmospheric methane shows a unique long-term trend.”

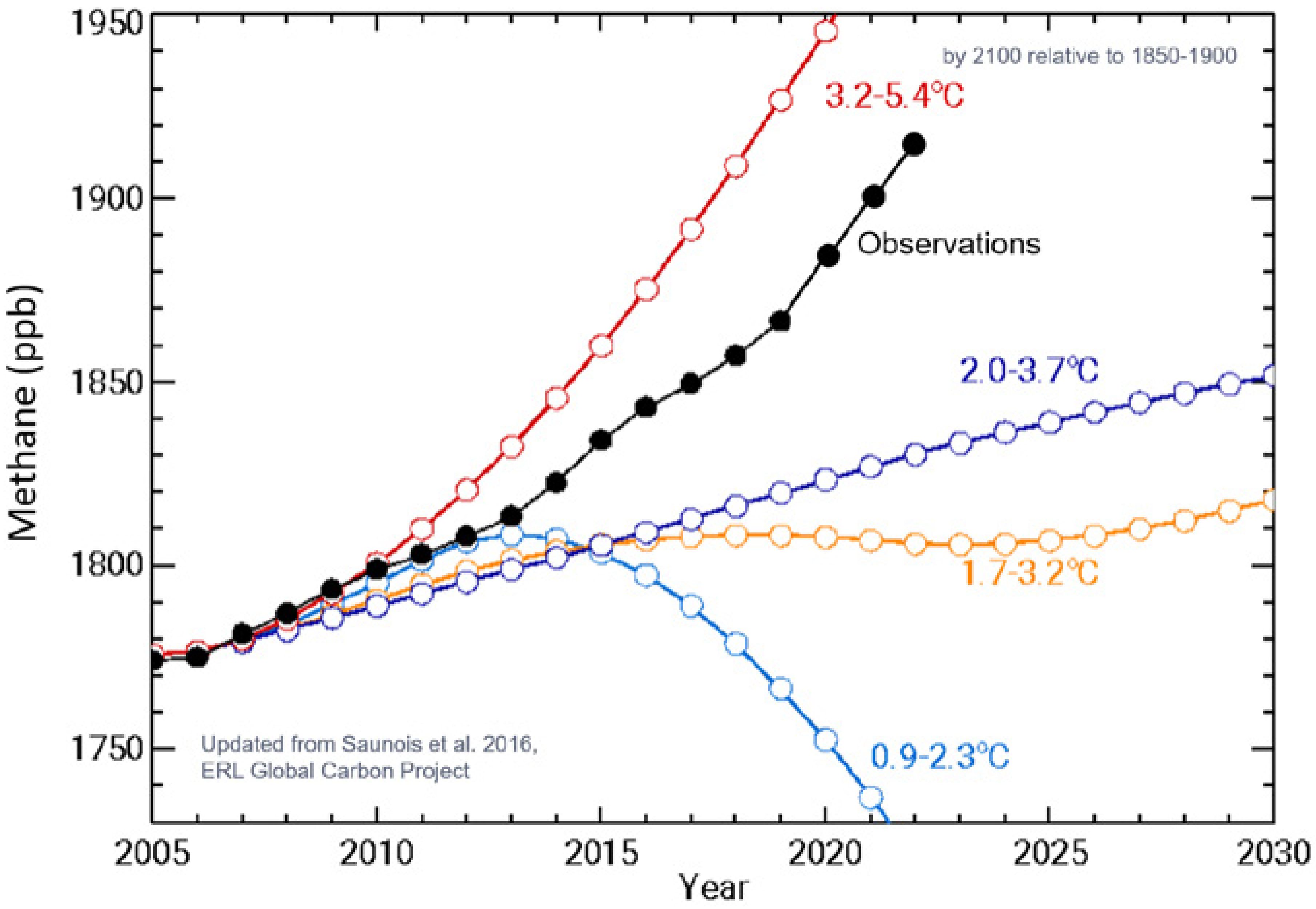
Methane’s effectiveness at absorbing energy is at the root of the problem—it is around 28 times more efficient[1] than carbon dioxide at trapping heat in the atmosphere, heat that contributes to a warming planet. Using climate-chemistry models to estimate the contribution of carbon dioxide and methane to observed changes in globally-averaged temperature since pre-industrial times, scientists have found that methane can have a large impact on temperature (0.5°C (0.25-0.8°C)) even though its radiative forcing is relatively small (radiative forcing is when the amount of energy entering the Earth’s atmosphere is different than the amount leaving). “This is because methane affects other radiative forcers that are also greenhouse gases through chemistry,” Dr. Oh explains. For example, chemical reactions between methane and other elements in the atmosphere can lead to an increase in tropospheric ozone, another potent greenhouse gas and harmful air pollutant.



Left: Regular levels of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are created by normal life processes, trapping some of the sun's heat and preventing the planet from freezing. Right: The rampant emission of CO_2, CH_4, and N_2O from burning fossil fuels and other anthropogenic sources traps excess heat and results in an increase in the average temperature of the planet. Source: Adapted from an image created by Will Elder, National Park Service, https://www.nps.gov/goga/learn/nature/climate-change-causes.htm.

Atmospheric methane is rapidly approaching a worst case scenario. Projections for four International Panel on Climate Change (IPCC) emissions scenarios alongside methane observations (right) show that methane in the atmosphere (black) is approaching IPCC's warmest emission scenario (red) in which global surface temperatures could increase by as much as 5.4°C by the year 2100. An increase of this scale would have devastating consequences to human health and security, the economy, and the environment, likely resulting in water scarcity, reduced crop yields, increased heat-related illness and mortality, coastal dead zones incapable of supporting aquatic life, increased deforestation, human migration, species loss and extinction, unstable economic markets, suppressed economic growth, and more intense extreme weather events like droughts, floods, wildfires, and storms, just to name a few examples. Communities that rely on agriculture or coastal resources are at highest risk for experiencing the brunt of such impacts, as are disadvantaged and vulnerable populations.

There is hope: "The fact that methane is chemically reactive makes it possible to have a disproportionately large effect on temperature change, but it also presents an opportunity because reducing methane emissions can have a relatively quick climate benefit because of its short lifetime," Dr. Oh points out. "The lifetime of methane is nine to ten years, which is much shorter than the lifetime of carbon dioxide [between 300 to 1,000 years], meaning if we reduce methane emission right now, we could see the changes in atmospheric methane in ten years." More than 100



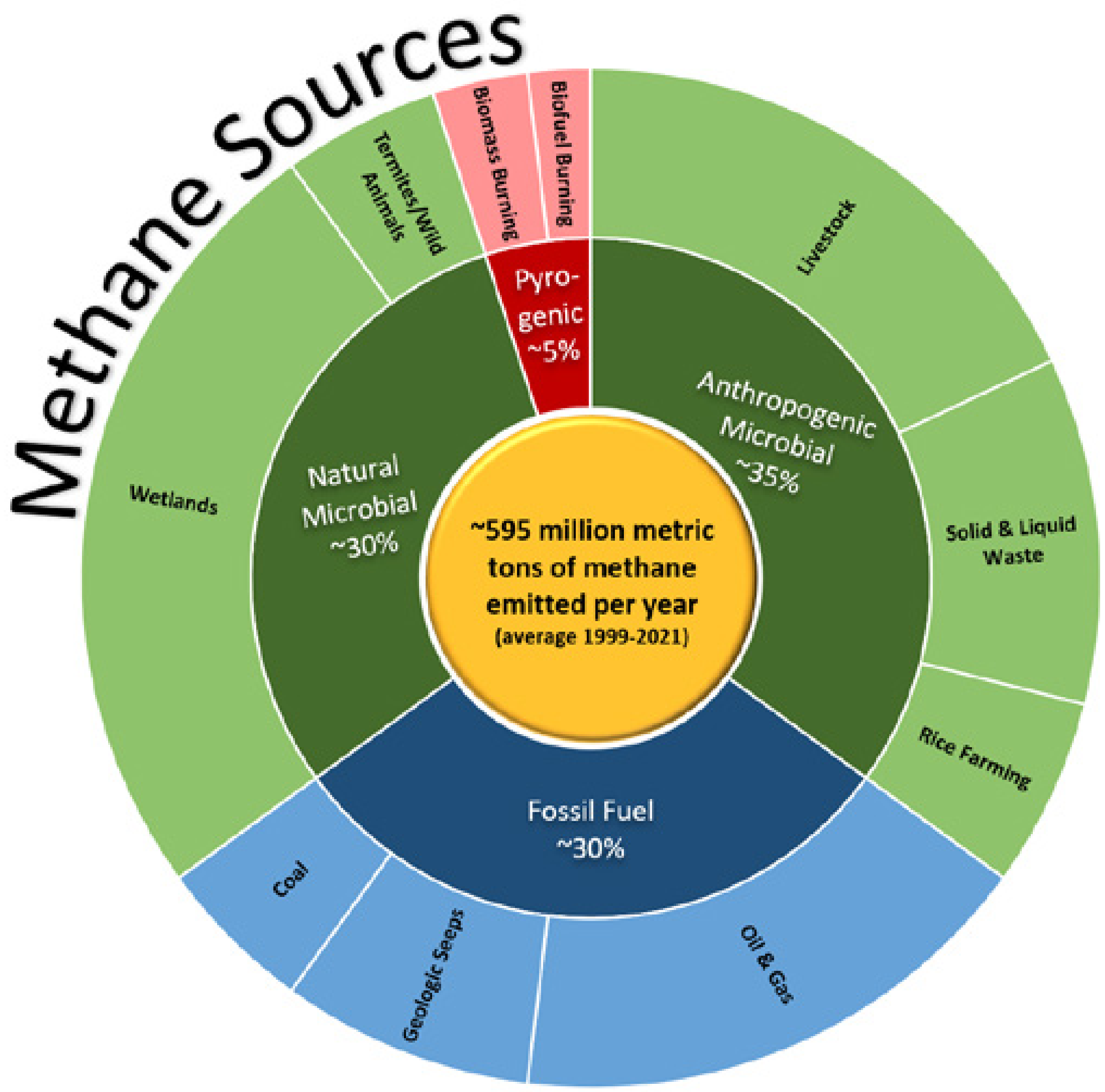
Projections of atmospheric methane mole fraction for four IPCC global warming scenarios from 2005 to 2030.

countries have recognized the importance of acting now, pledging to take voluntary action to reduce global methane emissions by at least 30% by 2030 from 2020 levels through the Global Methane Pledge launched in 2021.

Scientists need a clear understanding of methane sources and sinks to provide effective solutions for reduction, but the causes of the recent rapid growth in atmospheric methane are widely debated. To help provide answers, scientists at the NOAA Global Monitoring Laboratory have developed an atmospheric assimilation system called CarbonTracker-CH_4 that uses atmospheric methane measurements to estimate global methane emissions by source and assesses the effect of methane removal from the atmosphere. In addition to providing valuable information for research, scientists are also using CarbonTracker-CH_4 to evaluate the sensitivity of the JPSS Cross-track Infrared Sounder (CrIS) to atmospheric methane. At an April LEO Science Seminar, Dr. Oh and Dr. Lori Bruhwiler, a physical scientist at the NOAA Global Monitoring Laboratory and co-lead for the project, presented an overview of recent and planned developments for the CarbonTracker-CH_4 model.

UNDERSTANDING METHANE SOURCES AND SINKS

Atmospheric methane is an important trace gas that keeps the planet warm and habitable. Trace amounts of methane are normal, the result of natural environmental processes that occur in wetlands, for example. But the soaring concentrations seen today are largely from human (anthropogenic) activity like agriculture, oil and gas production, coal extraction, and waste facilities, or natural climate feedback due to anthropogenic environmental changes. Altogether, nearly

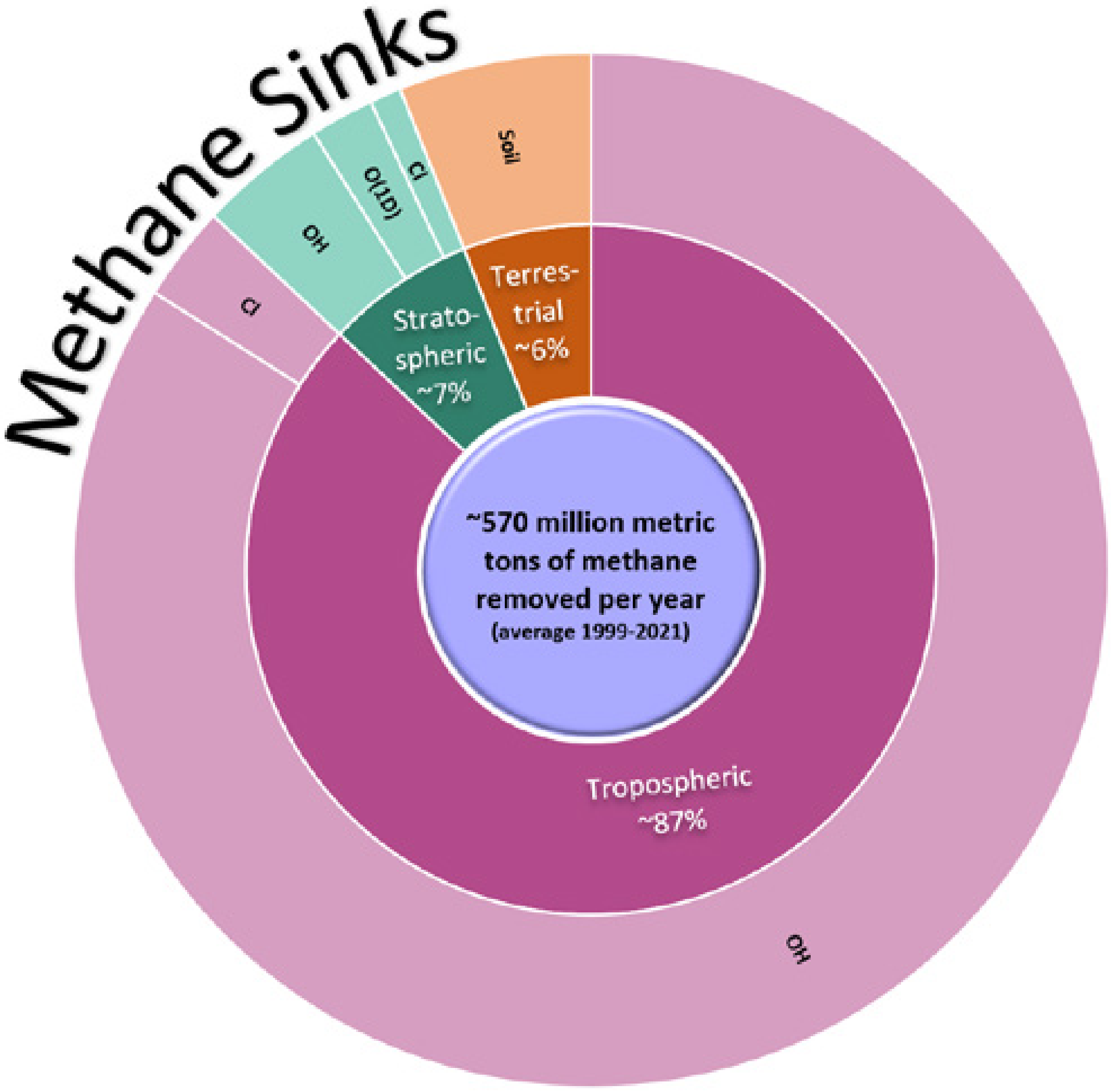


600 million metric tons of methane are emitted each year[2]—a mass equivalent to 5 trillion bananas!

Natural and human-induced methane emissions fall into three main source categories: fossil fuel, pyrogenic, and microbial. While methane emission estimates are highly uncertain, recent data suggests that fossil fuel sources account for around one-third of the total methane emitted annually, mostly from oil, natural gas, and coal production and use, as well as natural geologic seeps. The smallest contributor of emitted methane is pyrogenic sources, making up a mere five percent of the total yearly methane emissions. Pyrogenic methane emissions are produced under intense heat, like that from biofuel or biomass burning.

The largest contributor is microbes, which create methane as they produce energy to survive through an anaerobic process called methanogenesis. “Anthropogenic microbial emissions from livestock, waste, and rice [farming] account for 35 percent of total emissions, and natural microbial emissions from wetlands, termites, wild animals, and other aquatic sources account for another 30 percent of total emissions,” notes Dr. Oh. Added up, microbes are responsible for about two-thirds of all the methane emitted each year—a huge amount for such tiny organisms.

Greenhouse gas sinks are critical to counterbalance greenhouse gas emissions. Sinks are any process or activity that removes a greenhouse gas from the atmosphere by capturing, securing, and storing it in another form. For methane, chemical reactions in the atmosphere are the largest sink—methane reacts with atoms in the air to form new molecules. For example, hydroxyl (OH) radicals in the



troposphere cause atmospheric methane to break down into water vapor (stays in the atmosphere for days versus years for methane) and carbon dioxide (less potent than methane). In fact, hydroxyl radicals are responsible for removing about 85% of atmospheric methane each year and are such an effective sink that Nobel Prize winning meteorologist and atmospheric chemist Paul Crutzen once called them the “detergent of the atmosphere.”

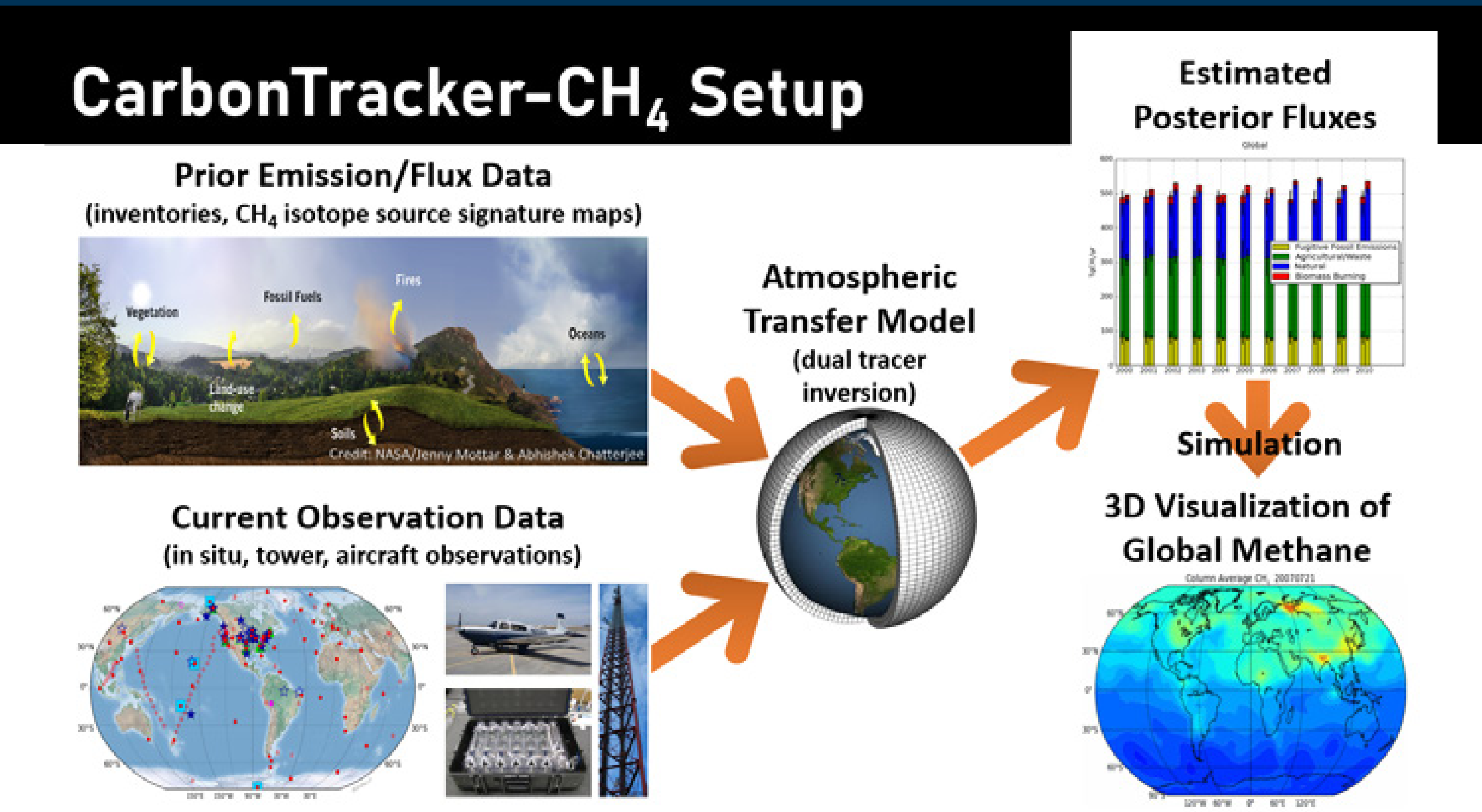
To a lesser extent, methane is also removed from the atmosphere through other reactions, like when methane meets an excited oxygen (O(1D)) or chlorine (Cl) atom. A small fraction of methane is also removed through microbial soil oxidation. All in all, an estimated 570 million metric tons of methane is removed annually from the atmosphere through these sinks, about 30 million metric tons less than the amount of methane emitted. While “the methane sink is of similar magnitude to the [methane] emissions,” says Dr. Oh, “the difference between them causes an increase in atmospheric methane abundance.”

UNRAVELING METHANE EMISSIONS WITH CARBONTRACKER-CH_4

The Global Methane Pledge aims to cut 105 million metric tons of methane per year, but this goal is not possible by cutting fossil fuel emissions alone. What’s more, uncertainty plagues the separation of emission sectors, making it hard to know which sources to target for reduction actions. One thing is certain: “We will need to address anthropogenic microbial emissions,” stresses Dr. Oh. “We need to understand these microbial processes in order to improve our ability to make

Atmospheric Inverse Models

Atmospheric inverse models are used to identify regional patterns of greenhouse gas emissions and uptake by sinks. They do so with a "top-down" approach that inversely estimates emissions based on observed atmospheric greenhouse gas concentrations. Generally, regional fluxes estimated from atmospheric inverse models have smaller uncertainties compared to "bottom-up" methods that use emission factors.



projections of future climate change, and craft policies that are consistent with climate goals."

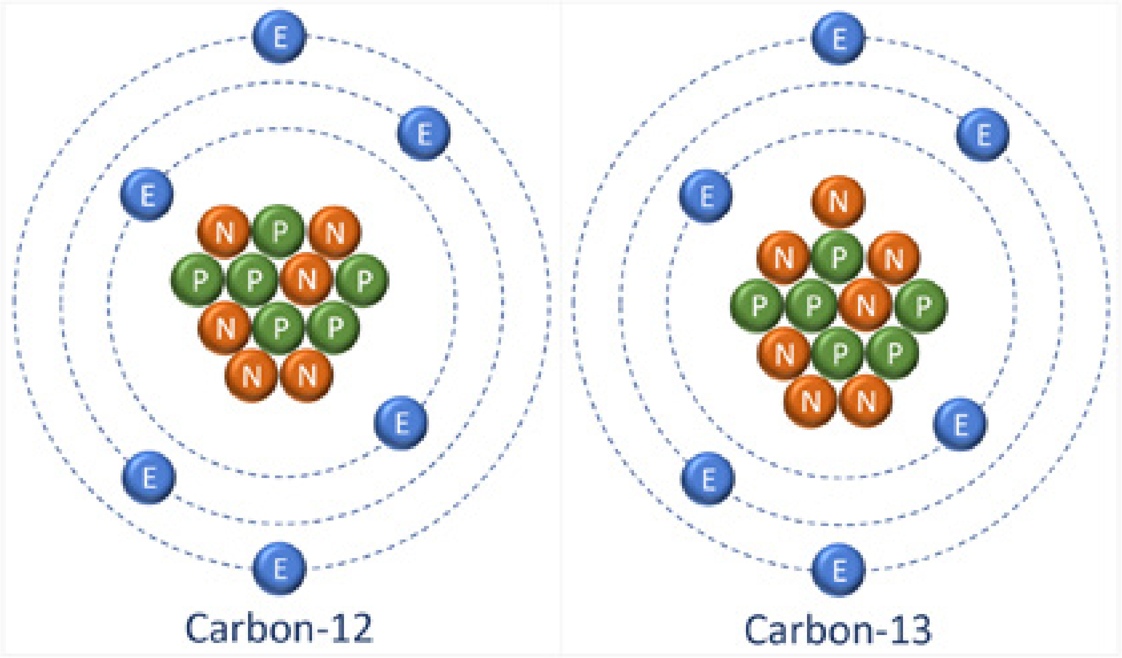
CarbonTracker-CH_4 was developed to tackle these challenges—to estimate global methane emissions at policy relevant spatial scales and provide insight into the effects of sinks in the atmosphere. "Using the CarbonTracker-CH_4, we can also quantify the natural emissions and we can see if the emissions are related to the climate feedback and see what the role of land use change is," Dr. Oh adds.

CarbonTracker-CH_4 is a top-down atmospheric inverse model. The system combines prior emission estimates and assimilated surface (in situ) and near-surface (aircraft and tower) observations from the NOAA Global Greenhouse Gas Reference Network in an atmospheric chemical transport model to infer methane emission trends and produce analyses. The figure above is a simplified representation of the CarbonTracker-CH_4 data assimilation setup.

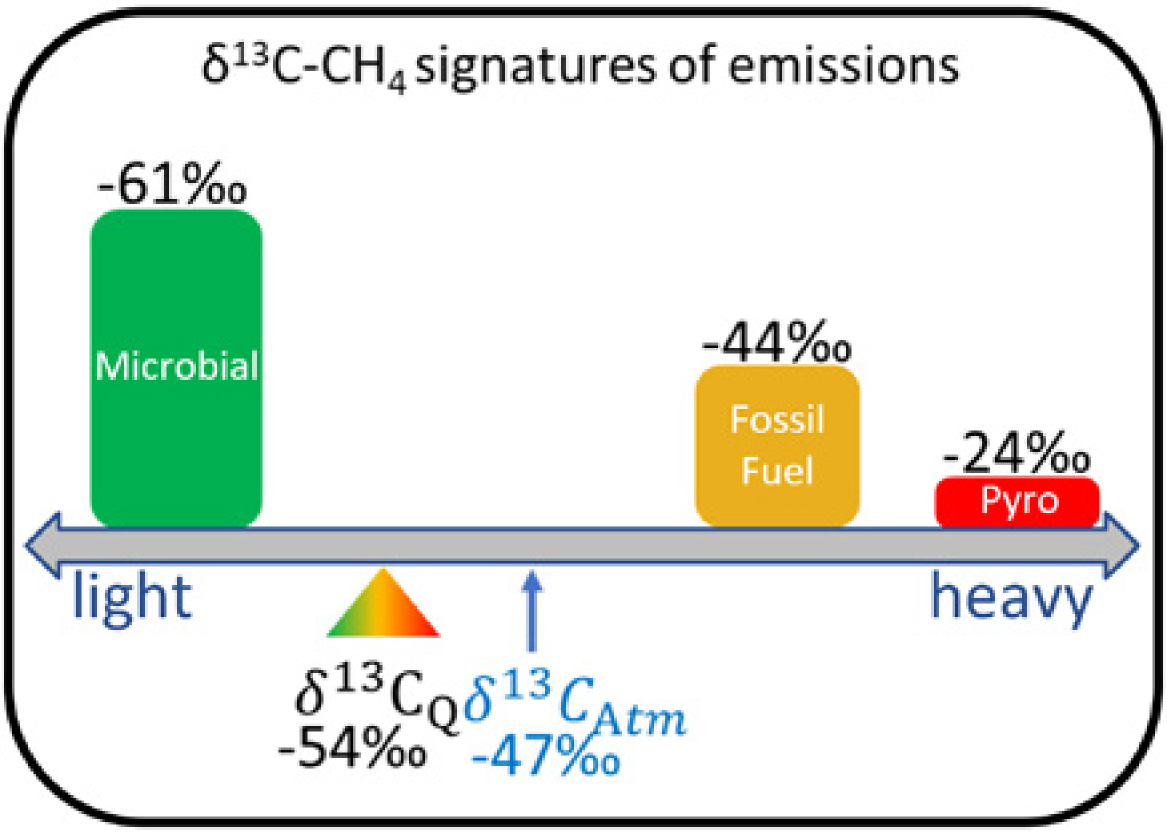
The Unique Wisdom of Isotopes

One of the difficulties in determining what is behind the recent surge in atmospheric methane lies in understanding the contribution of methane from different emission sources. "It's really hard to tell where methane emission is from because different emission sources are usually collocated," says Dr. Oh. For instance, a municipal solid waste landfill (a microbial emission source) may be located near a natural gas-fired power plant (a fossil fuel emission source) making it hard to quantify the emissions from each source. The key to making this distinction, it turns out, is isotopes.

Isotopes are different forms of the same element. They have the same number of protons and electrons, but a different number of neutrons. Methane is made up of one carbon (C) atom and four hydrogen (H) atoms, hence the notation "CH_4". The standard carbon atom is carbon-12 having six neutrons and six protons (6 + 6 = 12). However, carbon also occurs naturally as carbon-13 with seven neutrons and carbon-14 with eight neutrons. All three are carbon isotopes—same protons and electrons, but a different number of neutrons.



What does this have to do with methane? Methane emission sources each have a distinctive fingerprint—a source-specific isotopic signature that is the measure of the ratio between carbon-12 and carbon-13 in a sampled methane molecule as compared to a reference standard. The relative difference in ratios is expressed as the "delta notation," written as $\delta^{13}C$. "If the delta notation is more negative that means it [the molecule] is lighter and if it's less negative, then it's heavier," Dr. Oh explains.



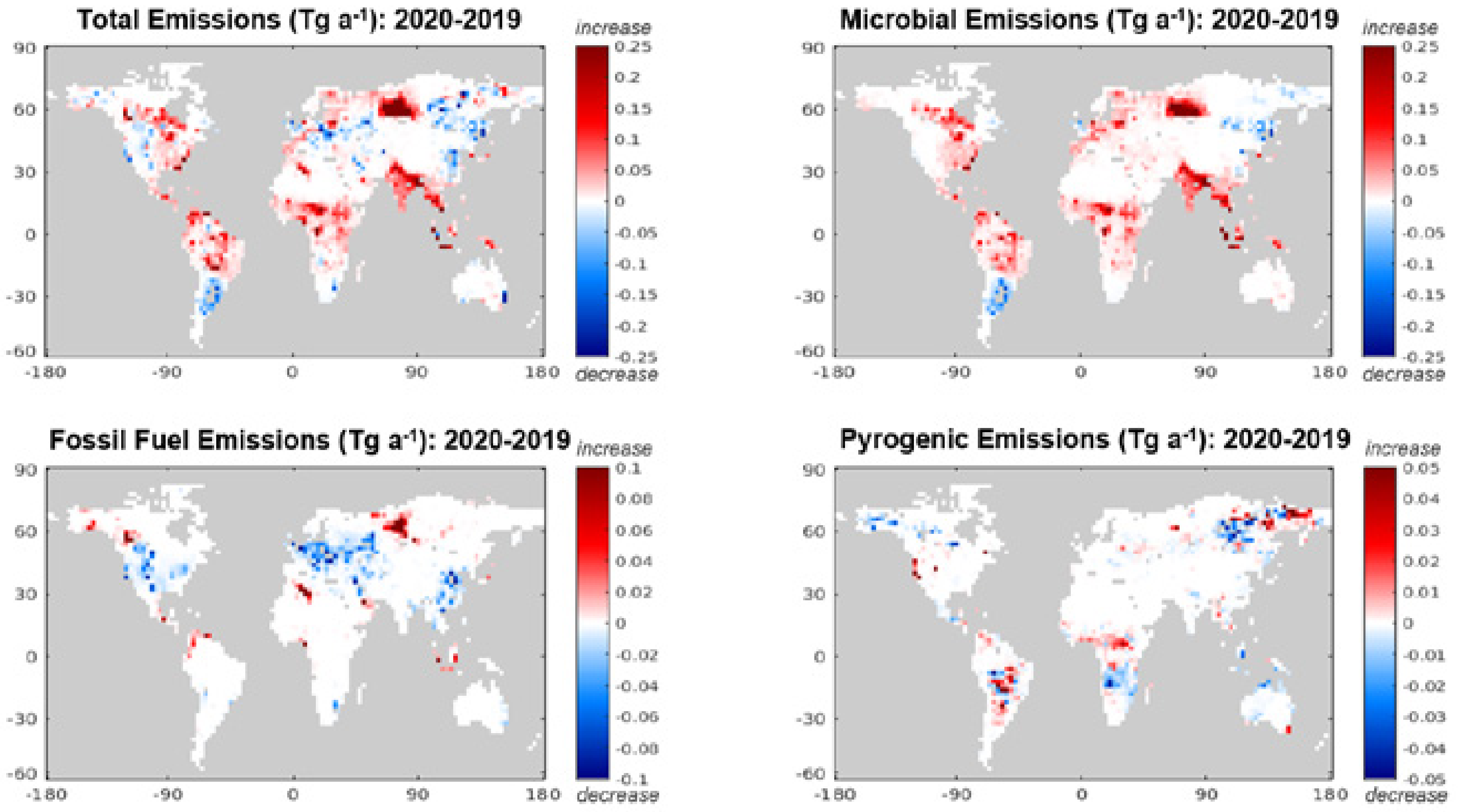
This see saw plot shows the δ13C values for methane emissions from natural and anthropogenic microbial sources (green), fossil fuel sources (yellow), and pyrogenic (red) sources. These values have units of "per mil" symbolized by "‰".

For atmospheric methane, emissions from microbial sources (natural and anthropogenic) are lighter than fossil fuel and pyrogenic emissions because microbial emissions have fewer carbon-13 atoms. CarbonTracker-CH_4 exploits this attribute by jointly assimilating measurements of methane and the stable isotope ratio of methane ($\delta^{13}C$-CH_4). With a unique isotopic fingerprint for each source category, the model can quantify monthly global emissions by sector to identify long term trends—critical knowledge for implementing targeted methane reduction actions.

"We Want To Understand What Is Driving the Trend"

Below is an example CarbonTracker-CH_4 simulation illustrating the impact of assimilating methane isotope information. The plots show the change in methane emissions from 2019 to 2020, indicated by color—red for increased emissions and blue for decreased. Microbial, fossil fuel, and pyrogenic sources are separated from the total number of emissions (top left). Dramatic growth in microbial emissions is seen globally (top right), while a large decline in fossil fuel emissions (bottom left) is observed across the U.S., Europe, and China, presumably the result of pandemic-related lockdowns that caused a record plunge in greenhouse gas emissions in 2020. Pyrogenic emissions (bottom right) also generally decreased from 2019 to 2020, an expected drop since 2019 was a more active year for wildfires.

These and other results from CarbonTracker-CH_4 generally agree with other models, says Dr. Oh. "The long term trends in $\delta^{13}C$-CH_4 [delta notation] show that the atmospheric methane has been getting lighter—a strong hint that the recent methane increase is from microbial sources that can be anthropogenic or natural sources." Sector-specific trend analyses such as these are helping scientists determine which source or sources are behind the recent surge in emissions. "We want to understand what is driving the trend," she emphasizes. So where does satellite data fit in?

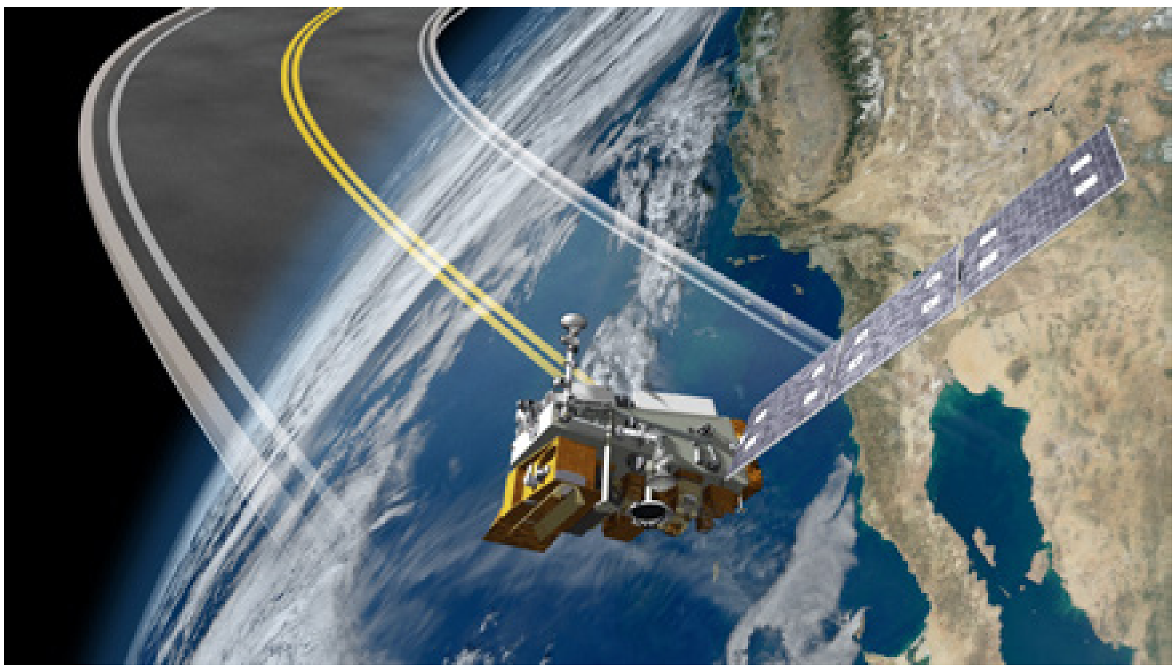


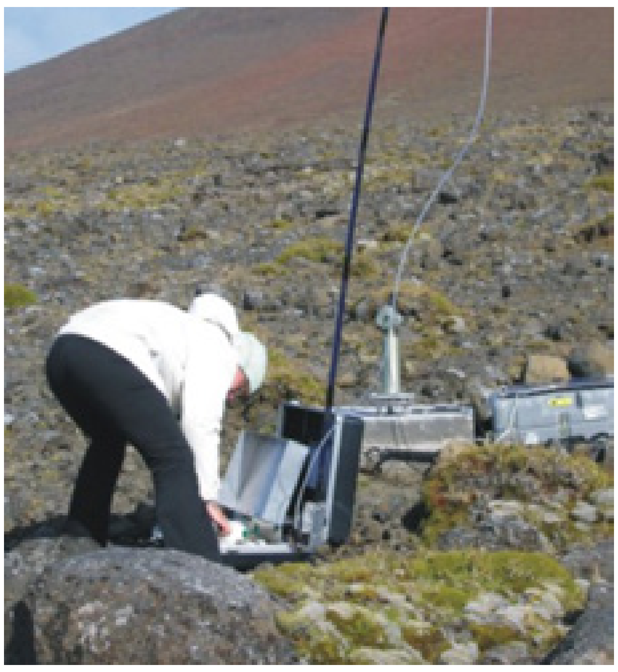
COMPLEMENTARY OBSERVATIONS FROM SURFACE AND SPACE

"A caveat of [CarbonTracker-CH_4] is that we are only using in situ [surface] data—we do not have good coverage over the sea barrier region or the tropics," says Dr. Oh. For areas like these where surface measurements are scarce, satellites can help fill gaps, offering scientists a more complete picture of methane fluxes and their seasonal variability—information needed to understand mitigation opportunities.

The surface and near-surface measurements assimilated in CarbonTracker-CH_4 provide a precise snapshot of atmospheric methane at a specific time and location. Satellites, in contrast, collect vast amounts of data repeatedly over large areas—globally in the case of JPSS—which is good for capturing dynamic measurements like atmospheric gases. The downside is that satellite measurements are indirect, which makes them less precise than in situ methods (direct measurements). But when in situ and satellite observations are combined, models tend to improve. Knowing this, Dr. Oh says, "we plan to incorporate satellite data into the CarbonTracker-CH_4 model in the future."

While satellites help fill large spatial gaps, in situ measurements play a critical role in calibrating and validating satellite sensors and algorithms, essentially acting as "truth" data against which satellite measurements are evaluated. This is especially important when looking at seasonality in atmospheric methane concentrations since atmospheric chemistry can influence satellite measurements. And when satellite retrievals are inconsistent with "truth" data, investigation is needed to understand why. A group of scientists at NOAA and its affiliates are using CarbonTracker-CH_4 to do just this—to evaluate a difference in the timing of seasonal variations in atmospheric methane from in situ observations and satellite sounding retrievals.

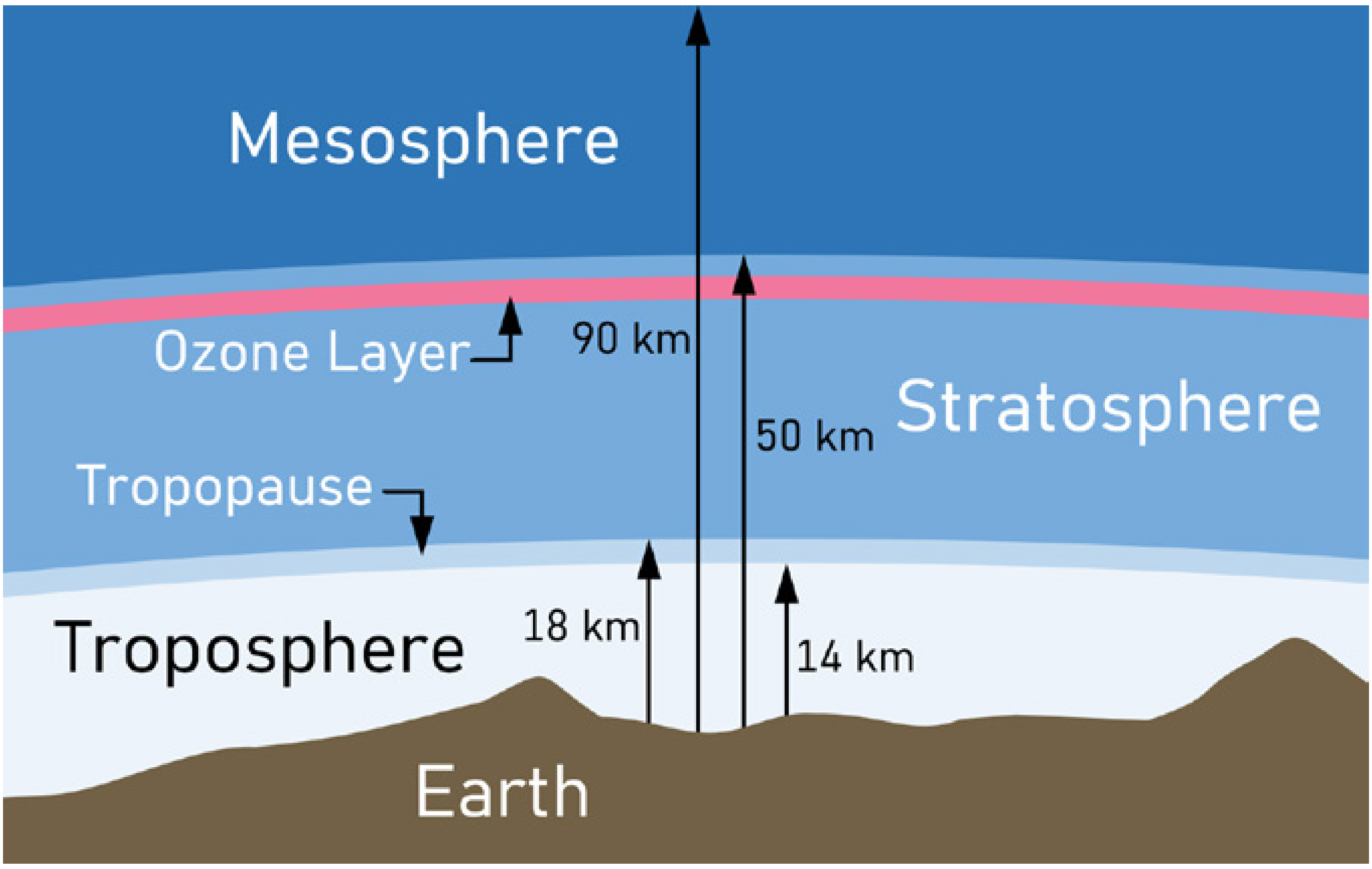




Above (Left): An artist rendering of the NOAA-20 satellite and its swath. Above (Right): A person setting up an in situ air sampling station.

Shifting Seasonality: The Sensitivity of Satellite Sounders to Methane

Hyperspectral infrared sounding instruments ("sounders"), such as the Cross-track Infrared Sounder (CrIS) onboard JPSS satellites and the Atmospheric Infrared Sounder (AIRS) onboard NASA's Aqua satellite, have been monitoring global methane concentrations in the mid to upper troposphere for decades. These observations are one way that researchers identify global long-term trends in methane spatial and temporal variability—information important for understanding methane sources and sinks. But thermal infrared sounders like CrIS and AIRS can also detect methane in the lower stratosphere near the tropopause, the boundary layer between the troposphere and stratosphere (see illustration). This sensitivity causes a seasonal (temporal) shift in methane concentrations retrieved from CrIS and AIRS in the mid to high latitudes of the Northern Hemisphere—where surface emissions are higher—compared to corresponding surface measurements ("truth" data).

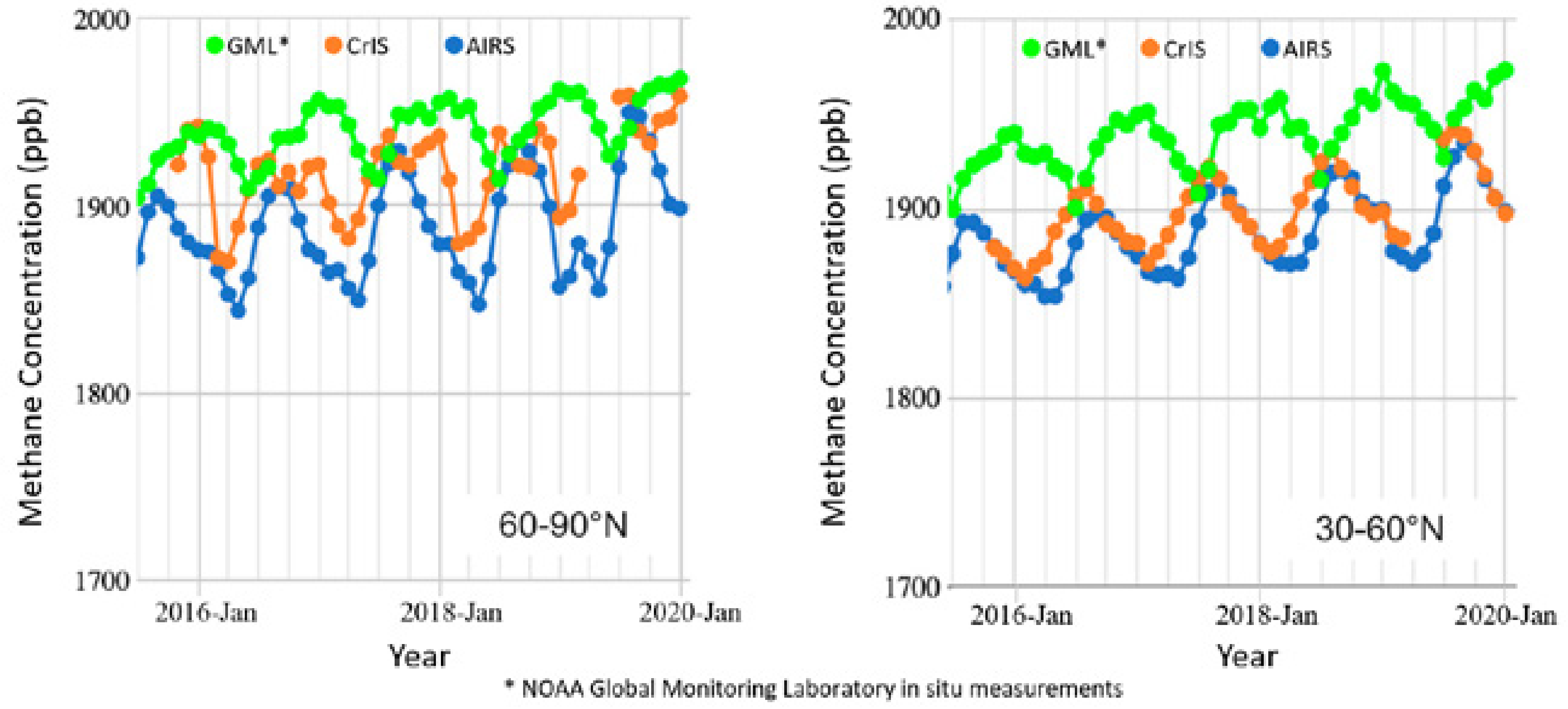


The lowest three layers of the atmosphere are the troposphere, stratosphere, and mesosphere, above which is the thermosphere and exosphere (not shown). The tropopause is the boundary between the troposphere and stratosphere. Credit: NASA/National Science Foundation.

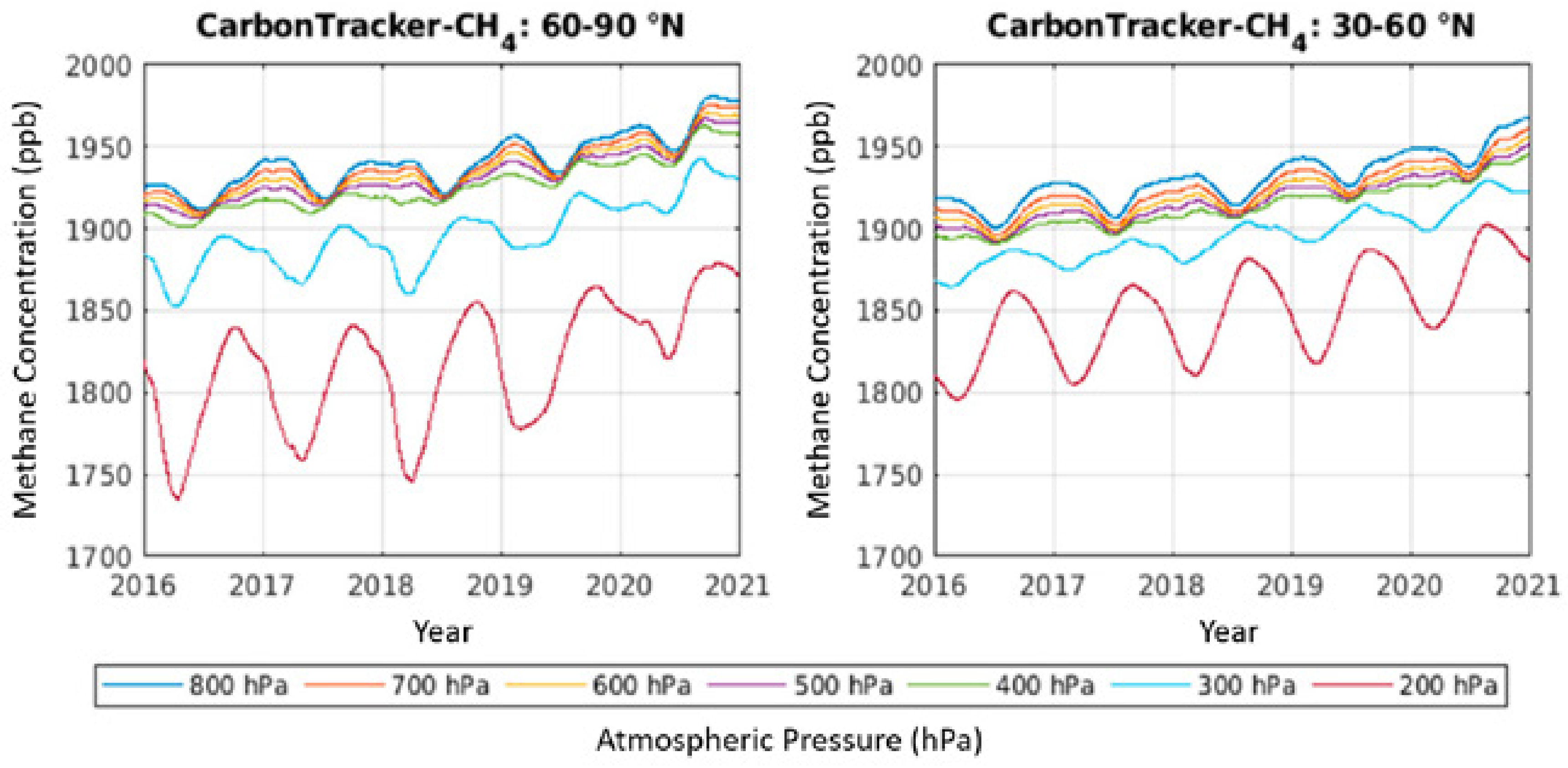
Seasonal fluctuations in atmospheric methane are a normal part of the methane cycle, attributed to the seasonality of emission sources—rice field flooding, permafrost melting, plant growth in wetlands during the summer, and so on. But these normal variations in atmospheric methane concentration do not explain the seasonal shift in CrIS and AIRS measurements mentioned above.

To better understand this puzzling phenomenon, Dr. Lihang Zhou, a scientist with the NOAA Joint Polar Satellite System Program Office, and her colleagues examined data from CarbonTracker-CH_4, which can detect seasonal variability in emission

Time Series of Methane Retrieved From NOAA GML* in situ Measurements, CrIS, and AIRS (Centered on 400 hPa) for Zonal Bands 60-90°N and 30-60°N



Time Series of Zonally Averaged Methane From CarbonTracker-CH_4 at 200-800 hPa for Zonal Bands 60-90°N and 30-60°N



fluxes at northern latitudes. CarbonTracker-CH_4 identified the same seasonal shift in atmospheric methane concentration that CrIS and AIRS did in the tropopause in the middle to higher latitudes of the Northern Hemisphere.

The graphs above illustrate the phenomenon. Looking at methane concentration between 60-90°N latitude (top left) and 30-60°N latitude (top right), temporal patterns from CrIS (orange) and AIRS (blue) generally agree, but both differ from surface measurements from the NOAA Global Monitoring Laboratory (green). The unusual seasonal shift in methane concentration detected by CrIS and AIRS is confirmed by CarbonTracker-CH_4 (bottom plots), where a temporal shift is shown at 300 hPa (blue) and 200 hPa (red), around the tropopause.

What the researchers believe they are seeing is the influence of tropospheric and stratospheric chemistry on CrIS and AIRS measurements from the intrusion of stratospheric methane into the troposphere, across the tropopause. This signals that stratospheric methane abides by a different seasonal cycle than methane in the troposphere in mid to high latitudes of the Northern Hemisphere. While additional analysis is needed to fully understand the seasonal shift measured by CrIS and AIRS, these findings offer insight into the global methane budget and help explain uncertainties associated with troposphere-stratosphere exchange. This knowledge matters because understanding and quantifying methane sources, sinks, and transport is important for finding realistic pathways to mitigate climate change.

THE ROAD AHEAD

Development on CarbonTracker-CH_4 continues to move toward a tool that can monitor, diagnose, and perhaps even predict the behavior of the global methane cycle—capabilities that would transform climate change science and policy. "There's a lot of interest in tracking methane these days because it's perceived as a way we can make some progress with our climate change problem, and so, these kinds of systems [such as CarbonTracker-CH_4] are being considered for use in evaluating inventories of methane emissions," says Dr. Lori Bruhwiler, a physical scientist at the NOAA Global Monitoring Laboratory and co-lead for the CarbonTracker-CH_4 project.

One question that CarbonTracker-CH_4 has effectively answered: What is behind the recent spike in methane emissions? By all indications, microbes are to blame but as of now natural and anthropogenic microbial emissions are indistinguishable. Researchers eventually want to make this separation—attributing microbial emissions spatially and by sector—but "this is difficult because from the isotope measurement we can't really distinguish these two," explains Dr. Oh. New approaches have been proposed by NOAA scientists, and while natural microbial emissions may be hard to quantify, there is promise in using economic information and other measurements to estimate anthropogenic microbial emissions. "Some countries have a good estimate [of anthropogenic microbial emissions] so maybe improving the bottom up inventory will help us to separate these two," says Dr. Bruhwiler. "We're always looking for new datasets to try out and new approaches to improve our prior estimates."

It also stands to reason that assimilating satellite-based data in CarbonTracker-CH_4 will improve the ability to observe methane emission fluxes on politically relevant spatial scales. Space-based measurements are especially beneficial in data sparse areas like the tropics, a region that is important (most methane emissions today are thought to be from tropical microbial sources) but where CarbonTracker-CH_4 does not have good coverage. With enough observations, it will become possible to track regional methane emissions—a scale at which policies can target specific emission sectors. Such information is vital for identifying the most impactful measures for methane abatement. Sensors onboard low Earth orbit satellites, like JPSS, will help scientists achieve this goal. ✦

STORY SOURCE

The information in this article is based, in part, on the April 6, 2023, LEO Science Seminar titled "Methane Modeling" presented by Dr. Youmi Oh, Research Scientist, NOAA Global Monitoring Laboratory in Boulder, Colorado, and Dr. Lori Bruhwiler, Physical Scientist, NOAA Global Monitoring Laboratory. It features work being led by Dr. Nicholas Nalli (NOAA NESDIS/STAR); Drs. Bianca Baier, Andrew R. Jacobson, Xin Lan, and Colm Sweeney (NOAA Global Monitoring Laboratory); and Dr. Juying Warner (University of Maryland/Earth System Science Interdisciplinary Center). This article also features work led by Dr. Lihang Zhou, Physical Scientist, NOAA NESDIS Office of Low Earth Orbit Observations (LEO).

FOOTNOTES

1 Over a 100-year timescale.

2 Averaged over 1999 to 2021.

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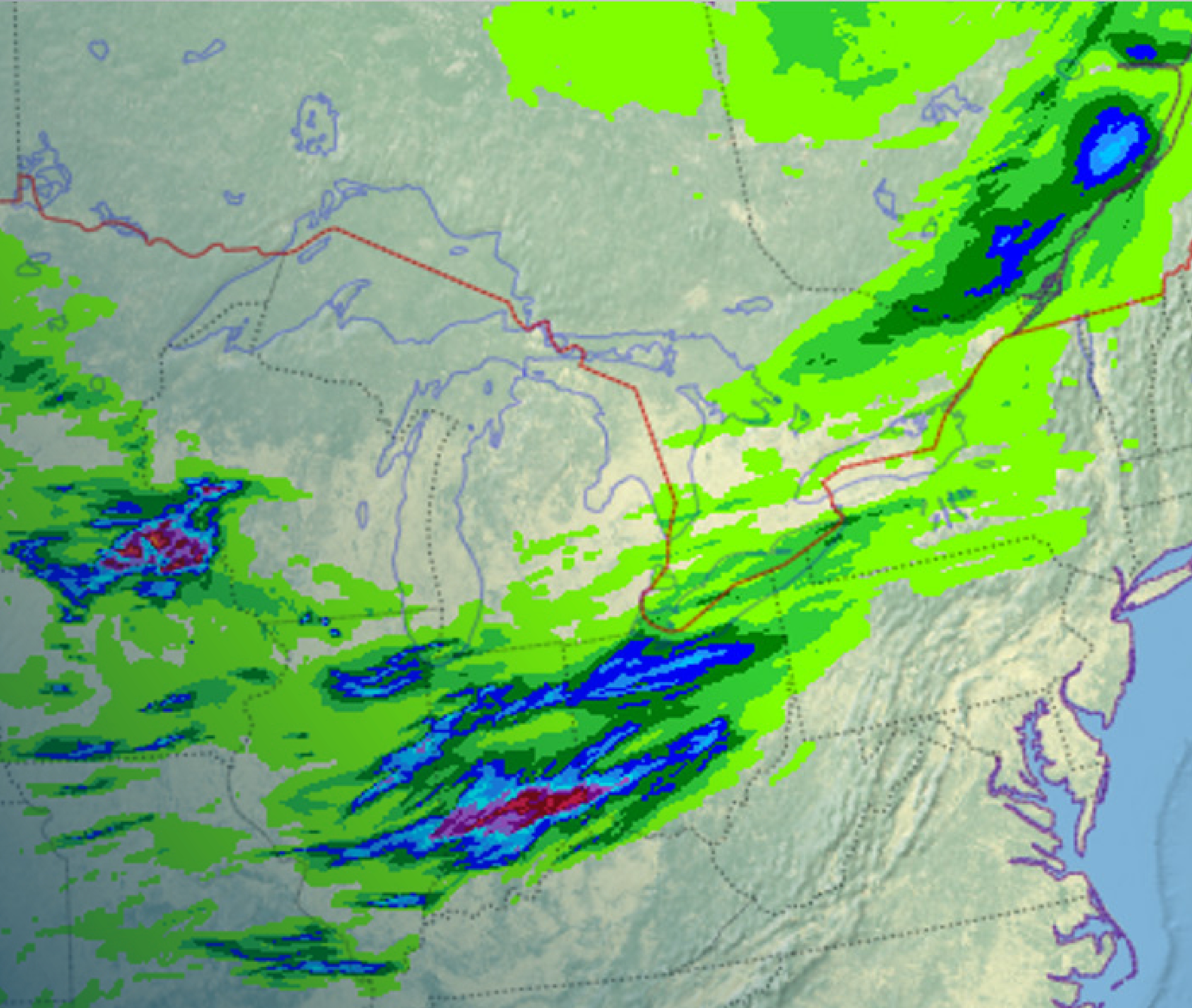


FEATURE 5

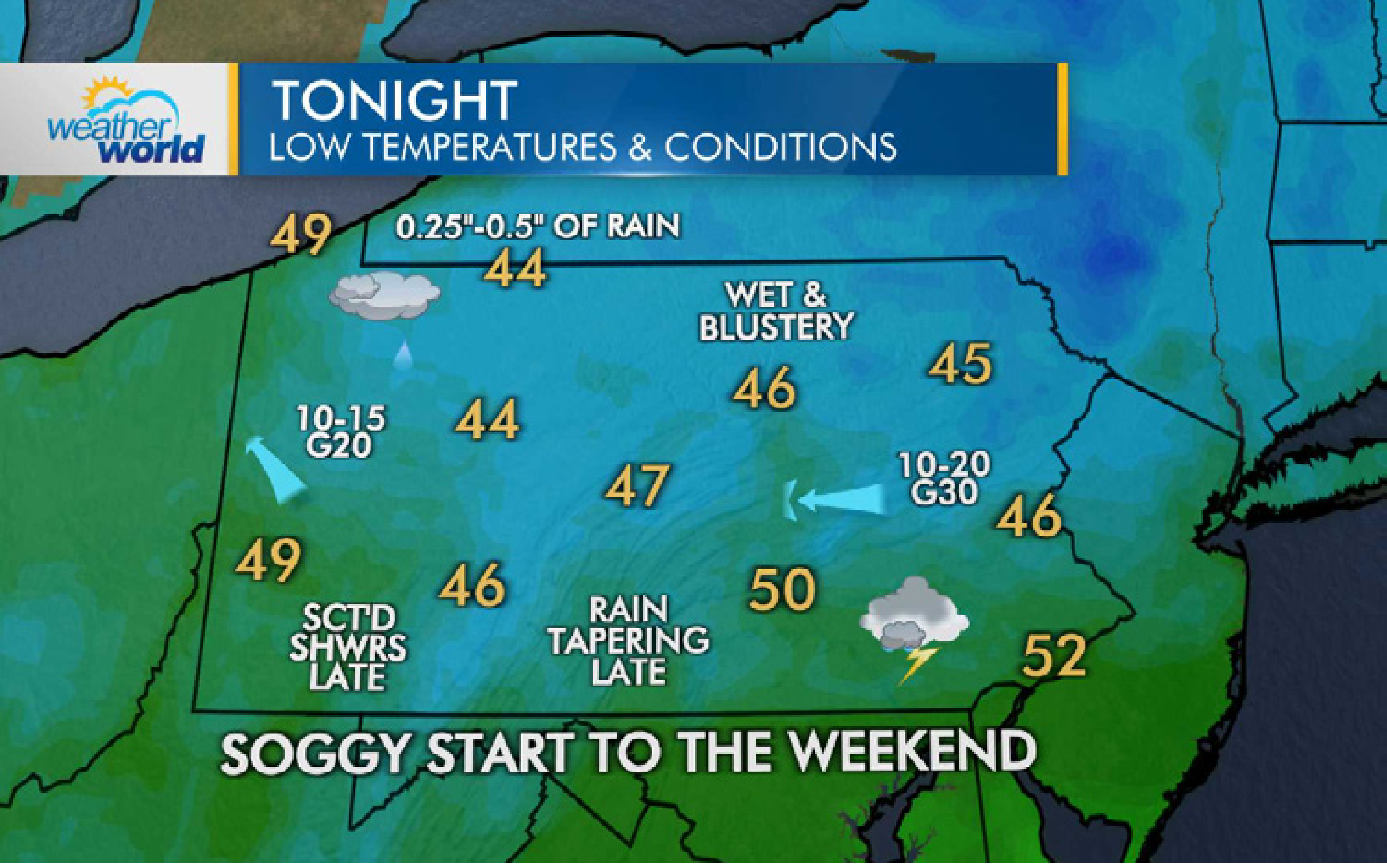
Revolutionizing Weather Forecasting: How Low Earth Orbit Satellites Have Changed the Game

Sample 3-km forecast output from the United Forecast System-Short Range Weather (UFS-SRW) application depicting 6-hour accumulated precipitation in inches from the FV3-LAM model (initialized 1800 UTC 15 June 2019, valid 0000 UTC 16 June 2019). The short-range weather application is based on the Unified Forecasting System (UFS) framework and is the foundation of NOAA's future convection-allowing ensemble forecast system, the Rapid Refresh Forecast System. Source: National Weather Service, https://www.weather.gov/news/210403-ufs.

Clockwise from top left: Florida Power & Light crews at the Sarasota Fairgrounds ready to respond to Hurricane Ian (credit: Florida Power & Light); a side view of an intense updraft punching through a cumulonimbus cloud "anvil" from the view of an airplane (credit: NASA Deep Convective Clouds and Chemistry Project); a mine blast creates a plume of dust and sediment (credit: USEPA); a construction crane installing a pedestrian bridge (credit: City of New York).

Weather forecasts play an essential role in the daily lives of Americans from the trivial—umbrella or sunscreen—to the critical—evacuate or find shelter. Generating more than $30 billion in economic benefits annually, weather forecasts are relied upon by nearly every sector of the U.S. economy. For instance, utilities use them to help estimate energy demand and pre-position resources ahead of storms. Pilots and airlines use them for route planning to avoid hazardous weather and to save time and fuel by hitching a ride on the jet stream. Wind and temperature forecasts are even used by mining companies to plan blast activities and minimize health risks from dust plumes, and construction companies need them to keep crews safe and projects on schedule. Americans check the weather an average of 3.8 times per day and the importance of this information is undeniable.

People often look to short-range weather forecasts to plan their day. Short-range forecasts offer a look into future atmospheric behavior on a timescale of less than an hour to a couple of days, making them critical during high-impact weather events like hurricanes, floods, and blizzards. Medium-range weather forecasts extend farther out, about three to seven days in the future, and can provide early warning of hazardous weather. Both short- and medium-range forecasts give detailed information about hundreds of meteorological elements like cloud cover, temperature, air pressure, and precipitation.

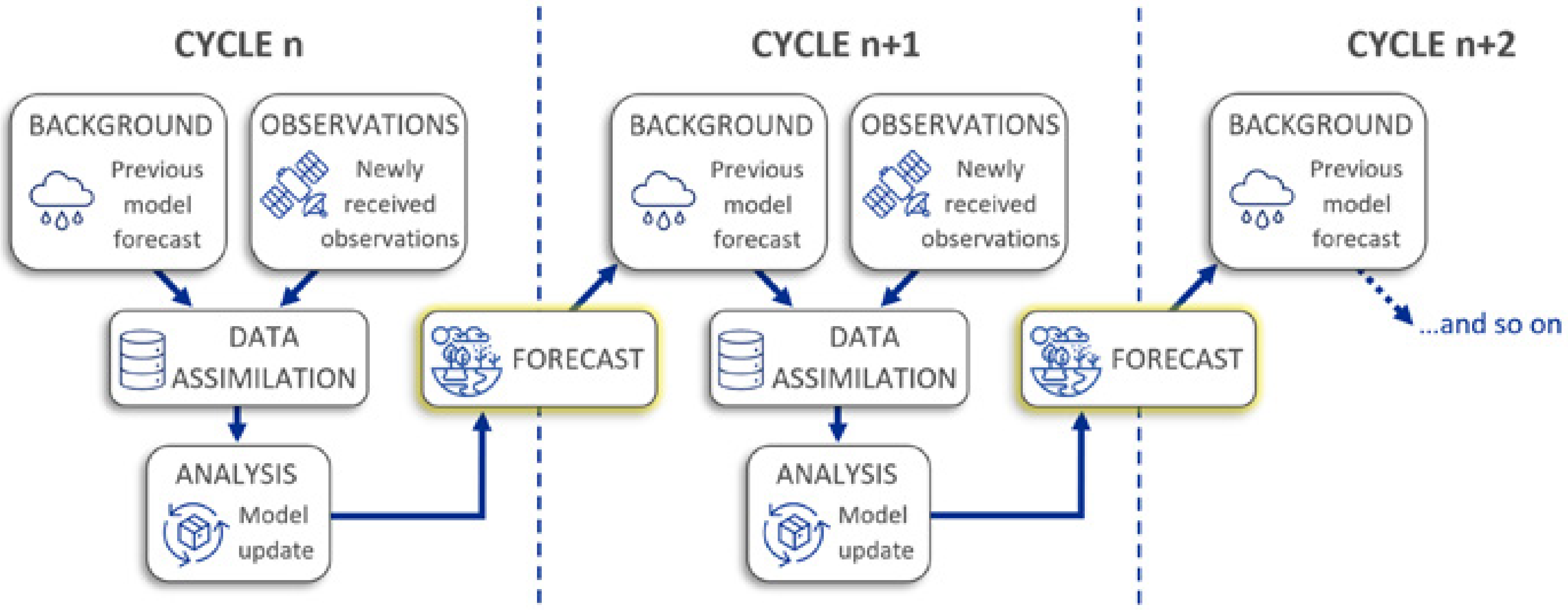


Example two-day forecast for Pennsylvania. Source: Penn State University.

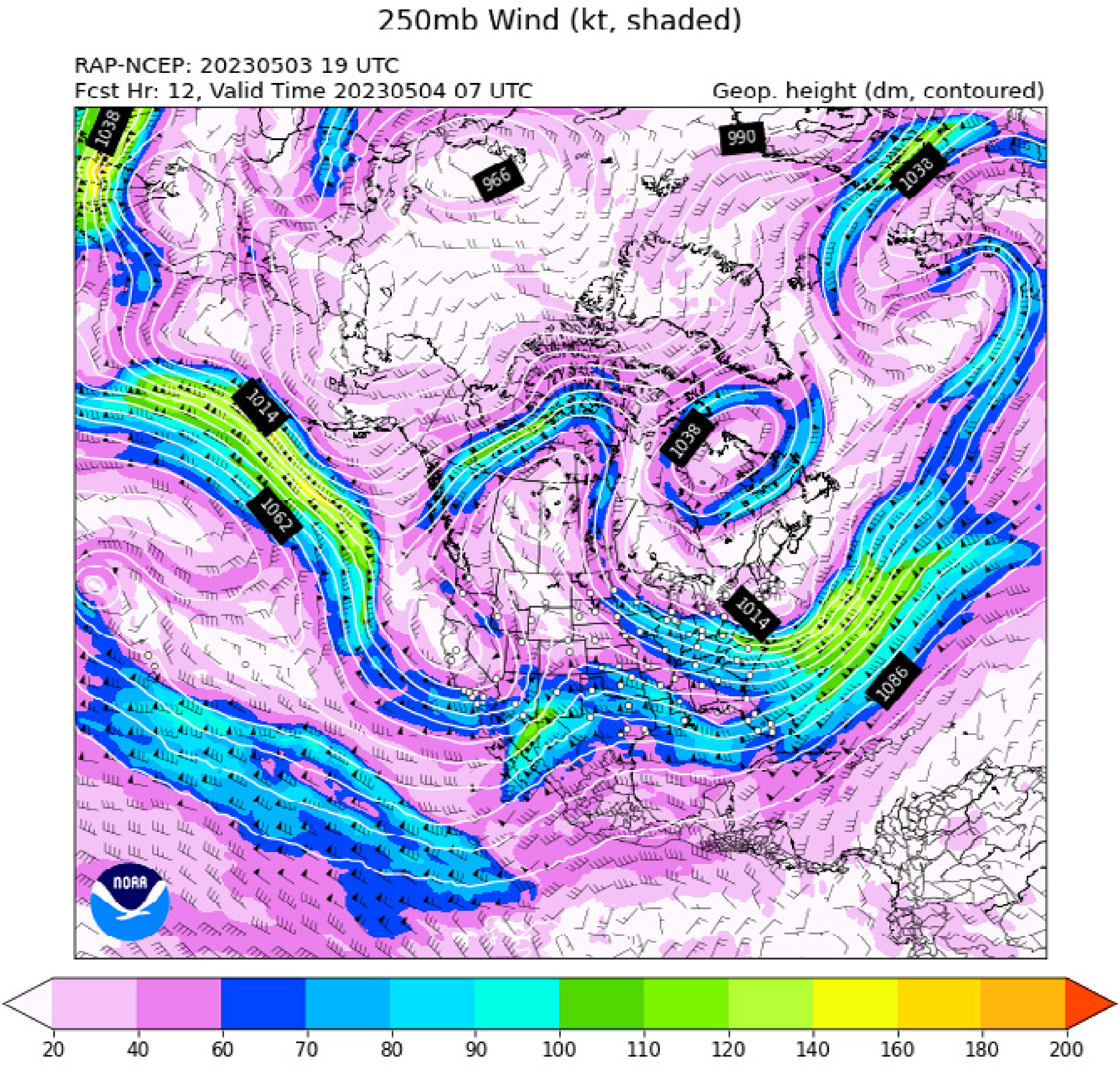
The Earth's atmosphere is a highly complex and dynamic system and predicting its future state is a challenging task. To help meteorologists produce a more reliable forecast, the NOAA National Centers for Environmental Prediction (NCEP) runs a suite of powerful numerical weather prediction (NWP) models that use current weather observations as input. Some of these observations come from airborne and surface instruments, but low Earth orbit satellites, like JPSS satellites, provide the most data and have the greatest impact due to their continuous global coverage. Considered the backbone of forecasting, low Earth orbit satellites (also called polar-orbiting satellites) supply more than 80% of the data assimilated in NWP models.

Data Assimilation

Data assimilation is the fitting of a prediction model to observed data—essentially a reality check to guide the model. In numerical weather prediction, data assimilation involves combining observational data with previous forecast model data to create an updated forecast. The goal is to best predict atmospheric conditions for a location and to quantify uncertainty associated with the prediction.



Today, NOAA's two main NWP models for high-frequency regional forecasting are the Rapid Refresh (RAP) and High-Resolution Rapid Refresh (HRRR) models, which work together to provide operational forecasters with hourly weather updates that extend out 18 hours for North America. These models, operational since 2012, are the baseline for NOAA's next generation regional hourly application known as the Rapid Refresh Forecast System that is planned to replace RAP/HRRR and other legacy short-range forecast systems in 2025. To help transition the Rapid Refresh Forecast System from research to operations, Dr. Haidao Lin, a research scientist at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University and the NOAA Global Systems Laboratory, is testing the impact of satellite radiance data assimilation and instrument channel selection in the Rapid Refresh Forecast System. At the March 2023 LEO Science Seminar, Dr. Lin shared an overview of his team's research, supported by the Office of Low Earth Orbit Observations (LEO) Proving Ground Risk Reduction (PGRR) program, and provided a look into the challenges associated with data assimilation in regional hourly forecast models.



Wind forecast at 250 mb in knots for North America on May 3, 2023, from the Rapid Refresh (RAP) model.

RAP/HRRR Models

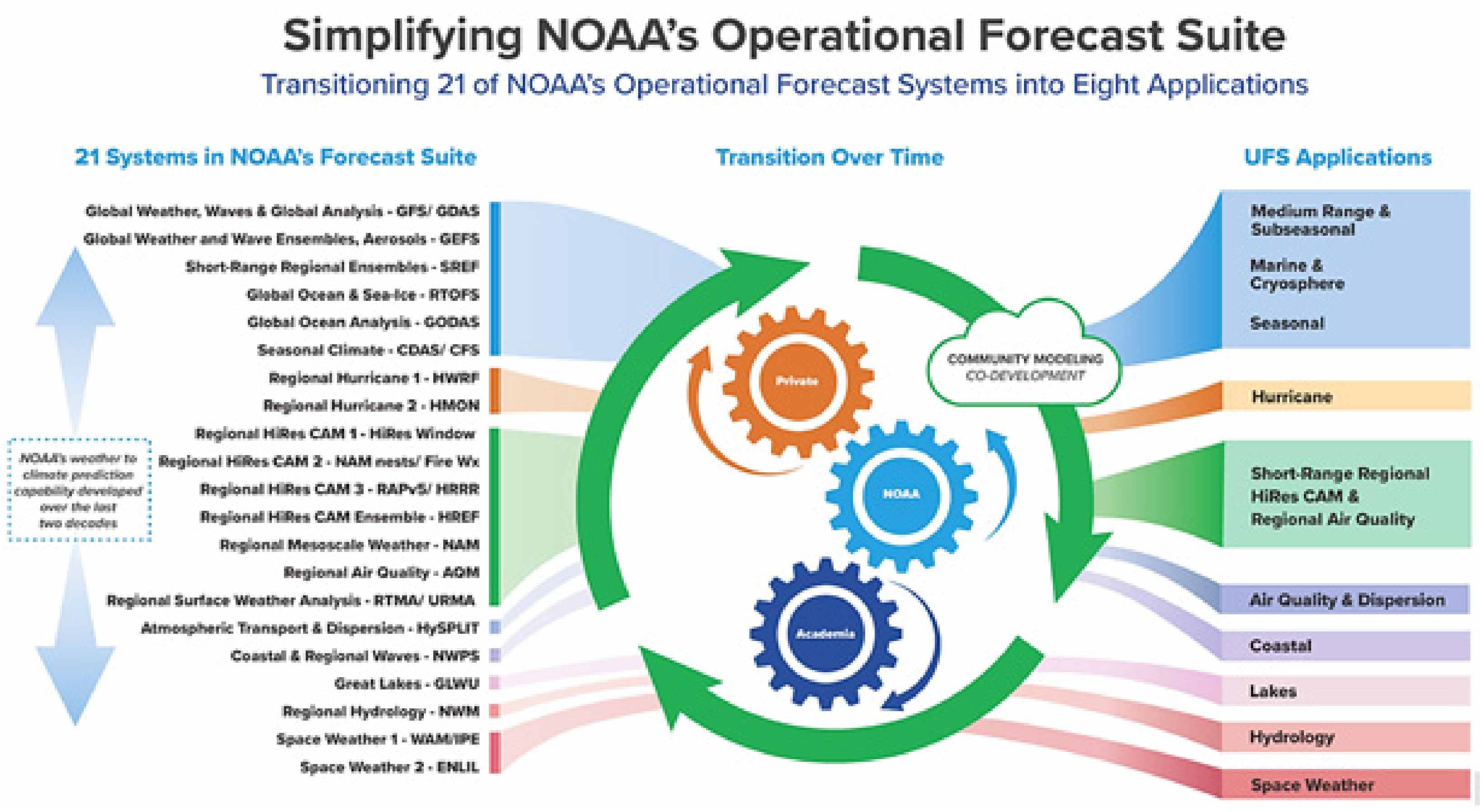
The **Rapid Refresh (RAP)** model has been operational at NCEP since May 2012. It generates weather data for a 13-km horizontal grid covering North America. Its high-resolution version, the **High-Resolution Rapid Refresh (HRRR)**, produces data on a 3-km grid for smaller areas of interest. Forecasts are generated hourly with forecast lengths up to 18 hours, and every six hours for forecast lengths up to 48 hours.

A NEW APPROACH TO WEATHER MODELING

NOAA's National Weather Service (NWS) has a mission to build a "Weather-Ready Nation" by providing better information to support decision-making that protects lives and property and enhances the economy. Backing this mission is the NCEP Production Suite, a set of 21 numerical weather prediction systems used by the NWS to provide official forecasts.

For two decades, the NCEP Production Suite has been the bedrock of most weather forecasting in the U.S., providing forecasters and researchers with weather, marine, and climate predictions across different geographic areas and time scales—from minutes to up to a year for seasonal outlooks. But its framework is overly complex making it difficult to coordinate research and use resources effectively.

In a move to modernize and simplify, NOAA is transitioning to a community-based, coupled, comprehensive Earth modeling system called the Unified Forecast System. Eight Unified Forecast System applications will replace the 21 forecast systems of the NCEP Production Suite. Each application combines an NWP model, data assimilation, post-processing, workflow, and other elements that are configured to support specific forecast requirements, like short-range weather and air quality. Designed as a single seamless system with a common modeling framework, the United Forecast System will create a simpler and more efficient environment for model enhancement, collaboration, and the transition from research-to-operations that is critical to improve forecasting.

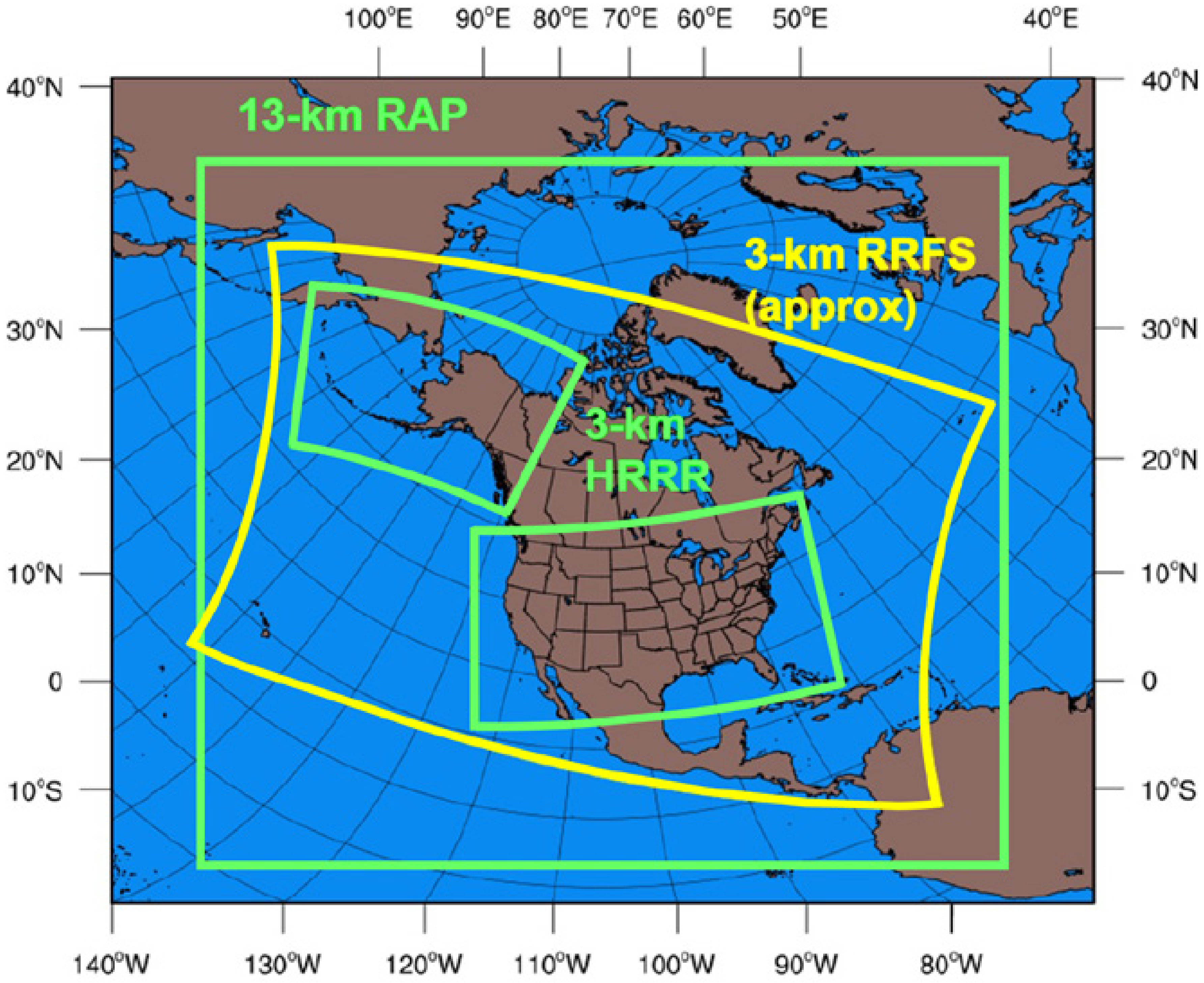


Unification of NOAA's operational forecasting systems through the Unified Forecast System. Source: Uccellini et al 2022.

Paving the Way For New Short-Range Forecasting Capabilities

As part of the new Unified Forecast System's Short-Range Weather application, the next generation Rapid Refresh Forecast System is poised to revolutionize forecasting of severe weather events when it becomes operational in 2025. With years of development backing it, the Rapid Refresh Forecast System's advanced capabilities, like rapid updates, multi-scale data assimilation, and high horizontal resolution (3-km), will allow for the retirement of legacy systems like the RAP/HRRR and others, simplifying the short-range forecast modeling space. The approximate geographic domains of the Rapid Refresh Forecast System and the RAP and HRRR models are shown in the image on the next page for comparison.

With new model development comes testing and validation to make sure they produce the best results. For the past few years, Dr. Lin and his team have been running experiments with the Rapid Refresh Forecast System to test its performance using different datasets and configurations. Their goal? To find the optimal formulation of low Earth orbit (LEO) observations with the greatest impact on forecasting.



The North American domains of the 13-km RAP model, 3-km HRRR model, and 3-km Rapid Refresh Forecast System. The RAP/HRRR model domains are in green; the Rapid Refresh Forecast System (RRFS) domain is in yellow. Credit: Dr. Curtis Alexander, Supervisory Meteorologist, Acting NOAA Global Systems Laboratory Deputy Director.

Rapid Refresh Forecast System: An Ensemble Prediction System

The Rapid Refresh Forecast System (RRFS) generates deterministic forecasts once an hour out to 18 hours and deterministic and ensemble forecasts four times a day out to 60 hours. What does this mean?

A forecast is created by estimating the current state of the atmosphere ("initial conditions") based on measured observations, then calculating how those conditions will evolve using an NWP model. But tiny errors in the initial conditions can lead to big errors in the forecast.

In ensemble forecasts, the model is run many times using slightly different initial conditions to produce many forecasts. Similar forecasts mean less uncertainty in future conditions. The idea is to give forecasters more (or less) confidence in the prediction. Ensemble forecasts are better at predicting uncertainty out several days than out a few hours because of their coarse resolution.

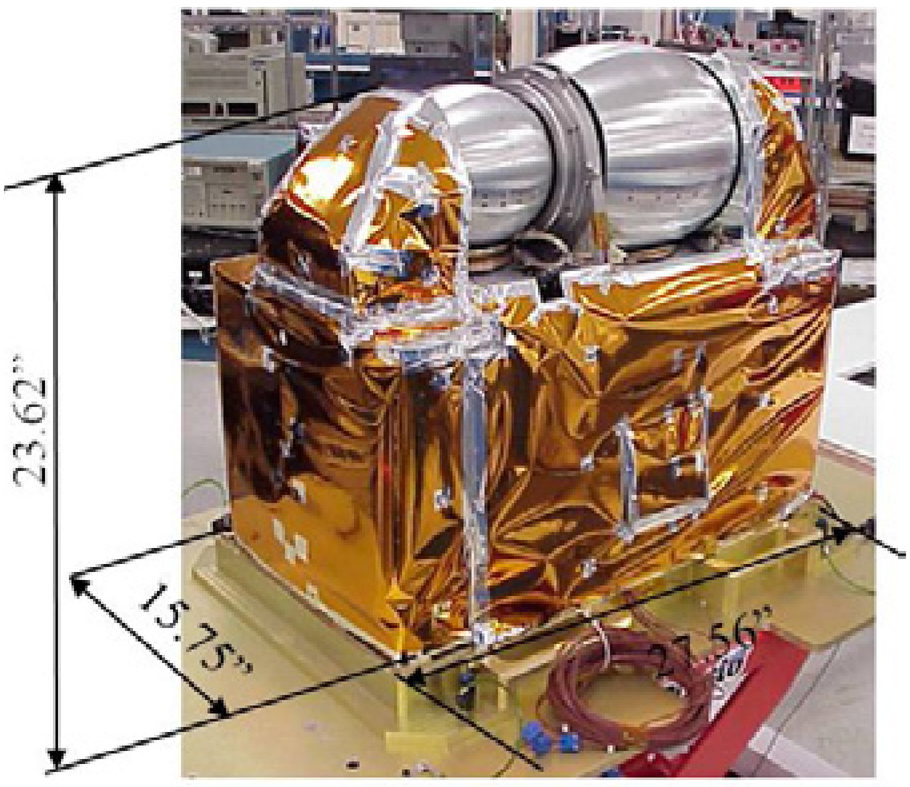
Deterministic forecasts, on the other hand, are when a model runs at the highest resolution possible using one set of initial conditions. They produce very detailed and accurate forecasts for the near-term for specific locations by providing one single outcome.

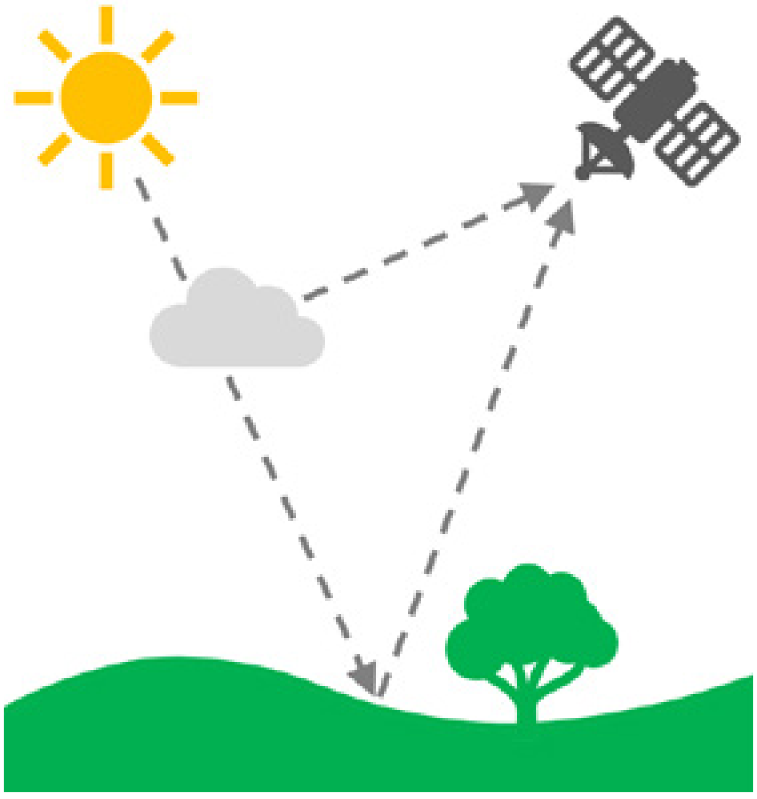
Both types of forecasts are critical for life-saving weather forecasts in the U.S. during extreme weather events, each serving a unique purpose and fulfilling a different need.

THE IMPACT OF POLAR OBSERVATIONS ON NUMERICAL WEATHER PREDICTION

Sounding instruments ("sounders") onboard JPSS and other LEO (polar-orbiting) satellites probe the atmosphere for details on properties like temperature, water vapor, and wind, that heavily influence weather patterns. They observe how these properties change with altitude and are key contributors to numerical weather prediction, producing vertical atmospheric profiles called "soundings" that improve forecast accuracy for critical applications like early storm warnings.

Sounders do not directly measure temperature, moisture, wind, or the various other features they observe. Instead, they measure Earth's outgoing radiation—energy emitted by the Earth's surface and atmosphere. Soundings are then inferred from these radiance data using computer algorithms. The illustration (below right) is a simplified view of how radiance is measured by satellites.





Above (Left): The Advanced Technology Microwave Sounder (ATMS) onboard JPSS satellites measures microwave radiances at 22 channels. Above (Right): A simplified view of the principle of radiance measurement in remote sensing.

“We use a lot of polar-orbiting data” from LEO sounders in operational RAP models, says Dr. Lin (see table), and its use has revolutionized numerical weather prediction. But, how? Assimilation of sounder radiance data into NWP models produces more precise initial conditions—the current observed state of the atmosphere, that is, the starting point upon which models build forecasts. These data enhance a model’s ability to capture small-scale weather phenomena, such as localized convective systems, mesoscale features, and atmospheric boundary layer conditions. Also, the availability of real-time sounder radiance data[1] enables frequent model updates, allowing forecasters to monitor rapidly evolving weather situations and issue timely warnings to protect life, livelihoods, and property.

Satellite Radiance Data Used in RAP v.5* Model

Satellite Sensor	Orbit
Advanced Technology Microwave Sounder (ATMS)	LEO
Cross-track Infrared Sounder (CrIS)	LEO
Infrared Atmospheric Sounding Interferometer (IASI)	LEO
Microwave Humidity Sounder (MHS)	LEO
Special Sensor Microwave Imager/Sounder (SSMIS)	LEO
Advanced Microwave Sounding Unit-A (AMSU-A)	LEO
Advanced Baseline Imager (ABI)	GEO

*Version 5 is the final configuration of the RAP model, updated in 2022

One of Dr. Lin's research goals is to enhance sounder radiance data assimilation capabilities in the Rapid Refresh Forecast System in advance of its planned operation in 2025 by maximizing the benefits of low Earth orbit satellites. But doing so presents several challenges: Observation bias, thousands of instrument channels, and data latency can complicate data assimilation in regional hourly forecast models. Through many experiments, Dr. Lin’s team worked through these issues to find solutions with the greatest positive impact to forecasting.

The Bias Problem in Data Assimilation

One of the most challenging aspects of radiance data assimilation in numerical weather prediction is observation bias. All data assimilation systems are affected by biases. With satellite radiances, they can be caused by problems with observation data, instrument errors, radiative transfer calculations, and other issues. Observation bias can affect the quality of data assimilation and, ultimately, the modeled forecast, so correcting biases is important for radiance data to benefit forecasting.

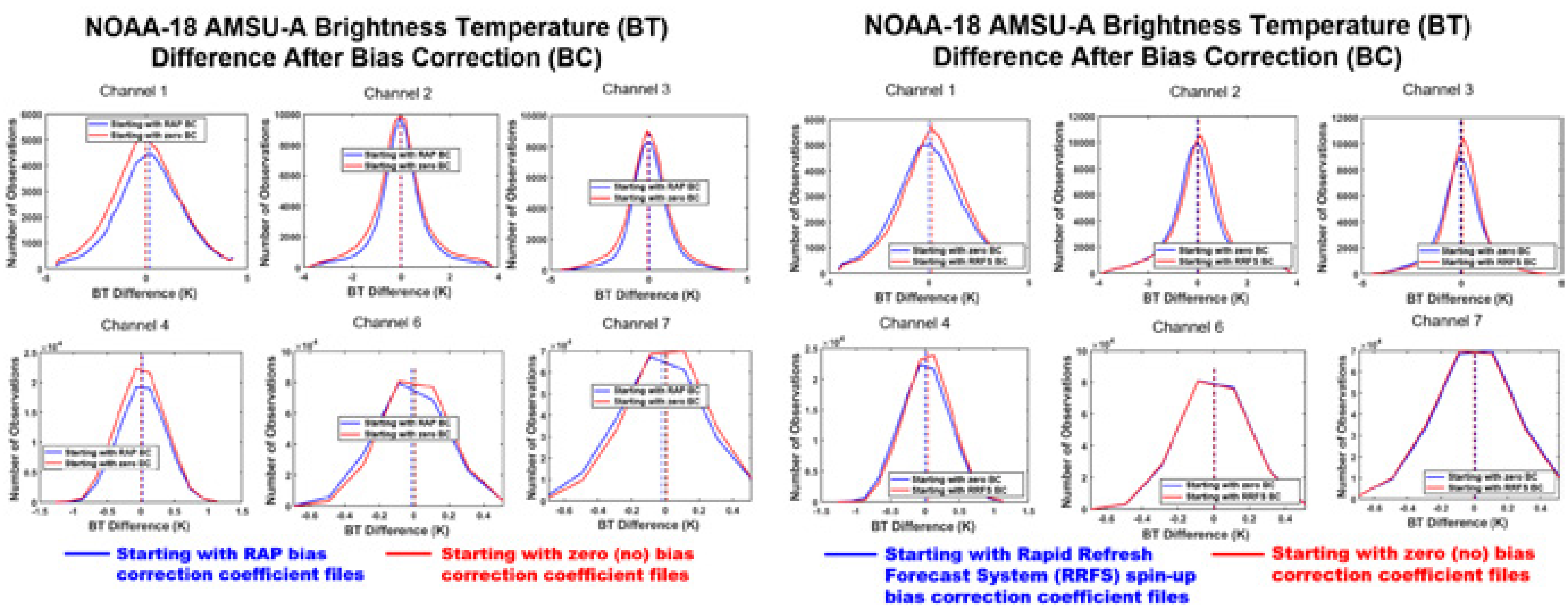
What is bias?

The term bias broadly includes any error that is systematic and can be corrected, rather than random errors that cannot be corrected due to their randomness.

Bias correction schemes are not always straightforward. They can be complicated by sensor resolution, spatial extent, and even by biases in the forecast model itself. In Dr. Lin's case, "bias correction is complicated by non-uniform data coverage," a result of limited domain extent and limited coverage from LEO satellites, he explains, which adds complexity to the process.

To evaluate bias correction performance within the Rapid Refresh Forecast System, Dr. Lin's team performed three experiments using all available radiance data including NOAA-18 Advanced Microwave Sounding Unit (AMSU-A) data. Each experiment started with a different set of radiance bias correction files: RAP model bias correction coefficient files, Rapid Refresh Forecast System[2] spun-up bias correction coefficient files, or no (zero) bias correction coefficient files.

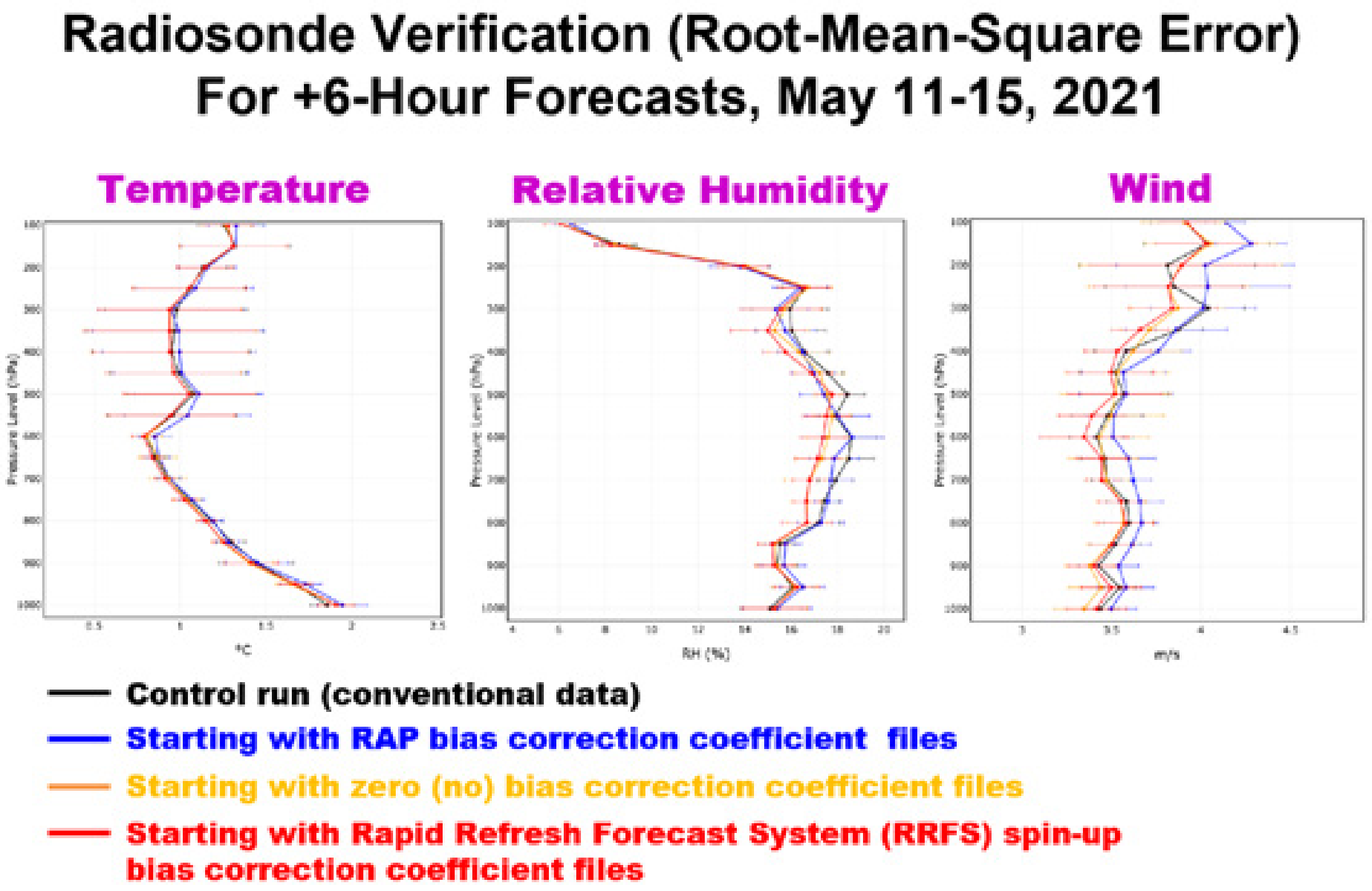
Looking at AMSU-A brightness temperature after bias correction (below), Dr. Lin explains: On the left, "we see that having an experiment starting from zero (red) has a better bias correction" than starting with RAP bias correction files (blue). On the right, "we can see that starting with Rapid Refresh Forecast System spun-up bias correction (blue) can assimilate more data and is a little bit better than using zero bias correction (red)," but the difference is less than the difference seen on the left (RAP bias correction versus zero bias correction). The bottom line, concludes Dr. Lin, is "radiance data are shown to have a small to modest positive impact with RRFS [Rapid Refresh Forecast System]." The point is to apply bias correction using the most appropriate starting files—here, the Rapid Refresh Forecast System spun-up files—to enhance the effectiveness of sounder radiance data assimilation and improve forecast skill.



Retrospective Tests: Looking At Forecasts

"We use the bias correction coefficient files to start the radiance experiment," Dr. Lin explains, to test the impact of sounder radiance data assimilation on short-range forecasting. In the example on the next page, the team assimilated bias-corrected satellite radiances in a prototype 13-km North America Rapid Refresh Forecast System (a RAP-like domain) for a 5-day retrospective period (May 11-15, 2021), comparing forecast results with radiosonde observations for verification. A look at the results for 6-hour temperature, relative humidity, and wind shows smaller errors for forecasts that start with Rapid Refresh Forecast System spun-up bias correction coefficient files (red) and zero bias correction (yellow). Smaller errors (lines farther left) mean greater improvement in forecast accuracy. "The worst one is starting from the RAP bias correction files [blue]; it is worse than the conventional control run [black]," concludes Dr. Lin.

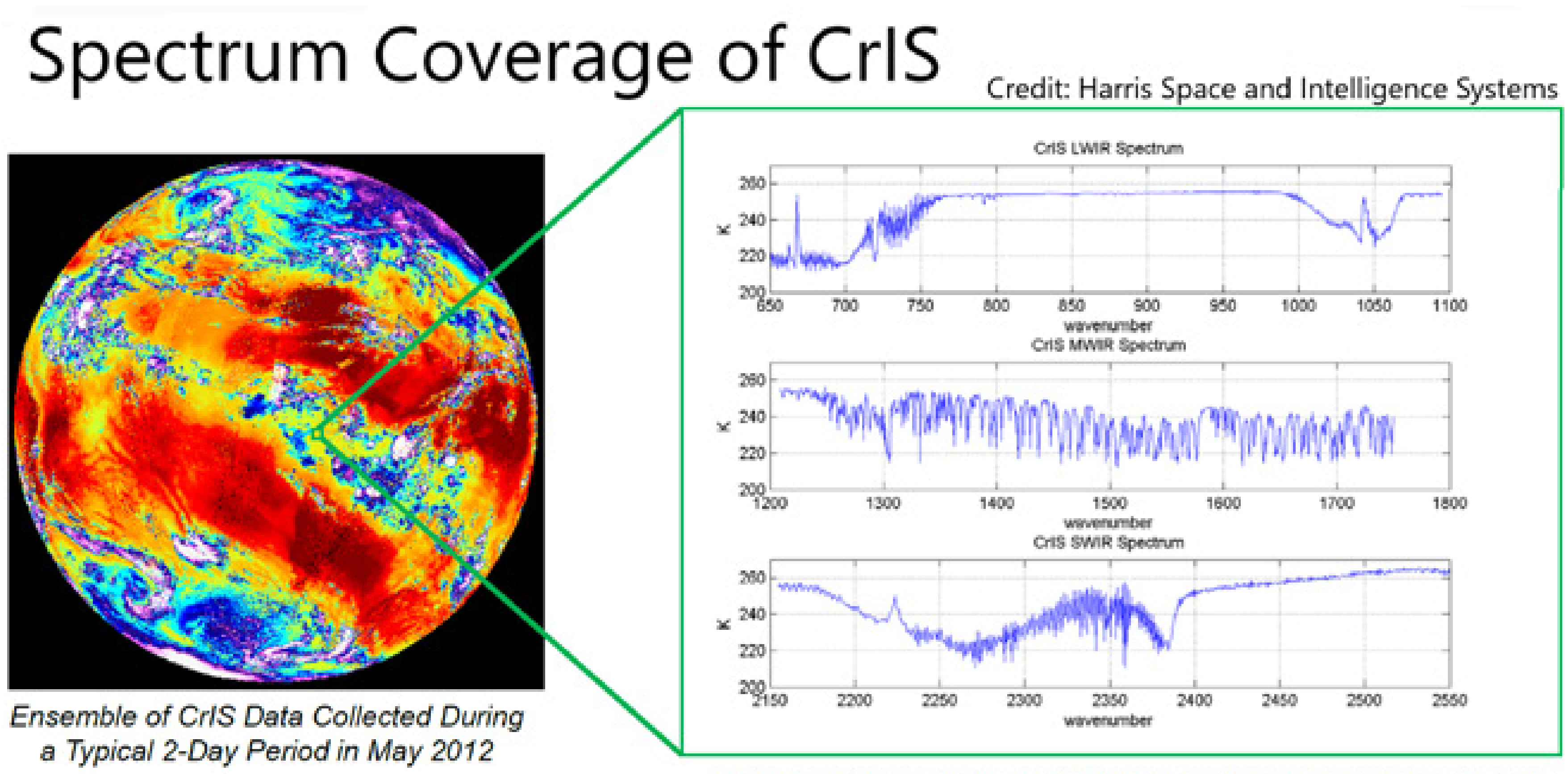
In other experiments,[3] the team continued to show promising results for assimilation of bias-corrected satellite sounder radiances in the Rapid Refresh Forecast System. In an 18-hour forecast radiosonde verification test, starting with Rapid Refresh Forecast System spun-up bias correction files "had some moderate positive impact for temperature and for relative humidity and wind," Lin says. And for 1-21-hour forecast lengths, radiosonde verification showed that radiance data had "quite consistent positive impact for all hours for temperature, relative humidity, and wind." Time and again in testing, "positive impact from satellite radiance data have been seen by using the spun-up bias corrections files from the Rapid Refresh Forecast System," Dr. Lin remarks. His team continues to evaluate bias correction within the forecast model using other satellite radiance data types.



Retrospective runs for May 11-15, 2021, show 6-hour temperature, relative humidity, and wind forecasts developed using assimilated bias-corrected satellite radiance data in the Rapid Refresh Forecast System starting with RAP bias correction coefficient files (blue), zero bias correction coefficient files (yellow), and Rapid Refresh Forecast System spun-up bias correction coefficient files (red), along with a control run using only conventional data. The root-mean-square error (RMSE) is shown for different atmospheric layers (hPa). The smaller the error (the farther a line is to the left), the greater the improvement in forecast accuracy.

Is There Such a Thing as Too Many Channels?

Hyperspectral infrared sounders measure infrared radiation over thousands of spectral channels from which high resolution vertical profiles are developed. In full spectral resolution mode, the JPSS Cross-track Infrared Sounder (CrIS) generates soundings with 2,211 channels and the Infrared Atmospheric Sounding Interferometer (IASI) that flies on European Space Agency's MetOp polar-orbiting suite does the same with 8,461 channels. Using thousands of channels to measure emitted radiance is why these instruments are remarkable at providing detailed information about the atmosphere, but there are challenges with data assimilation. Assimilating all channels would overwhelm available computer resources (too much calculation!), slowing the analysis to a crawl and rendering the model practically useless for fast-moving severe weather events when forecast timeliness is critical. Thankfully, there are solutions.

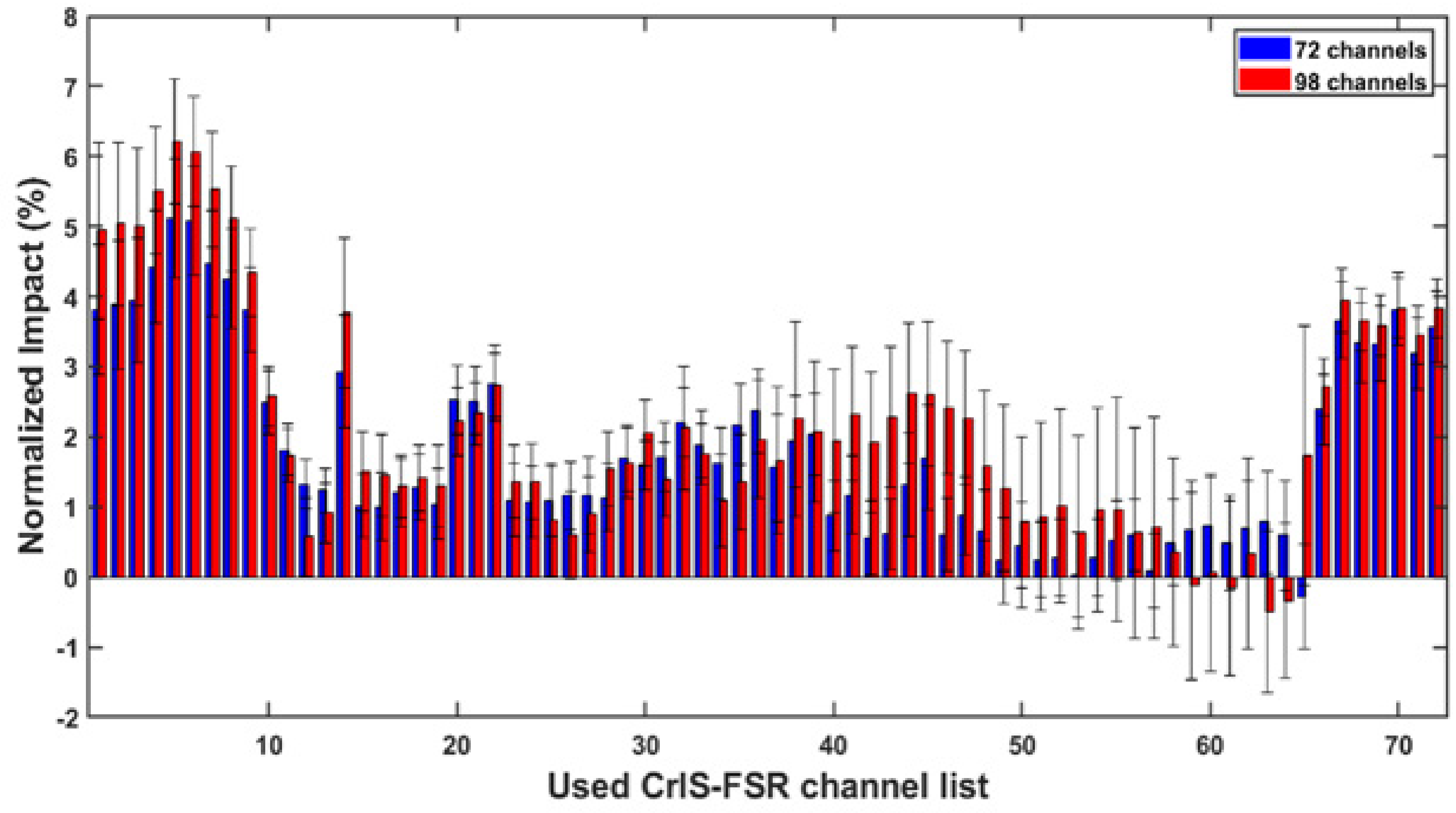


Ensemble of CrIS Data Collected During a Typical 2-Day Period in May 2012

Each Pixel Contains Over 2000 Spectral Channels Across 3 Bands

One common way to reduce the amount of data to be assimilated is channel selection, or thinning. Simply put, channel selection is the selection of a subset of channels for assimilation into a model. The challenge is figuring out which channels to select—different combinations may have different impacts. The process generally starts by deciding what information is needed by the model—for forecasting this means channels related to temperature, humidity, and ozone, for example. Then testing is needed to evaluate the impact of different channel combinations, or channel sets, on the forecast. With respect to hyperspectral IR sounders, many channels are highly correlated and produce redundant data, which can mean less information is lost when assimilating fewer channels.

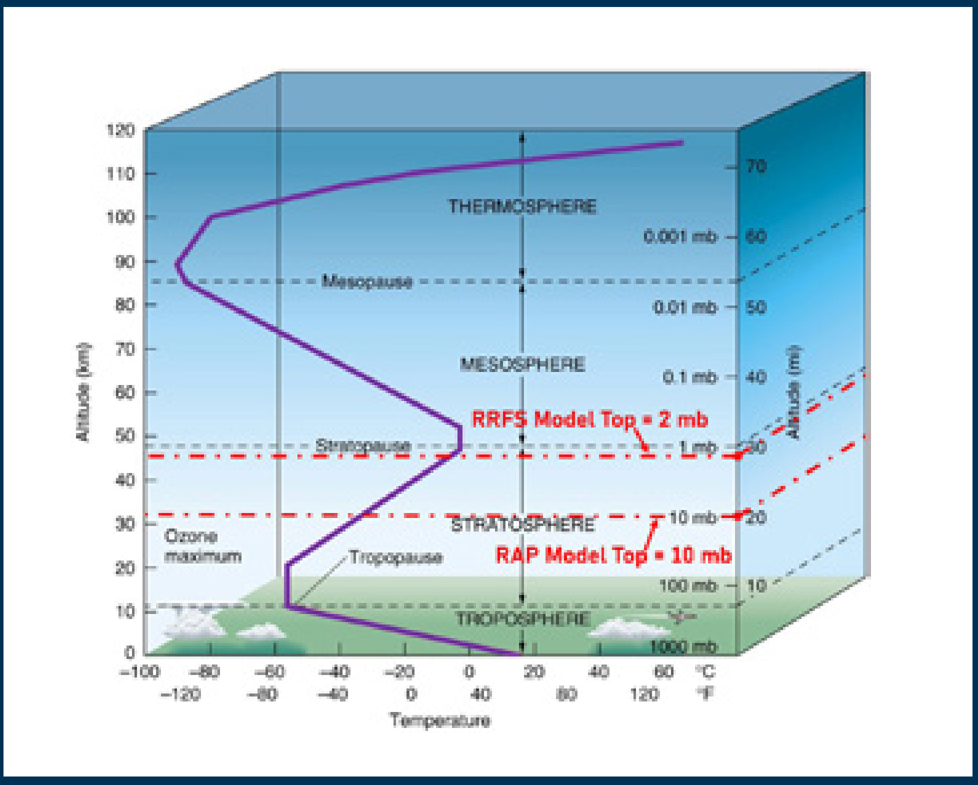
The current version of the operational RAP model uses 72 of CrIS's 2,211 channels. In the Rapid Refresh Forecast System, it is expected that more radiance channels will be needed to accommodate its higher model top. To figure out which channels to choose, Dr. Lin has been testing the impact of different NOAA-20 CrIS (full spectral resolution) channel sets in the Rapid Refresh Forecast System. In one



The normalized root-mean-square error (RMSE) impact (%) for a 6-hour forecast from the 72 NOAA-20 CrIS-FSR channel set (blue) and 98 NOAA-20 CrIS-FSR channel set (red) verified against observed NOAA-20 CrIS-FSR brightness temperature for the 72 CrIS-FSR channels. The control run only assimilated conventional data. The retrospective period is 11-19 May 2021. The error bar indicates the ±1.96 standard error from mean impact, representing a 95% confidence threshold for significance.

experiment, “we increase the model from 72 to 98 [CrIS] channels [and evaluate] the performance of adding a new channel set,” he says. Looking at the impact of the extra channels on a 6-hour forecast (right), “the 98 channel set run [red] has larger positive impact than the 72 channel set [blue], especially for some high level carbon dioxide channels—the channels on the left—owing to some high level carbon dioxide channels having been used in the 98 channel set run,” Dr. Lin explains.

The team has also been comparing the impact of NOAA-20 CrIS full spectral resolution data with MetOp-A IASI data and all satellite radiance data assimilated in the RAP model. The forecast impact from these retrospective runs has been verified against radiosonde data, which provides ground truth for satellite observations. Additionally, the forecast impact of radiance data from CrIS sounders has been verified against observed full spectral resolution CrIS brightness temperature.



What Is a Model Top?

Model top refers to how “high” in the atmosphere an NWP model calculates variables, that is, upper boundary conditions. Atmospheric levels are reported as air pressure at altitude in millibars (mb) or hectopascals (hPa).

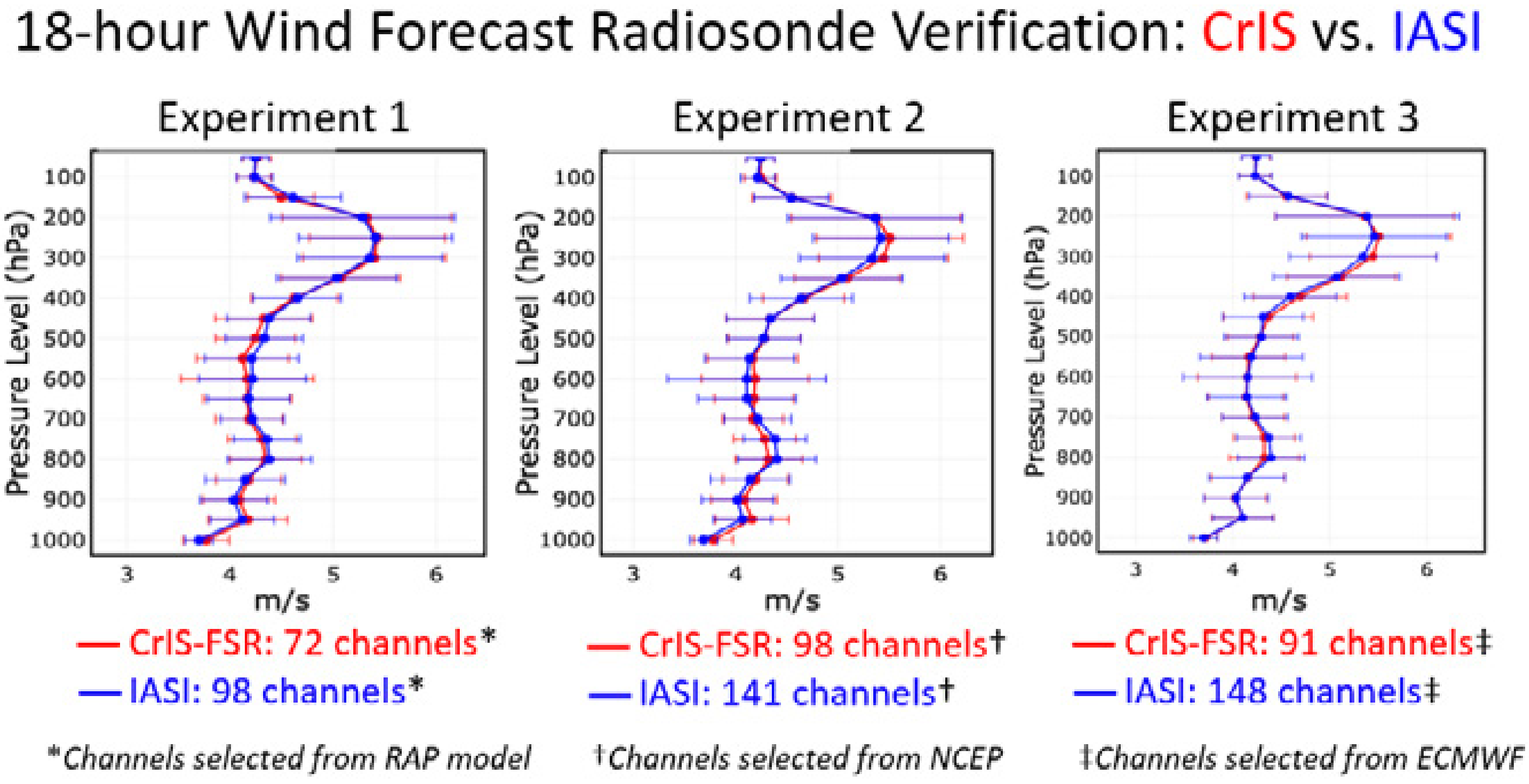
The top of the operational RAP model is 20 miles above the ground, equivalent to 10 mb in pressure. The Rapid Refresh Forecast System top is higher, about 28 miles above the ground, equivalent to 2 mb in pressure.

Above: A cross section through the atmosphere. Note mb (millibars) = hPa (hectopascals). The red lines indicate model tops for the RAP model (10 mb) and the Rapid Refresh Forecast System (RRFS) (2 mb). Source: Aguado and Burt 2009.

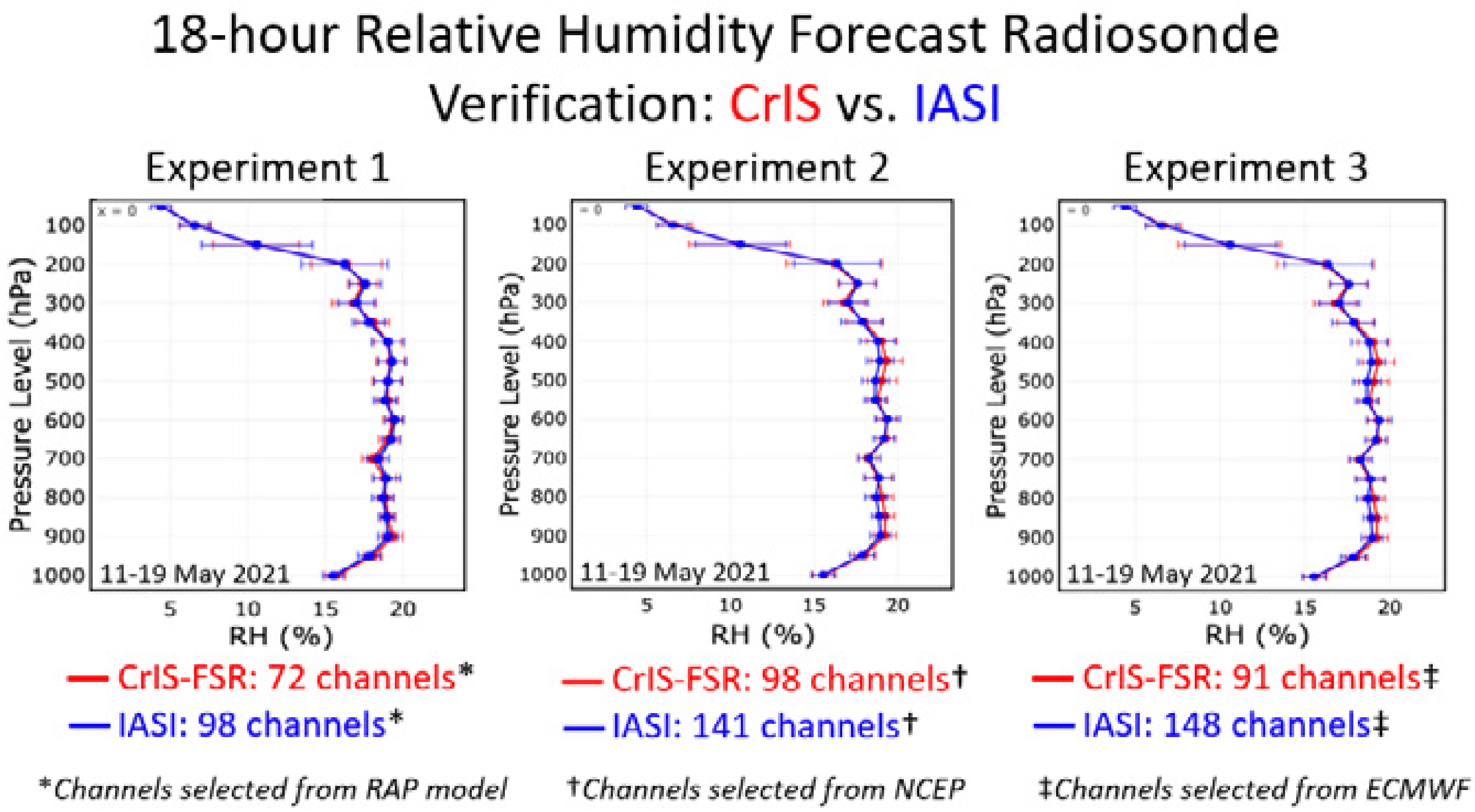
"Smaller Errors Mean Greater Improvement"

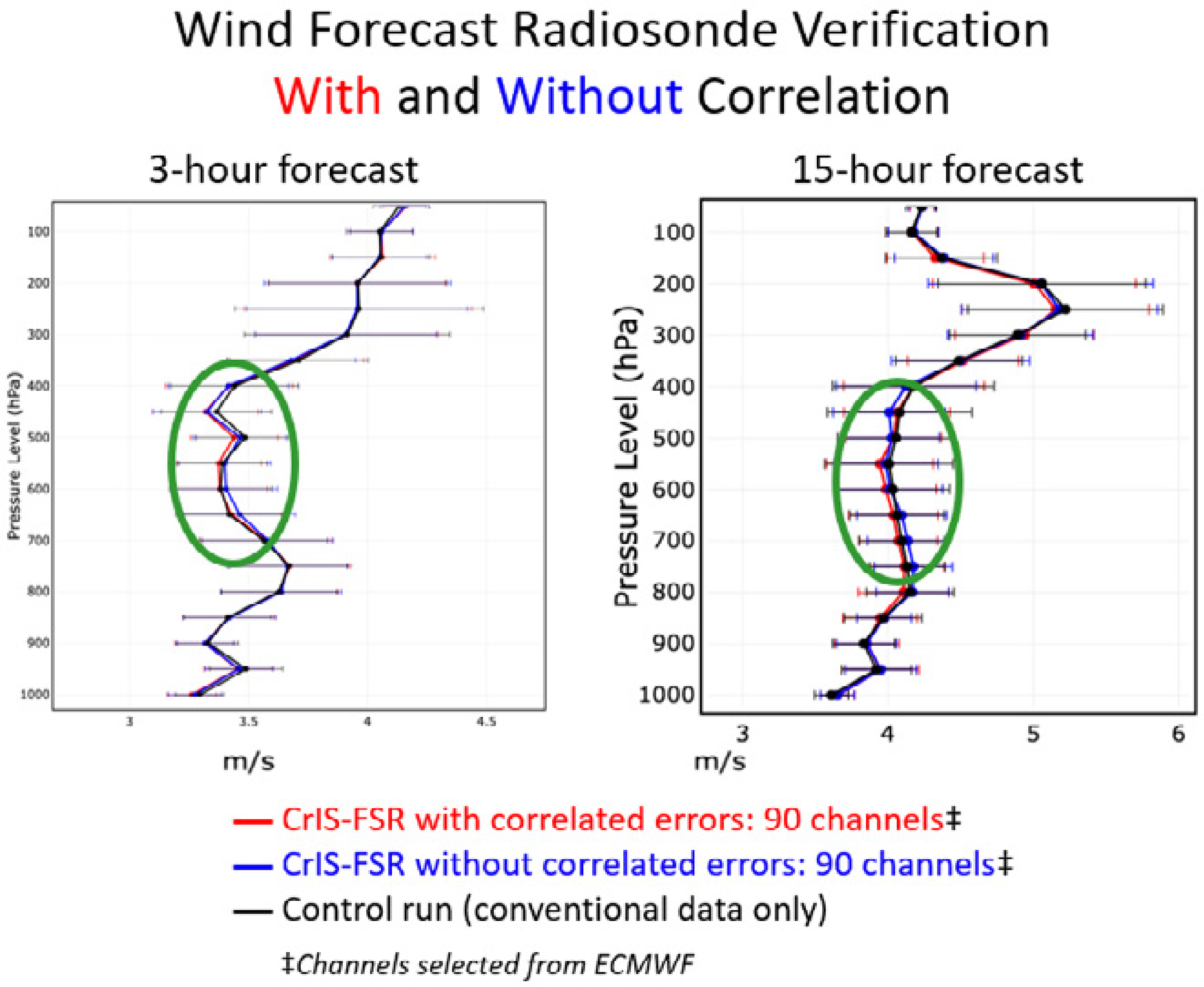
Evaluating the performance of different channel sets is important for Dr. Lin to determine the optimal data formulation for the Rapid Refresh Forecast System. The following two examples are results from a series of experiments that compared the impact of NOAA-20 CrIS and MetOp-A IASI sounders using different channel sets selected from different sources.[4] Here, says Dr. Lin, "smaller errors mean greater improvement" in the forecast.

In the three experiments below, IASI (blue) shows a slightly larger impact on the 18-hour wind forecast than CrIS (red), but "overall, they're pretty comparable," Dr. Lin remarks. The same can be said for 18-hour relative humidity forecast experiments, below. "Maybe sometimes IASI is a little bit better [than CrIS] but the difference is very small." CrIS and IASI data also appear to have an overall positive impact with radiosonde verification (not shown) when compared with the conventional-only data assimilated control run. All in all, the team found that using more channels in the Rapid Refresh Forecast System provides greater benefit, which was expected given its higher model top.



Other experiments have been designed to account for inter-channel correlation to reduce error. "We're using the CrIS-FSR observation correlation matrix to improve the CrIS data impact [and] using the Desroziers diagnostic method to calculate the error correlation," notes Dr. Lin. A utility developed by NCEP has been used to calculate the correlated errors. The comparison below shows wind forecasts for CrIS (using 90 channels) with and without correlation. Dr. Lin explains: "We want the red and blue line to be to the left of the black line [control]. Smaller errors mean greater improvement or impact. We see some small improvement for [the] 15-hour wind forecast for the dataset with correlated errors [red], but it's only slightly better [than the dataset without correlated errors in blue]." Both here and in experiments above, NOAA-20 CrIS and MetOp-A IASI sounders have comparable impacts to forecast skill. Work continues to test different channel sets and inter-channel error correlations to further improve the impact of CrIS within the Rapid Refresh Forecast System.





CONCLUSION

When NOAA's next generation convection-allowing Rapid Refresh Forecast System becomes operational some time in 2025 it will offer forecast guidance at timescales where rapidly updating information is critical, like aviation, severe convective weather, heavy precipitation, and winter weather. Evaluations like those led by Dr. Lin and others at the NOAA Global Systems Laboratory are necessary to make sure the Rapid Refresh Forecast System functions as well as or better than current state-of-the-art short-range forecast models and is ready for operations.

Dr. Lin's team has shown that satellite radiance data from LEO sounders have a positive impact on forecasts with the Rapid Refresh Forecast System, and that the overall impact is larger than radiosonde data. Real-time testing of the system is ongoing at the NOAA Global Systems Laboratory and the National Centers for Environmental Prediction with activities underway to transition from research to operations. Building on these successes, Dr. Lin is continuing his experiments with the inclusion of CrIS and Advanced Technology Microwave Sounder (ATMS) data from NOAA-21 within the Rapid Refresh Forecast System, inter-channel correlated errors, all-sky radiance data assimilation, and different channel sets, including short-wave channels, to further improve the impact of CrIS data on numerical weather prediction. Evaluations like these are crucial for the future of forecasting as new models, new satellite sensors, and new instrument channels are more frequently coming online. ✦

STORY SOURCE

The information in this article is based, in part, on the March 20, 2023, LEO Science Seminar titled, "Radiance data assimilation enhancements and impacts for the FV3-based Rapid Refresh Forecast System (RRFS)" presented by Dr. Haidao Lin, Research Scientist at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University and the NOAA Earth System Research Lab/Global Systems Laboratory in Boulder, CO.

FOOTNOTES

1 Real-time data coverage for LEO satellites is available through the Direct Broadcast Network (DBNet) and Regional ATOVS Retransmission Services (RARS). DBNet is a worldwide network of local receiving stations that allows for real-time acquisition and rapid delivery of LEO satellite data to the global user community. RARS are operational arrangements for the real-time acquisition of LEO satellite data over a wide region containing a network of direct readout stations, and for their rapid delivery to the global user community through regional processing centers.

2 A 13-km prototype Rapid Refresh Forecast System (a RAP-like domain) was used to save on computational cost.

3 Radiance experiments were conducted with a prototype 13-km North America Rapid Refresh Forecast System (a RAP-like domain) and the 3-km North America Rapid Refresh Forecast System (a RAP-like domain but slightly smaller in size).

4 Channel sets were selected from the channels used in the RAP v5 model, channels used by the NOAA National Centers for Environmental Prediction (NCEP), European Centre for Medium-Range Weather Forecasts (ECMWF), and from the channel set delivered through the NOAA NCEP.

5 Desroziers, G.; Berre, L.; Chapnik, B.; Poli, P. Diagnosis of observation, background and analysis-error statistics in observation space. Q. J. R. Meteorol. Soc. 2005, 131, 3385–3396.

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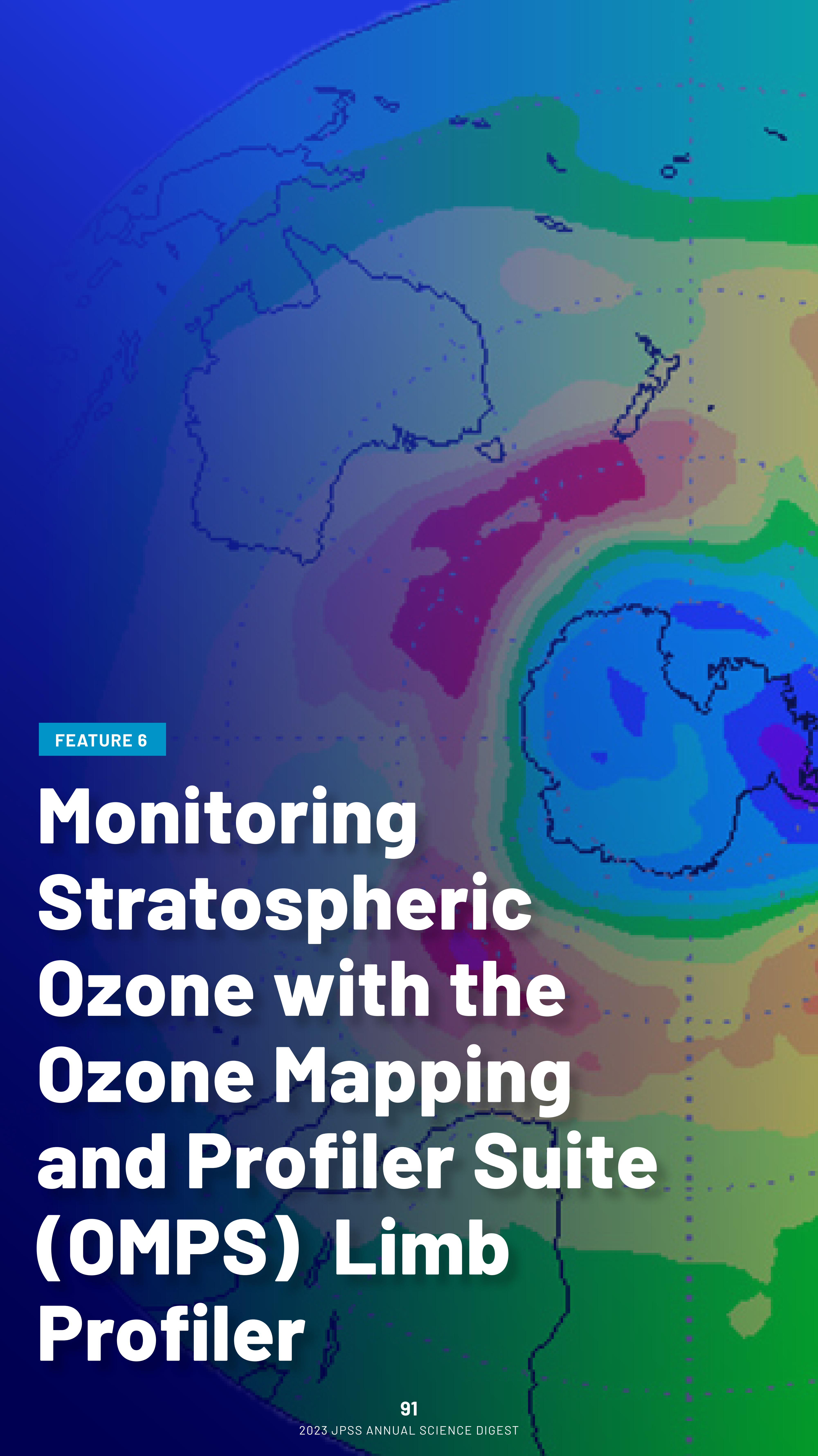
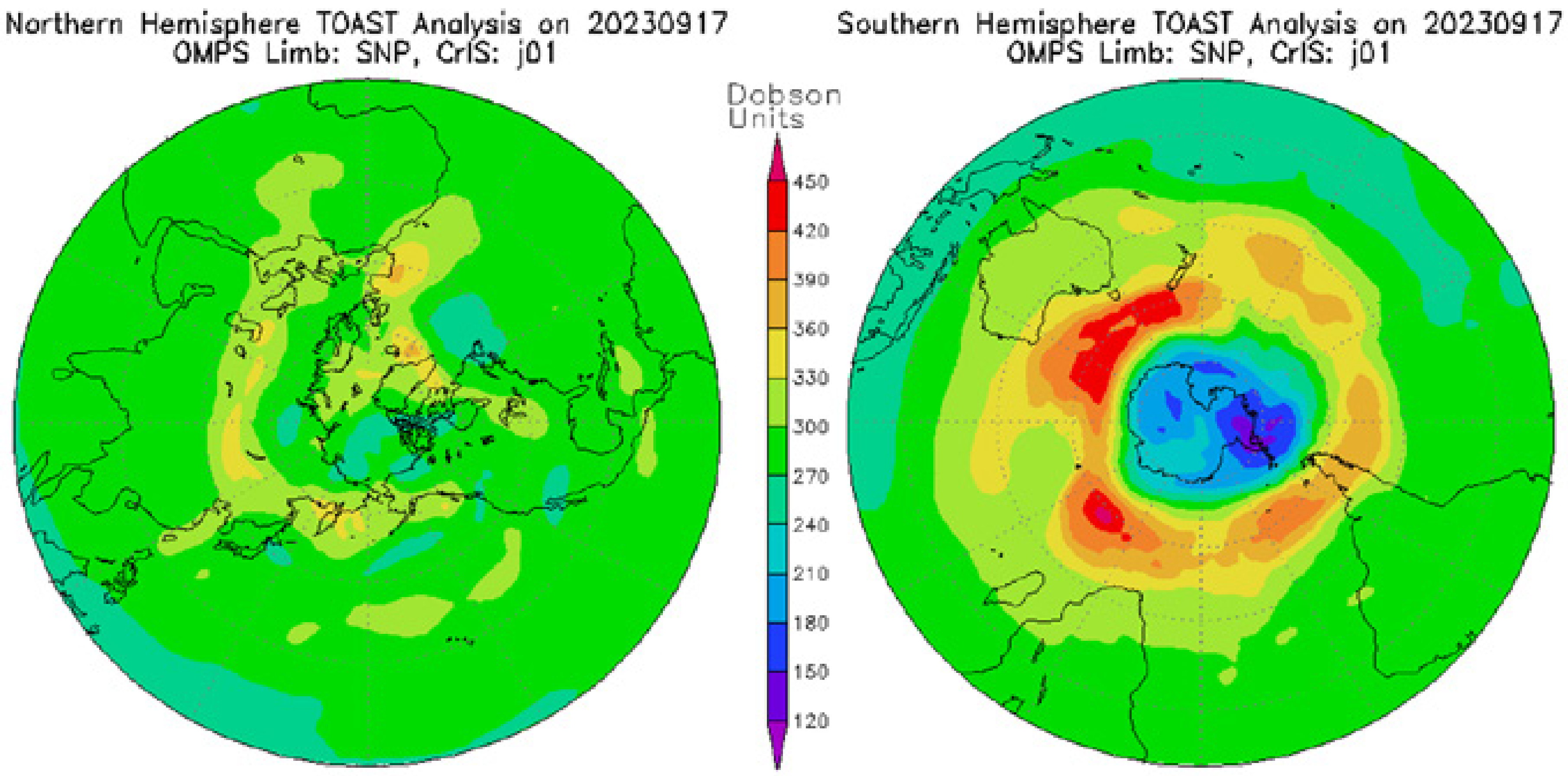


FEATURE 6

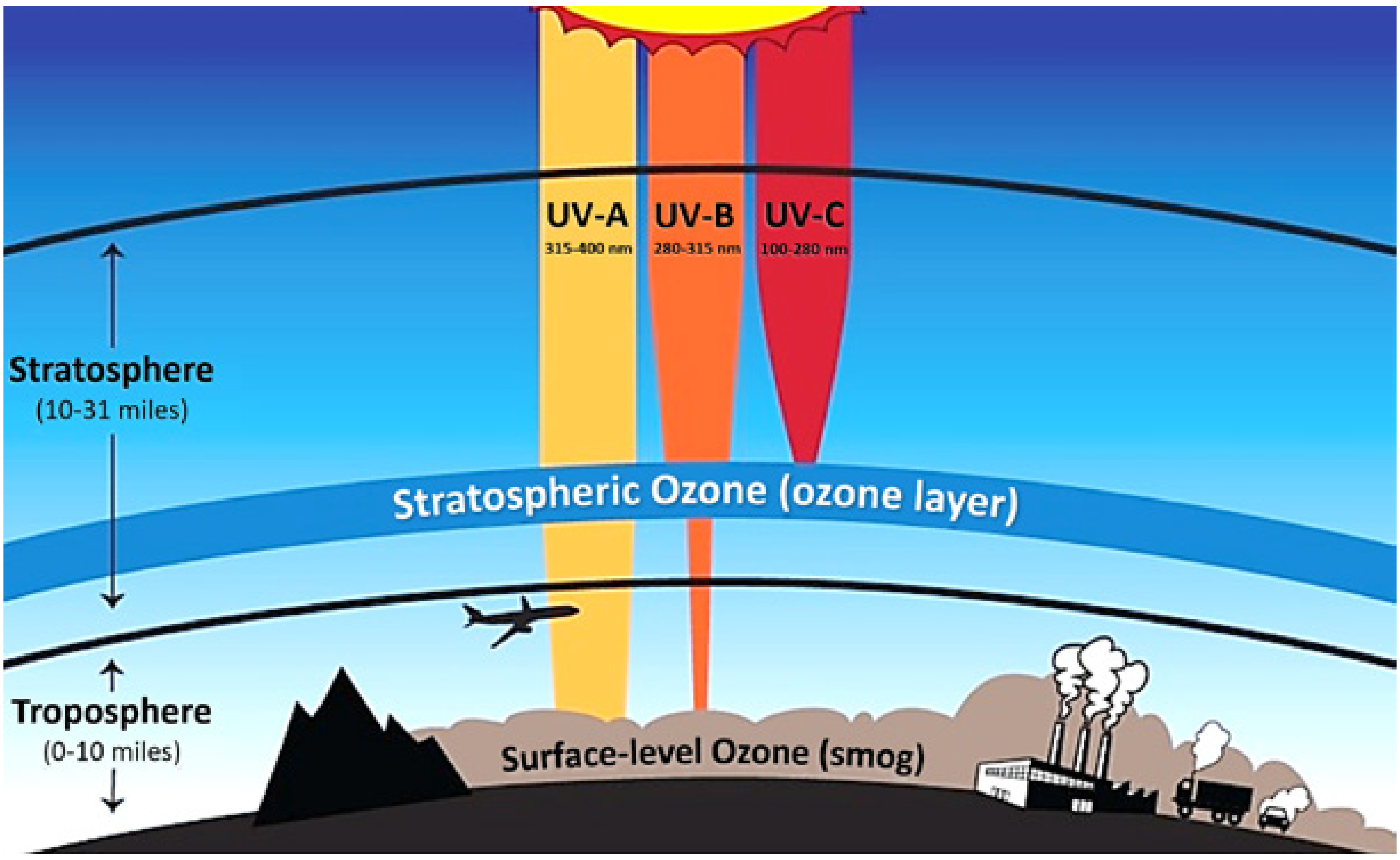
Monitoring Stratospheric Ozone with the Ozone Mapping and Profiler Suite (OMPS) Limb Profiler



Global TOAST analysis on September 17, 2023, for the Northern Hemisphere (left) and Southern Hemisphere (right). The L-TOAST algorithm blends the ozone products from the ultraviolet/visible sensor OMPS Limb Profiler and the infrared sensor CrIS (NUCAPS) onboard the Suomi-NPP satellite. Over the Earth's surface, the ozone layer's average thickness is about 300 Dobson Units (DU), shown by yellow-green colors. The ozone "hole" over Antarctica is an area where the ozone concentration drops to below the threshold of 220 DU, shown by light blue-purple colors. Source: NOAA.

Stratospheric ozone is critical for all life on Earth. It is mostly concentrated high up in the atmosphere between about 15 to 30 kilometers (9 to 18 miles) above the Earth's surface in a region known as the ozone layer. The ozone layer absorbs a substantial portion of incoming ultraviolet (UV) radiation, essentially acting as a shield that protects all life on Earth from the sun's harmful rays. But depletion of the ozone layer means that damaging levels of UV radiation reach the Earth's surface, having significant and far-reaching impacts on the planet.

Elevated UV radiation poses serious health risks to humans, as it can lead to higher rates of skin cancer, cataracts, and other health issues. Additionally, ozone depletion has environmental ramifications, impacting ecosystems and marine life.



Miles above the surface of the Earth, a thin layer of stratospheric ozone gas acts as a shield that protects all life on Earth from harmful ultraviolet light. Credit: NASA. Source: NASA.

High UV levels at the surface can disrupt the food chain, reduce photosynthesis, damage crops, harm phytoplankton, and affect aquatic species. Ozone depletion can also influence climate patterns, contributing to shifts in atmospheric circulation and potentially altering weather systems. Without the ozone layer, human health, food production, and ecosystem services would be threatened.

Ozone layer thickness—on average about 300 Dobson Units (DU) or about 3 millimeters thick if the ozone was compressed into a single layer—varies naturally depending on season, sunspot activity, and latitude (ozone concentration is lower in the tropics and increases in mid- and polar latitudes). But the ozone layer is thinner than it used to be thanks to man-made ozone-depleting substances like chlorofluorocarbons (CFCs) and other chemicals that linger for years in the atmosphere. It wasn't until the mid-1970s that scientists realized that CFCs—widely used as refrigerants and propellants since the 1930s—were rising high into the atmosphere and interacting with sunlight to release active chlorine and bromine molecules, potent agents that destroy ozone molecules.

In the mid-1980s, scientists reported an even worse finding: extremely low ozone concentrations over Antarctica during austral spring—springtime in the Southern Hemisphere. The ozone layer over Antarctica had been growing progressively thinner during austral spring months for nearly a decade, losing about one-third of its thickness during this period by 1984. This seasonal thinning became known

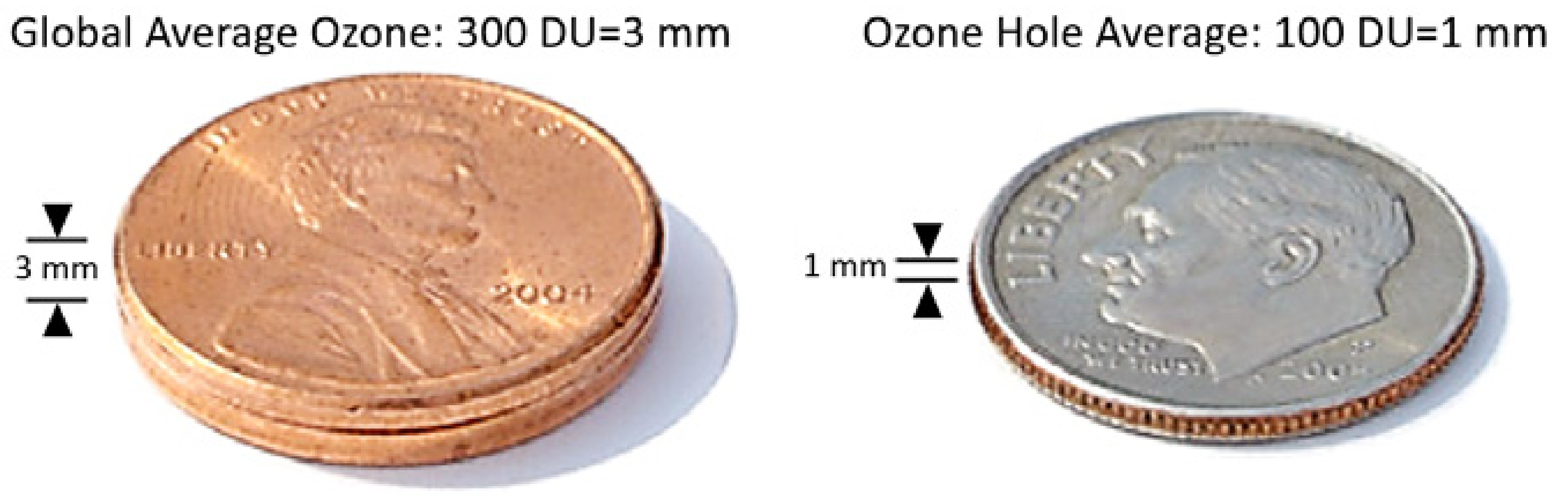
What is the Dobson Unit (DU)?

Ozone layer thickness is expressed in Dobson Units (DU). The American Meteorological Society defines the Dobson Unit as "the measure of the column abundance of ozone in the atmosphere," where the column extends vertically from the ground up to space. Over the Earth, the average thickness of the ozone layer is about 300 Dobson Units, equivalent to about 3 millimeters.

But the ozone layer is not a single layer of pure ozone—it is a region where ozone is more common compared to other altitudes. The Dobson Unit is a way to describe how much ozone there would be in a column if it were all squeezed into a single layer.

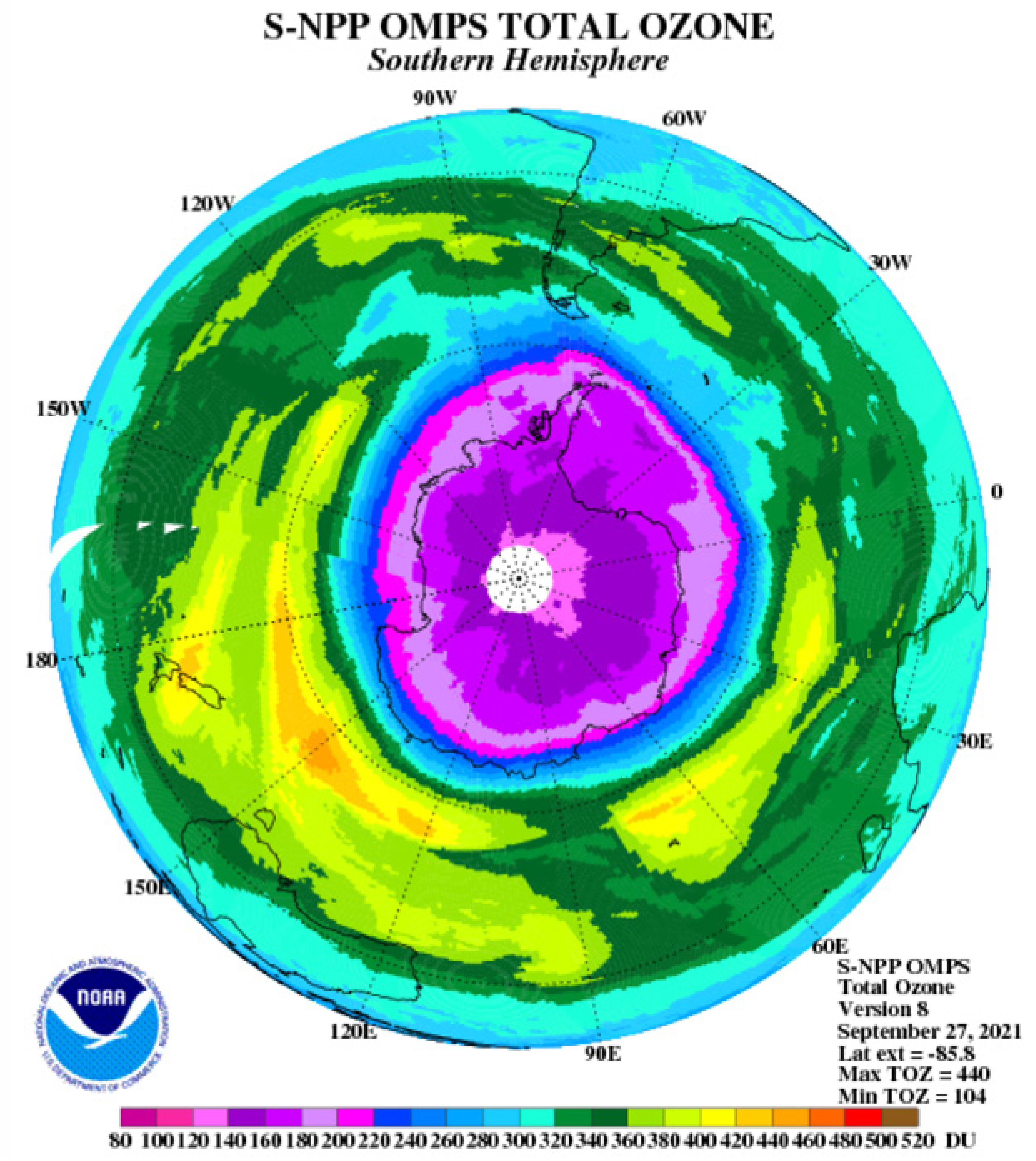
Compressed to sea-level pressure, stratospheric ozone would form a layer about the height of two pennies stacked together. Levels linked to the Antarctic ozone hole are much less—about the height of a single dime.

Source: NASA Goddard Space Flight Center

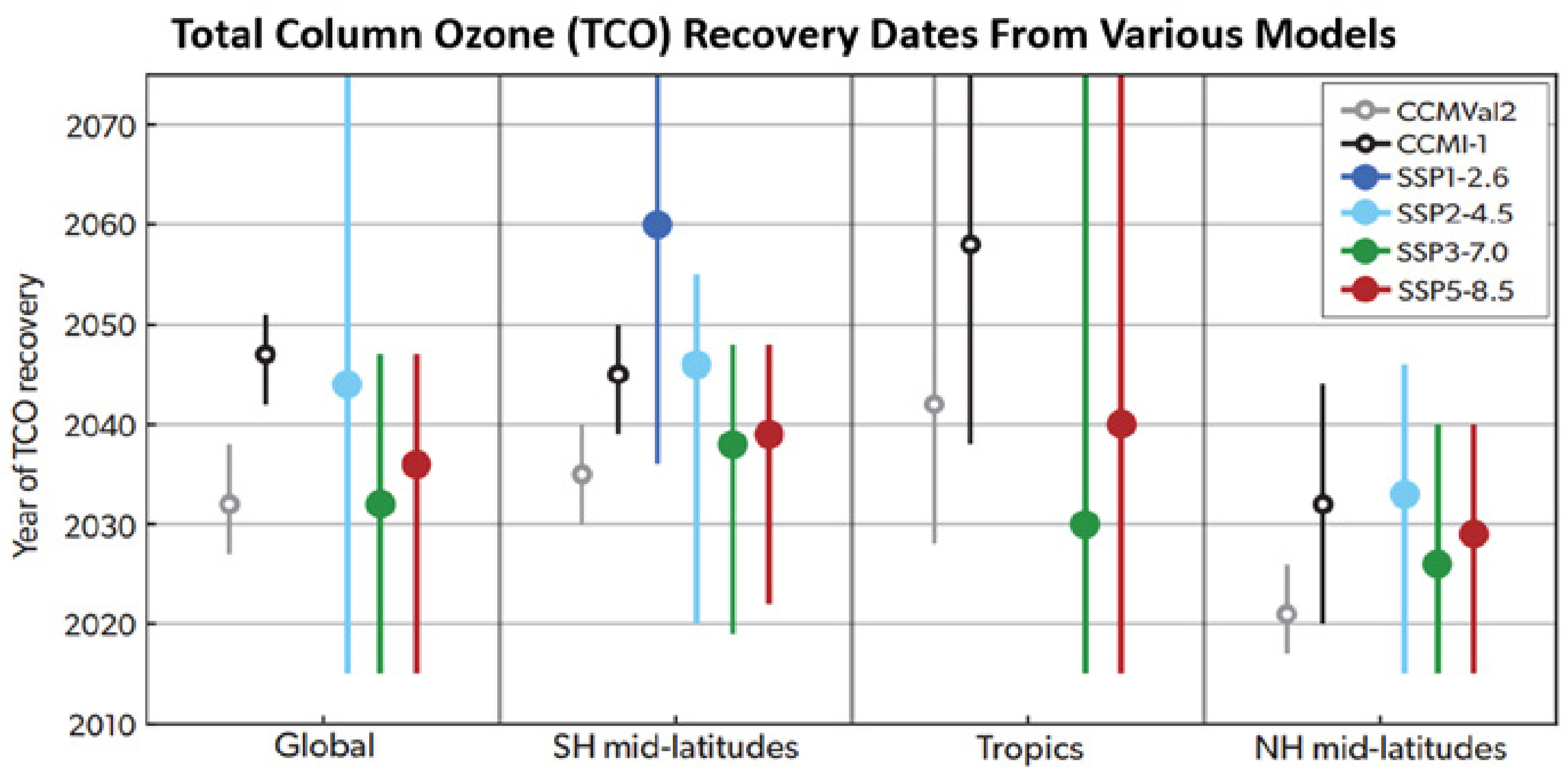


as the ozone hole, a metaphor for the area in which ozone levels drop below the historical threshold of 220 DU. To this day, the Antarctic ozone hole reappears annually thanks in part to the long atmospheric lifetime of CFCs and other ozone-depleting substances, which can circulate in the atmosphere for decades.

Discovery of the Antarctic ozone hole raised awareness of the need to protect the ozone layer, and in 1987, several nations signed the Montreal Protocol, an international treaty to discontinue the production and consumption of nearly all ozone-depleting substances. Since then, every country in the world has ratified the agreement, and as of today, about 98 percent of the targeted ozone-depleting substances have been phased out. The actions in response to this landmark treaty have led to the steady recovery of stratospheric ozone, with a return to pre-1980 levels expected over Antarctica around 2066, over the Arctic around 2045, and globally around 2040, although predictions vary by model as shown in the graph on the next page.



Total ozone showing the seasonal ozone hole over Antarctica on September 27, 2021. Data is derived from the Suomi NPP Ozone Mapping and Profiler Suite (OMPS).

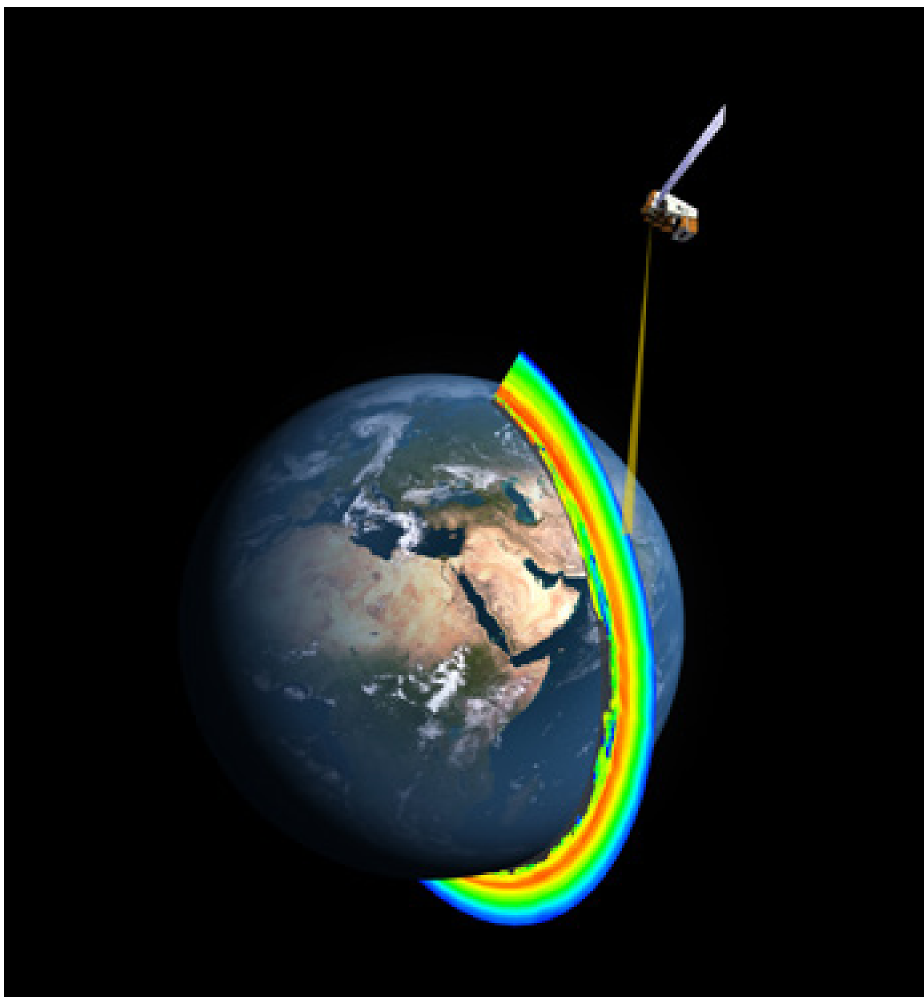


Predictions of total column ozone (TCO) recovery are based on model simulations. This figure shows the TCO recovery dates as predicted by six models: four shared socioeconomic pathways (SSPs) and experiments from the Chemistry Climate Model Validation Activity 2 (CCMVal2) and Chemistry-Climate Model Initiative (CCMI-1). SSPs are the main scenarios assessed in the 6th Intergovernmental Panel on Climate Change (IPCC) reports. The four SSP scenarios included here are scenarios for "Sustainability" (SSP1), "Middle of the Road" (SSP2), "Regional Rivalry" (SSP3), and "Fossil-fueled Development" (SSP5) pathways. Source: World Meteorological Organization, Ozone Research and Monitoring - GAW Report No. 278.

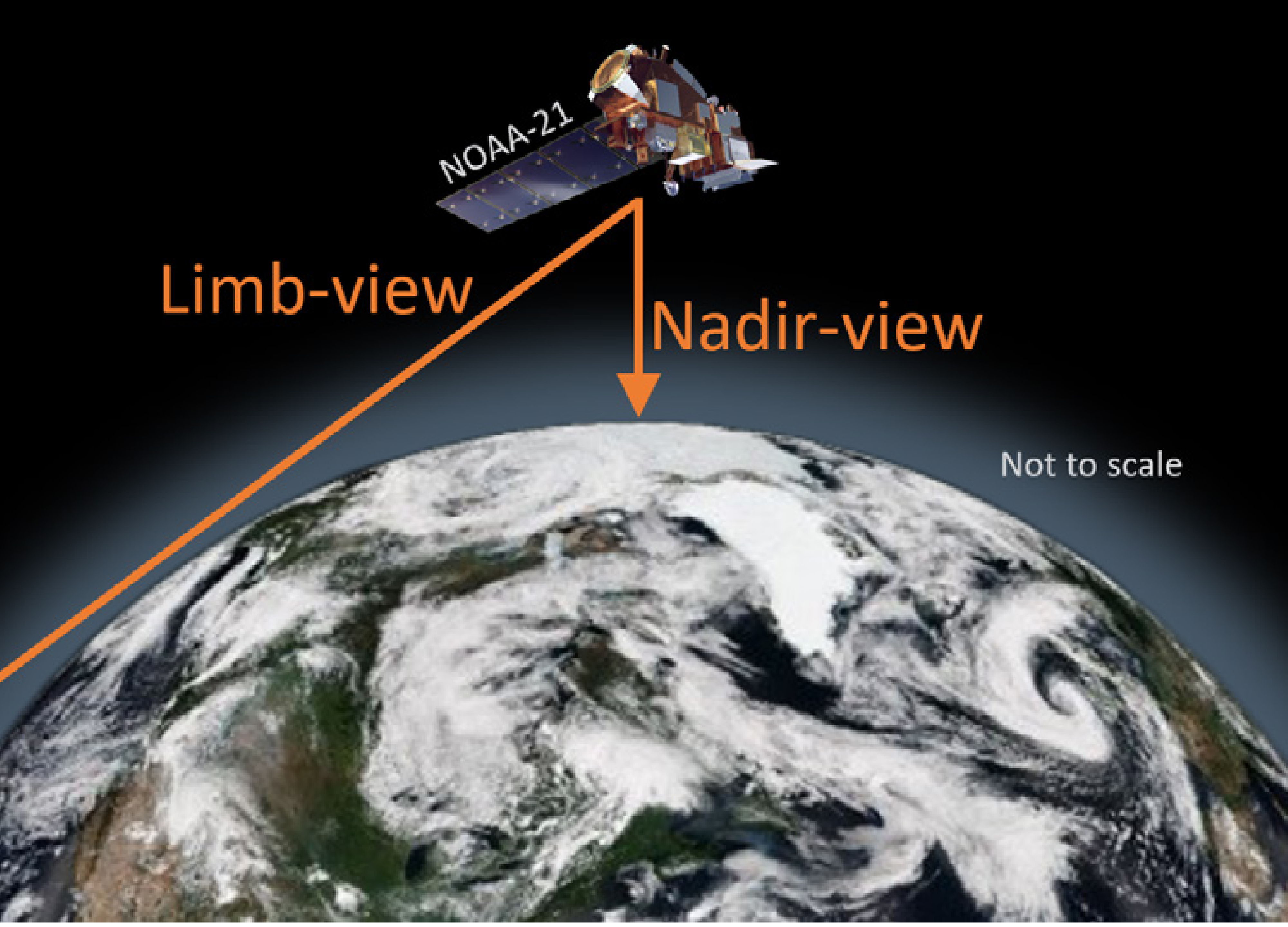
One way scientists monitor the rebound of stratospheric ozone and study its impact on global circulation and climate is with space-based sensors, like the Ozone Mapping and Profiler Suite (OMPS) onboard JPSS satellites, that provide information on how ozone concentration varies with altitude. At the June LEO Science Seminar, Dr. Natalya Kramarova, Research Scientist at the Atmospheric Chemistry and Dynamics Lab at NASA Goddard Space Flight Center, provided an overview of the OMPS Limb Profiler that included example applications and algorithmic improvements.

MEASURING OZONE FROM SPACE

Nimbus, a series of Earth observation satellites launched between 1964 and 1978 by NASA, was the first satellite series to measure ozone from space. It was, in fact, observations from the Total Ozone Mapping Spectrometer (TOMS) onboard Nimbus 7 that confirmed the presence of the Antarctic ozone hole and its annual recurrence. OMPS, the latest generation of ozone monitoring technology, continues the more than 50 year data record of satellite ozone observations.



A cross-section of the Earth's ozone layer as measured by the OMPS Limb Profiler aboard the Suomi NPP satellite. Smaller amounts of atmospheric ozone are shown in blue, while larger amounts are shown in orange and yellow. Source: NASA/NOAA.

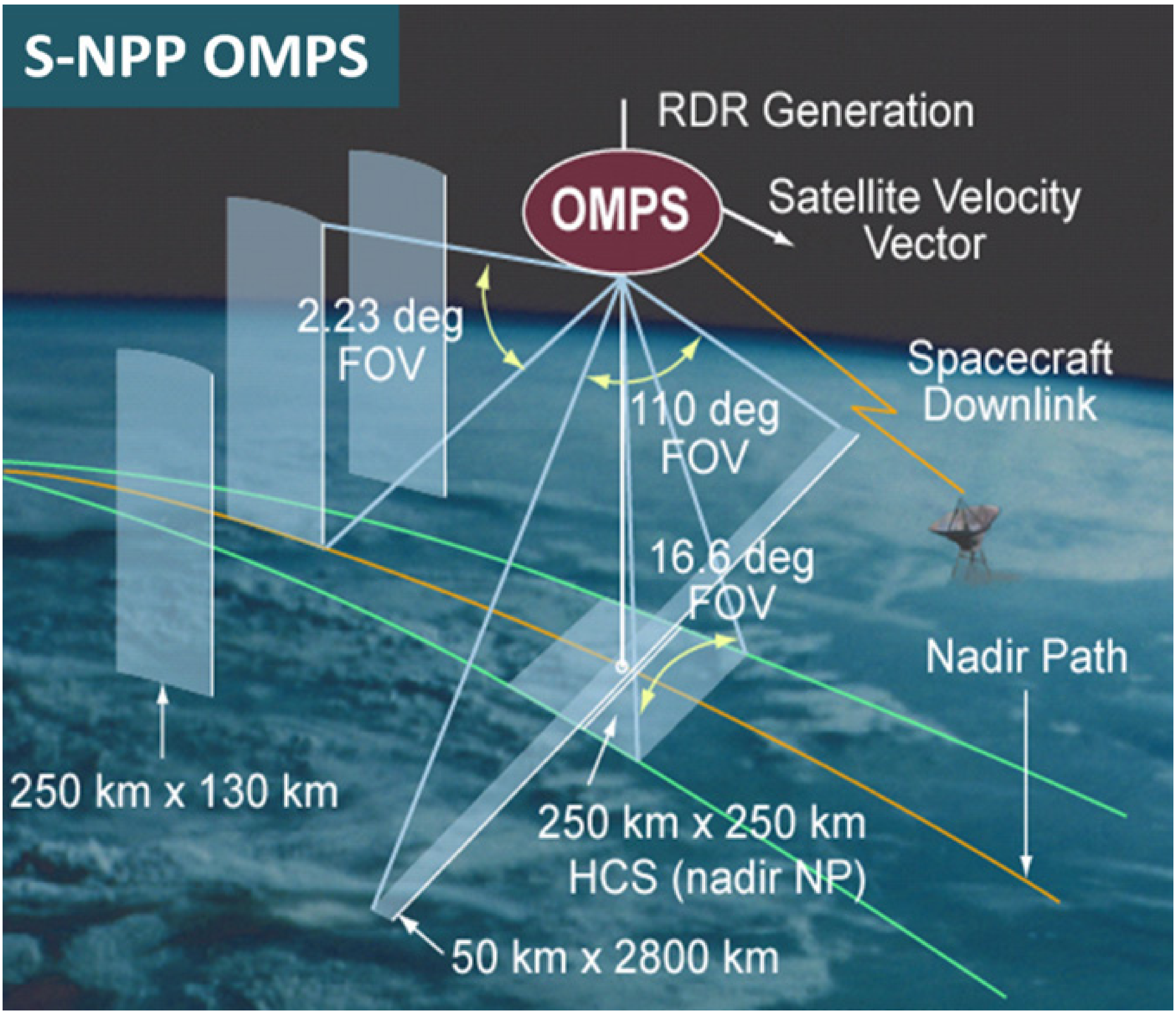


OMPS is a hyperspectral instrument that measures atmospheric ozone and other trace gases and how their concentrations vary with altitude. OMPS products help scientists track the recovery of the ozone hole and monitor ozone trends, as well as observe sulfur dioxide and ash that result from volcanic eruptions.

OMPS has two nadir-viewing spectrometers (Nadir Mapper and Nadir Profiler) that point straight down at the Earth. These measure total ozone through the entire atmospheric column, from top to bottom. The OMPS instruments onboard Suomi NPP and NOAA-21 also have a limb-viewing spectrometer (Limb Profiler) that looks diagonally through an atmospheric halo known as the Earth's limb (see image on previous page). Because of its viewing geometry, the OMPS Limb Profiler (LP) "sees" more of the Earth's atmosphere and takes spectral measurements over a range of altitudes compared to nadir-viewing sensors, making it suitable for measuring vertical profiles of ozone and aerosols. This unique perspective is important to better understand ozone layer depletion, study the impact of ozone on global atmospheric circulation, validate global climate models, and for many other applications.

The OMPS Limb Profiler Perspective

The primary purpose of OMPS LP is to monitor the vertical distribution of atmospheric ozone in the stratosphere. The profiler makes limb scattering measurements—about 160 to 180 per orbit with 14 orbits per day—viewing backwards along its path. "LP has three slits separated by about four-and-a-quarter degrees, which results in about a 250 kilometer difference on the ground," Dr. Kramarova explains. The LP successfully uses a charge coupled device (CCD) detector to



simultaneously measure radiances in ultraviolet and visible spectrum ranges (290 to 1000 nanometers) from the entire extent of the atmosphere from the ground to 80 kilometers (km). “From these observations we can retrieve vertical profiles of ozone and aerosols,” she says, noting that three ozone profiles (one for each slit) from cloud tops up to 55 km are produced every 19 seconds.

OMPS LP and other limb profilers rely on the sun as a source of illumination. As a profiler views the atmosphere from space, it picks up scattered light from the Earth’s limb—sunlight that is scattered by particles of atmospheric gases, clouds, aerosols, and Earth’s surface along the instrument’s line of sight. The profiler’s spectrometer measures the spectral characteristics of the scattered light at different layers of the atmosphere, which scientists use to determine the altitude and concentration of atmospheric substances. This technique works because different molecules and particles scatter and absorb light in specific ways, giving each a unique spectral signature—a distinctive metaphorical thumbprint—that changes with altitude.

Accounting For Altitude Registration Drift

The main source of uncertainty in limb scattering measurements is altitude registration error. Altitude, also called tangent height, represents the shortest distance between the Earth’s surface and the line of sight of the limb profiler. Altitude registration is the process of determining the height above the Earth's surface at which atmospheric limb measurements are taken.

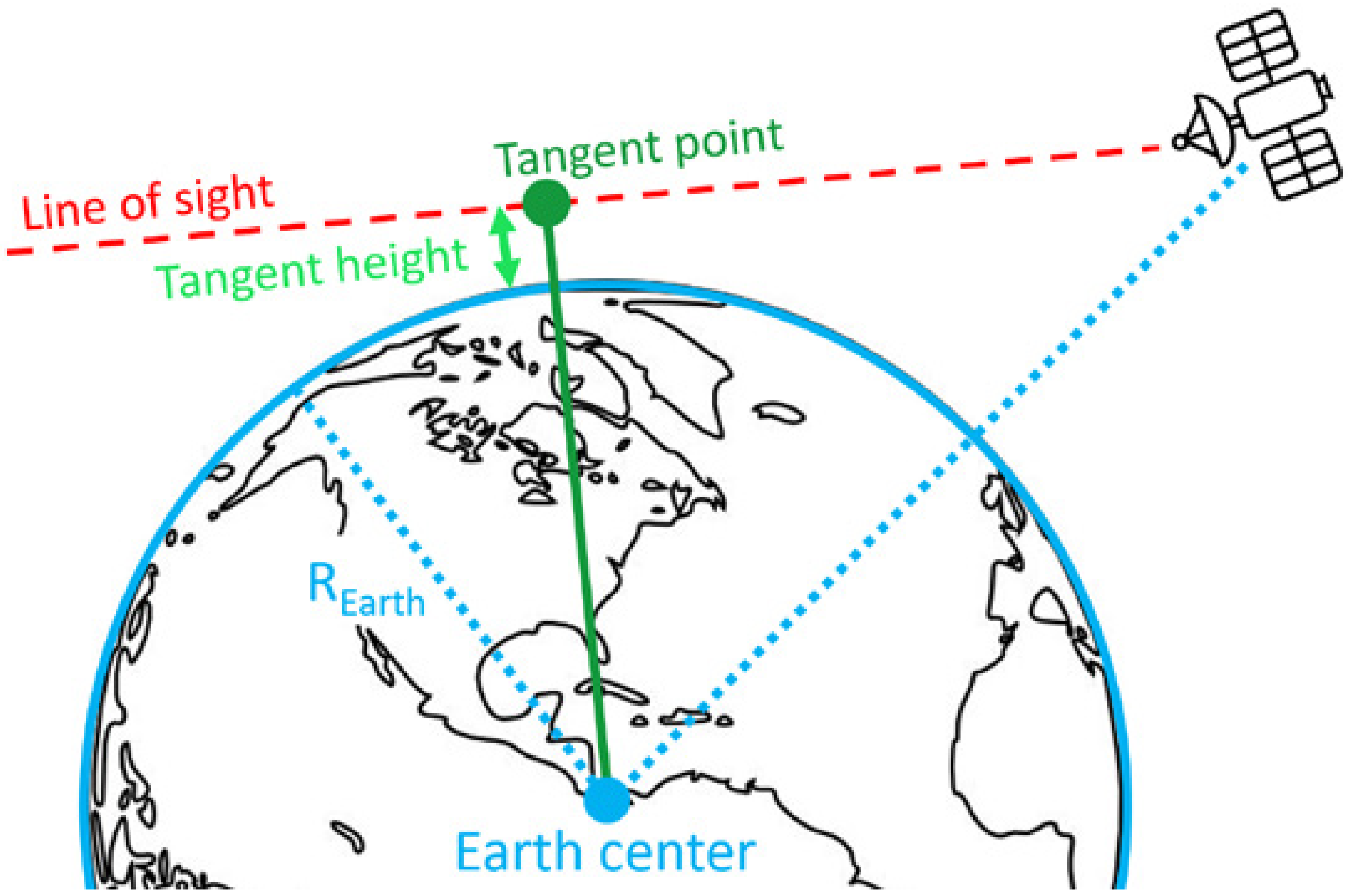
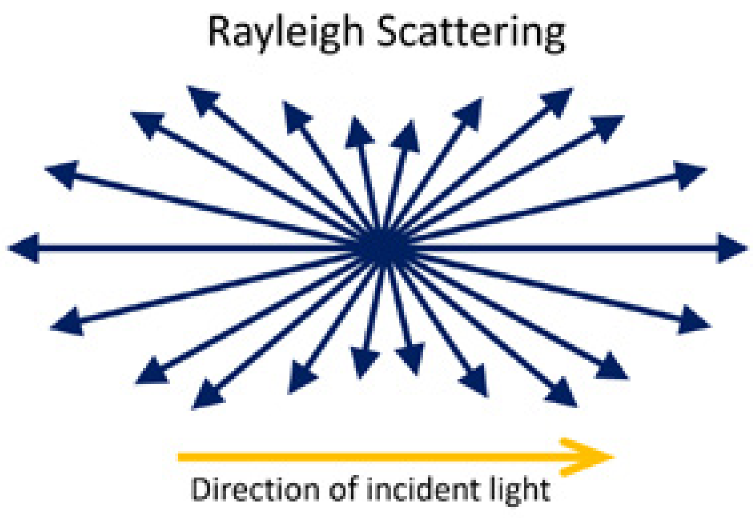


Illustration of the geometry of satellite limb profiler observations. REarth is the Earth's radius. Not to scale. Adapted from "GRACILE: a comprehensive climatology of atmospheric gravity wave parameters based on satellite limb soundings," by M. Ern, et al., 2018, Earth System Science Data, 10(2): 857-892, doi: 10.5194/essd-10-857-2018. Distributed under Creative Commons Attribution 4.0 License.

Accurate altitude registration is vital for making sure that vertical measurements of atmospheric trace gases are correctly associated with corresponding altitudes—in the case of stratospheric ozone, scientists need to know at what height ozone depletion is taking place, for instance. To detect small trends in ozone concentration, like those associated with the slow recovery of the ozone layer, atmospheric measurements must be extremely accurate.

Altitude registration drift—a sensor pointing error—occurs when measurements gradually deviate or "drift" in their recorded altitude values over time. This drift can occur due to various factors, including spacecraft adjustment maneuvers, thermal sensitivity of the instrument, aging of instrument components, or a shift in the relative position of the instrument and the satellite's star tracker during launch (a star tracker is an optical device that is used to determine the location and altitude of a satellite by analyzing the placement of surrounding stars relative to its payload). Altitude registration drift can have big implications, says Dr. Kramarova, noting that "even a small error in altitude registration can produce significant errors in ozone retrievals."

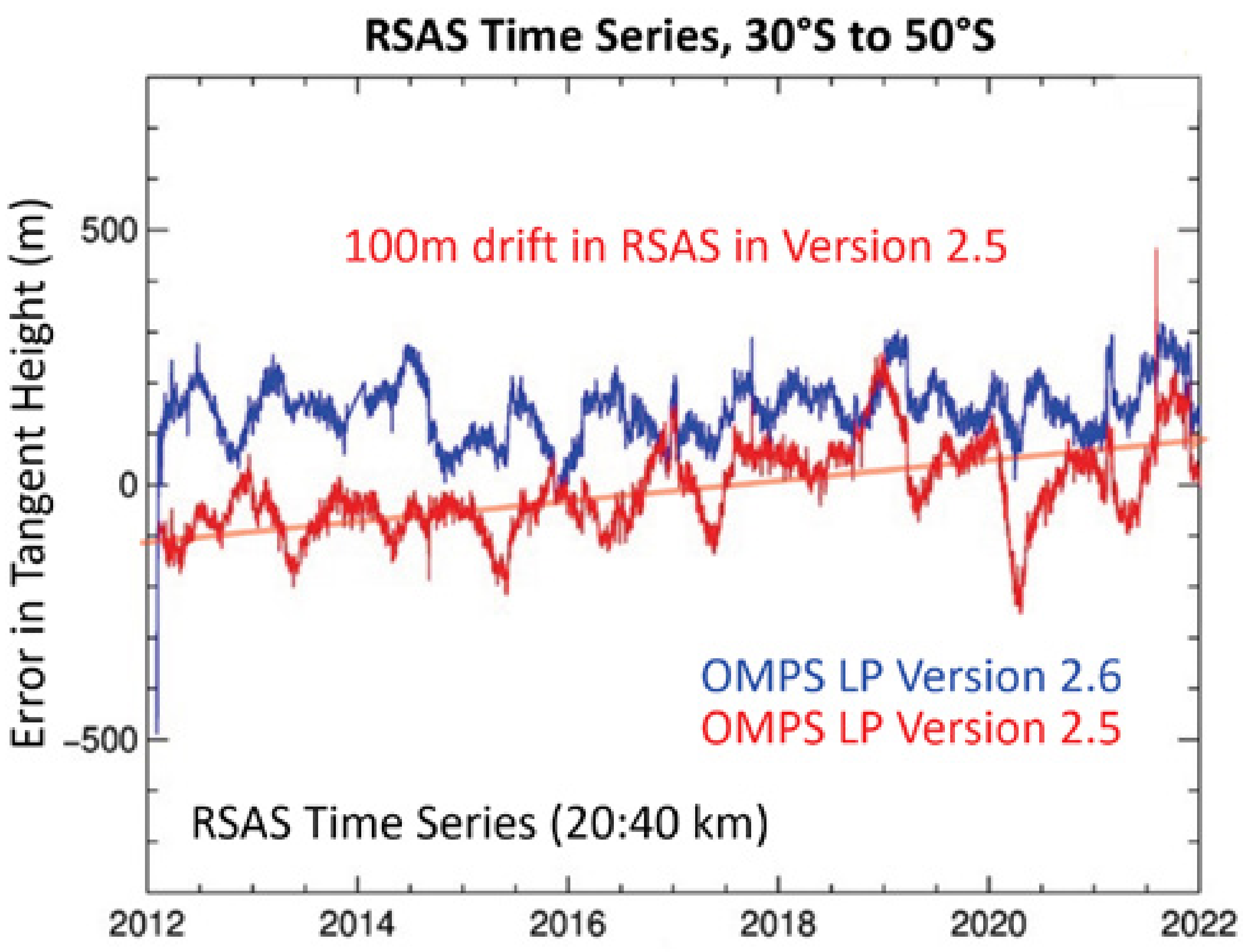
Two methods are used to monitor and adjust OMPS LP altitude registration to the accuracy needed for long-term ozone monitoring: Rayleigh scattering altitude sensing (RSAS)[1] and the absolute radiance residual method (ARRM)[2]. The utility of each method is linked to atmospheric conditions and the altitude at which measurements are made. "We don't



have a good reliable method that we can use under any conditions, which means the method used depends on the conditions," says Dr. Kramarova, and there are limitations to each. Together, however, these complementary techniques provide highly precise and accurate estimates of the altitude above the Earth at which a limb scattering measurement is taken.

RSAS exploits the increase in Rayleigh scattering radiances at 350 nanometers (nm), the wavelength where ozone absorption is negligible, for altitudes between 20 km and 40 km (in simple terms, Rayleigh scattering is the scattering of light in all directions by atmospheric particles or molecules). Using the RSAS method, "we can estimate an absolute error in altitude registration," says Dr. Kramarova. But RSAS is greatly affected by aerosols, so this method is limited to latitudes and time periods with minimal aerosol contamination.

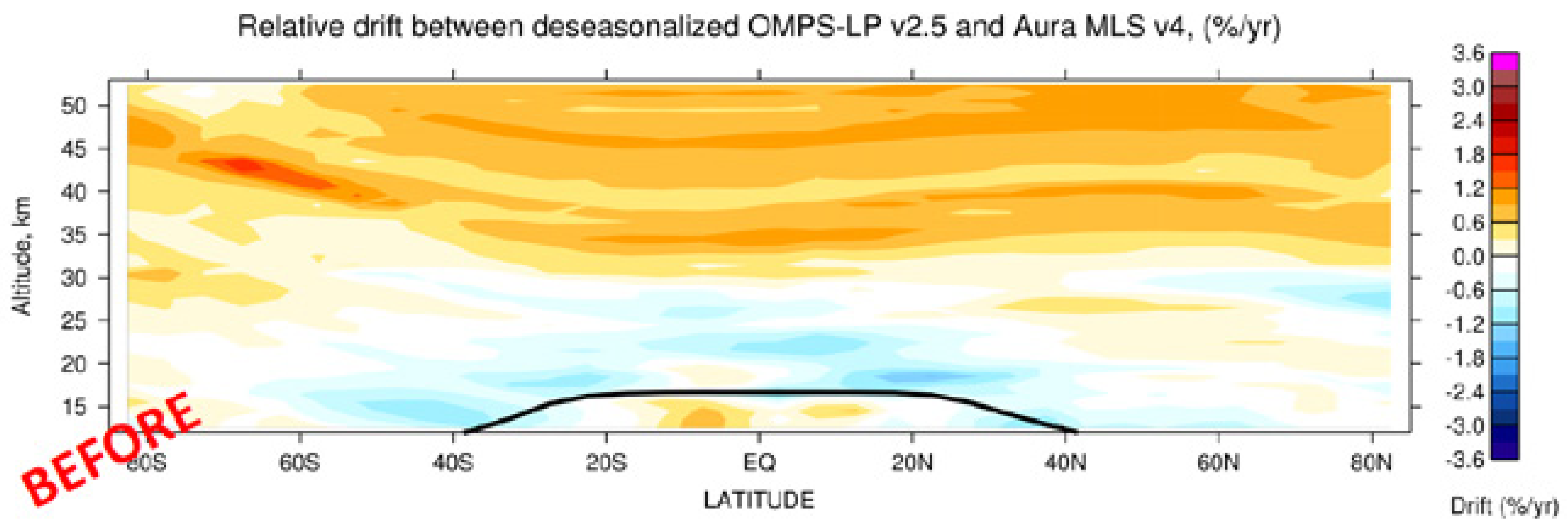
Because of these limitations, Dr. Kramarova also applies ARRM to determine relative limb altitude registration, a method proposed several years ago by Dr. P.K. Bhartia, a former NASA scientist. ARRM uses short wavelengths (about 295 nm) at altitudes between 40 km and 65 km to avoid aerosols and clouds, and a normalization factor to minimize the effect of uncertainties in meteorological data that are wavelength independent. "By contrasting measured and calculated radiances, the ARRM method allows [us] to derive a relative error in [altitude] registration," she explains.



Recent updates to the OMPS LP retrieval algorithm by Dr. Kramarova's team include aerosol corrections, increasing the number of wavelengths used in the algorithm, updating climatologies and ozone and nitrogen dioxide absorption cross sections, and combining ultraviolet and visible radiances to retrieve a single ozone profile. The graph (above) shows the improvement in RSAS altitude registration for the new retrieval algorithm, OMPS LP version 2.6 (blue line), as compared to the previous version 2.5 (red line).

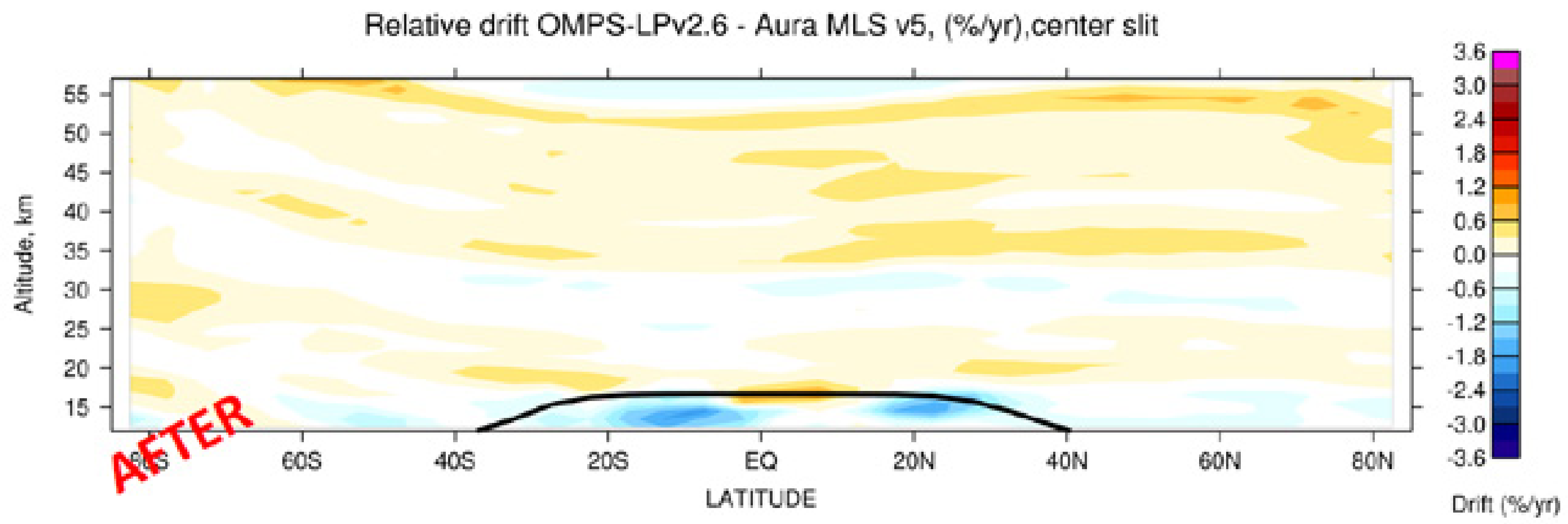
"What you can immediately see from the red line [old algorithm] is that there is a very strong drift over time and this drift is mostly related to erroneous corrections in September 2014 that produced this upward trend [red arrow]," Dr. Kramarova notes. Differences can also be seen in time dependence between the old and new algorithms. "The bottom line," says Dr. Kramarova, "is that the blue line [new algorithm] is more stable and we don't see the significant drifts in [OMPS LP] version 2.6 ozone."

How do the algorithmic improvements impact OMPS LP ozone retrievals? Looking at the relative drift between the old algorithm (OMPS LP version 2.5) and the NASA Aura Microwave Limb Sounder (MLS) (below), Dr. Kramarova explains: "We took ozone data from OMPS LP and Aura MLS over 10 years, removed seasonal cycles, calculated differences between two instruments, and fitted a linear trend [percent per year], which is shown as a function of altitude and latitude. The plot indicates a drift in the LP ozone record. The drift has a very pronounced pattern. You can see a positive drift [in observed ozone] above 30 kilometers, then the drift becomes negative below. This pattern is consistent with positive drift in altitude registration."



Relative drift in ozone (percent per year) at different altitudes between de-seasonalized OMPS LP version 2.5 and Aura MLS version 4.

She continues: "When we produced version 2.6 [new algorithm], we again check for drift using MLS data [below]. You can see a substantial decline in relative drift. There is still a small drift between LP and MLS, but there is no specific pattern that can be attributed to a drift in altitude registration." This indicates that correction of OMPS LP sensor pointing errors in version 2.6 resulted in improvements in the ozone retrievals. Reducing uncertainties in altitude registration methods helps to ensure a stability of the ozone record.



Relative drift in ozone (percent per year) at different altitudes between OMPS LP version 2.6 and Aura MLS version 5. These results are after improvements to the LP retrieval algorithm.

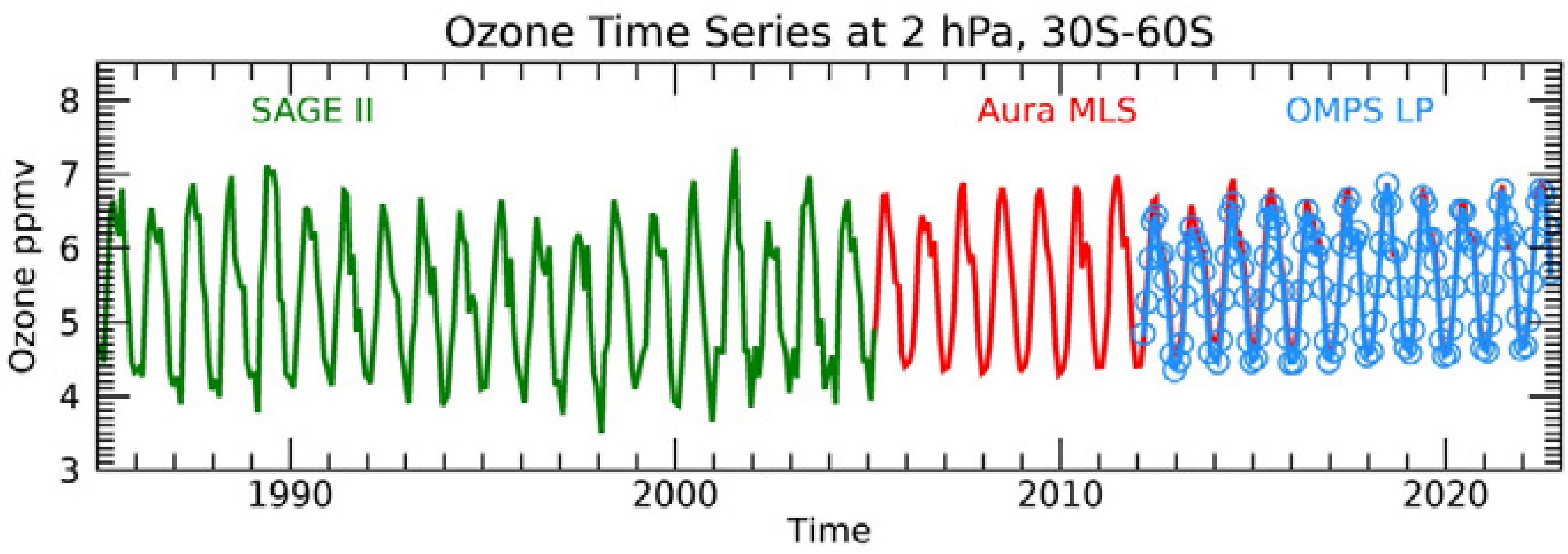
THE ROLE OF OMPS LP IN OBSERVING STRATOSPHERIC OZONE: A FEW EXAMPLES

OMPS LP provides critical data to extend the decades-long ozone profile records used by researchers to track the recovery of the ozone layer. The instrument's capacity for high-resolution vertical profiling also contributes to the observation of important indicators of ozone depletion over polar regions, like the presence of polar stratospheric clouds. Furthermore, LP-derived profiles are assimilated into numerical weather prediction models and atmospheric chemistry models, which provide insights into the dynamics of atmospheric processes. OMPS LP plays an indispensable role in advancing our knowledge of Earth's atmosphere and its interplay with global environmental phenomena. A few example applications are explained below.

Monitoring Global Ozone Layer Recovery

The overall concentration of ozone-depleting substances has been slowly but steadily declining in the stratosphere because of the implementation of the Montreal Protocol. But the ozone layer is impacted by more than just man-made CFCs—naturally occurring sulfate-containing aerosols emitted by volcanoes, for example, can impact stratospheric ozone. Continuous monitoring is essential to verify that the ozone layer is recovering as expected, given its vital role in supporting life on Earth.

Identifying trends in atmospheric ozone requires a long time series that extends over several decades to detect and isolate small changes in ozone from natural variations. NASA began collecting global observations of the distribution of ozone in the late 1970s, starting with the Solar Backscatter Ultraviolet (SBUV) instrument onboard Nimbus 7 and Stratospheric Aerosol and Gas Experiments (SAGE) on the International Space Station (ISS). With its global high vertical resolution measurements, OMPS will extend this historical record well into the 2030s as new JPSS satellites are launched. These consistent long-term observations help scientists better understand atmospheric processes, improve predictions of ozone layer recovery, and advance climate change modeling.



Ozone time series showing ozone concentration in parts per million by volume (ppmv) from 1985 to 2023 at about 58,500 feet (2 hPa) between 30°S and 60°S latitude, collected by SAGE II experiments and the Aura MLS and OMPS LP instruments.

Polar Vortex

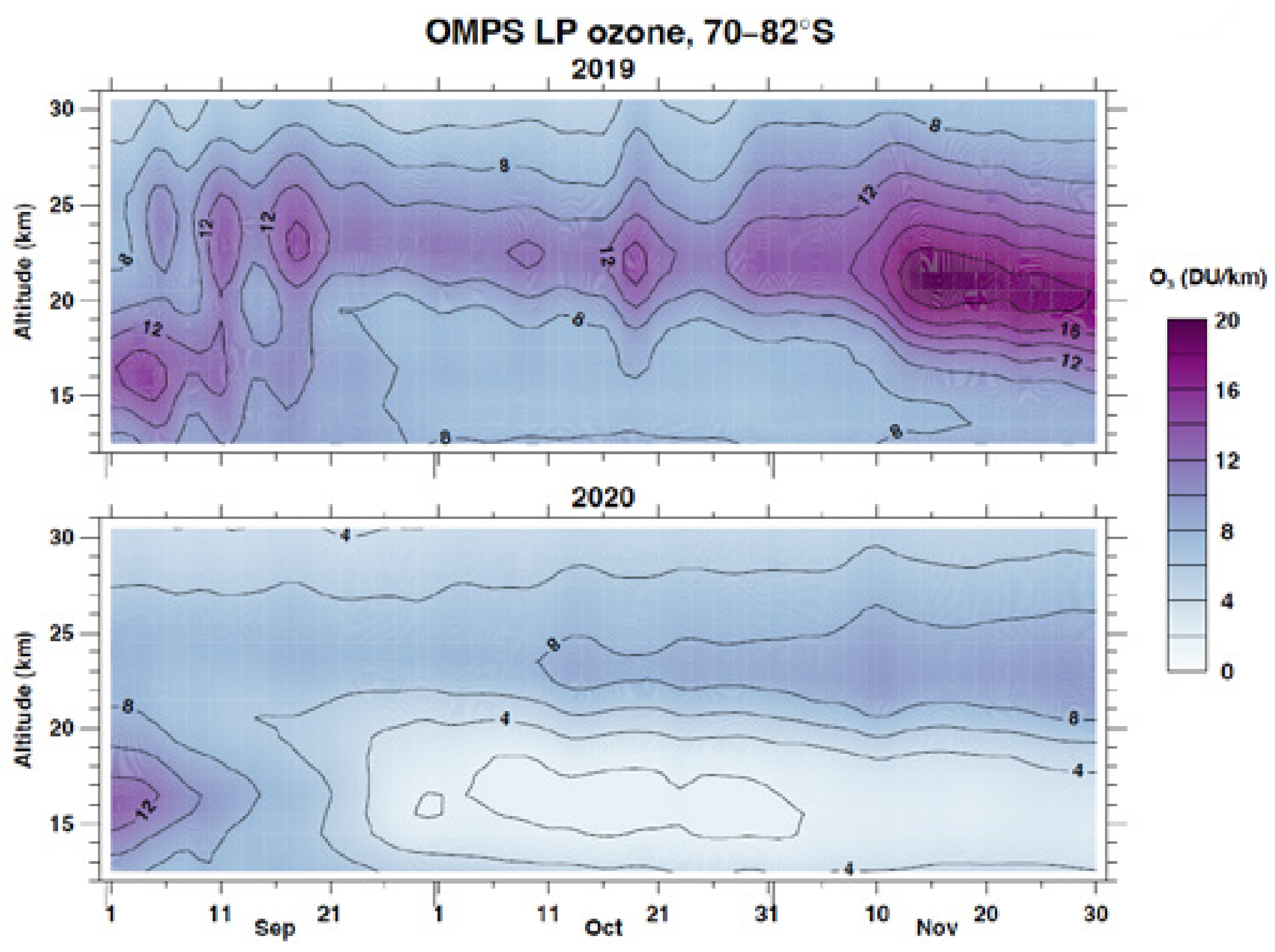
The polar vortex is a large region of cold, rotating air that surrounds the North and South Poles. The stratospheric polar vortex occurs at altitudes around 15 km to 50 km and is strongest in winter. It is associated with extreme cold and low ozone values.

Monitoring Ozone Depletion Over Polar Regions

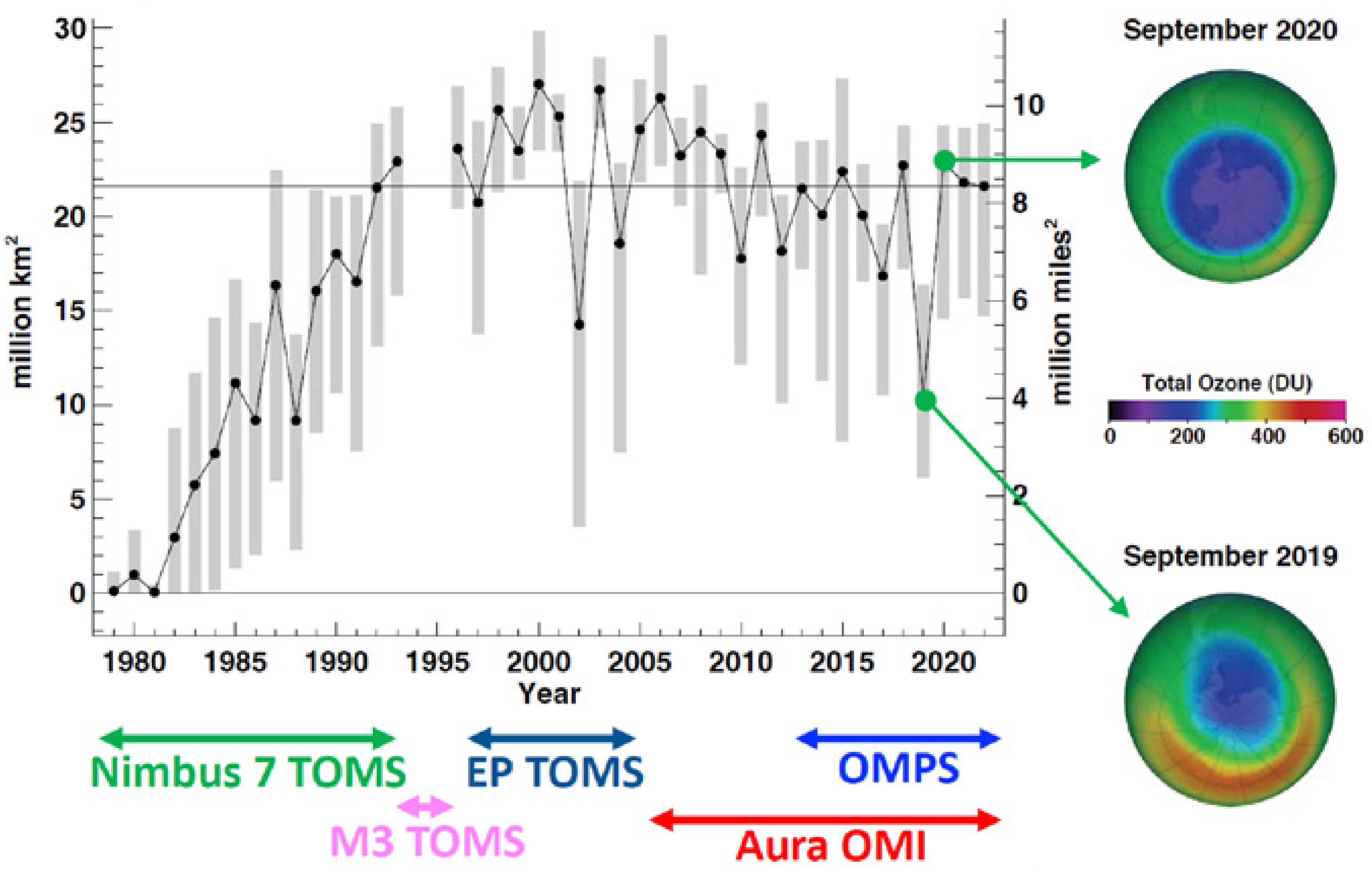
Ozone Loss Above Antarctica

Each year, the Antarctic polar vortex produces extremely cold temperatures, enabling polar stratospheric clouds to develop. As sun returns to polar latitudes in austral spring, heterogeneous photochemical reactions on the surfaces of these clouds release active chlorine and bromine molecules that destroy ozone. Stratospheric ozone levels drop. This seasonal "hole" fluctuates in size and duration depending on variations in stratospheric temperature and circulation. Typically, the Antarctic ozone hole starts opening in September with ozone levels returning to normal in November. But in 2020, an unusually large hole persisted into December. "What is interesting is that the year before in 2019 we had a very small ozone hole—it was small because of dynamical conditions that rapidly increased temperatures in the lower Antarctic stratosphere, leading to earlier vortex disruption," remarks Dr. Kramarova.

Data from OMPS LP is used to look at trends over time for specific areas and altitudes. An example: "We can look at vertical ozone distribution inside the vortex [plot below] and we see that for both 2019 and 2020, ozone depletions start in September and progress to the beginning of October," Dr. Kramarova explains, also noting that "in 2019, that depletion was relatively mild—the ozone concentration dropped from about 14 to about 8 [DU/km]—but in 2020 [the depletion] was significantly larger." In fact, 2020 ozone concentrations dropped to single digits over most of the region (indicated by light blue in the bottom plot below).



OMPS LP vertical ozone concentrations (Dobson Units per km) between 70°S and 82°S from September 1 to November 30 in 2019 (top) and 2020 (bottom). Light blue color indicates ozone depletion (low ozone concentration in the ozone layer).



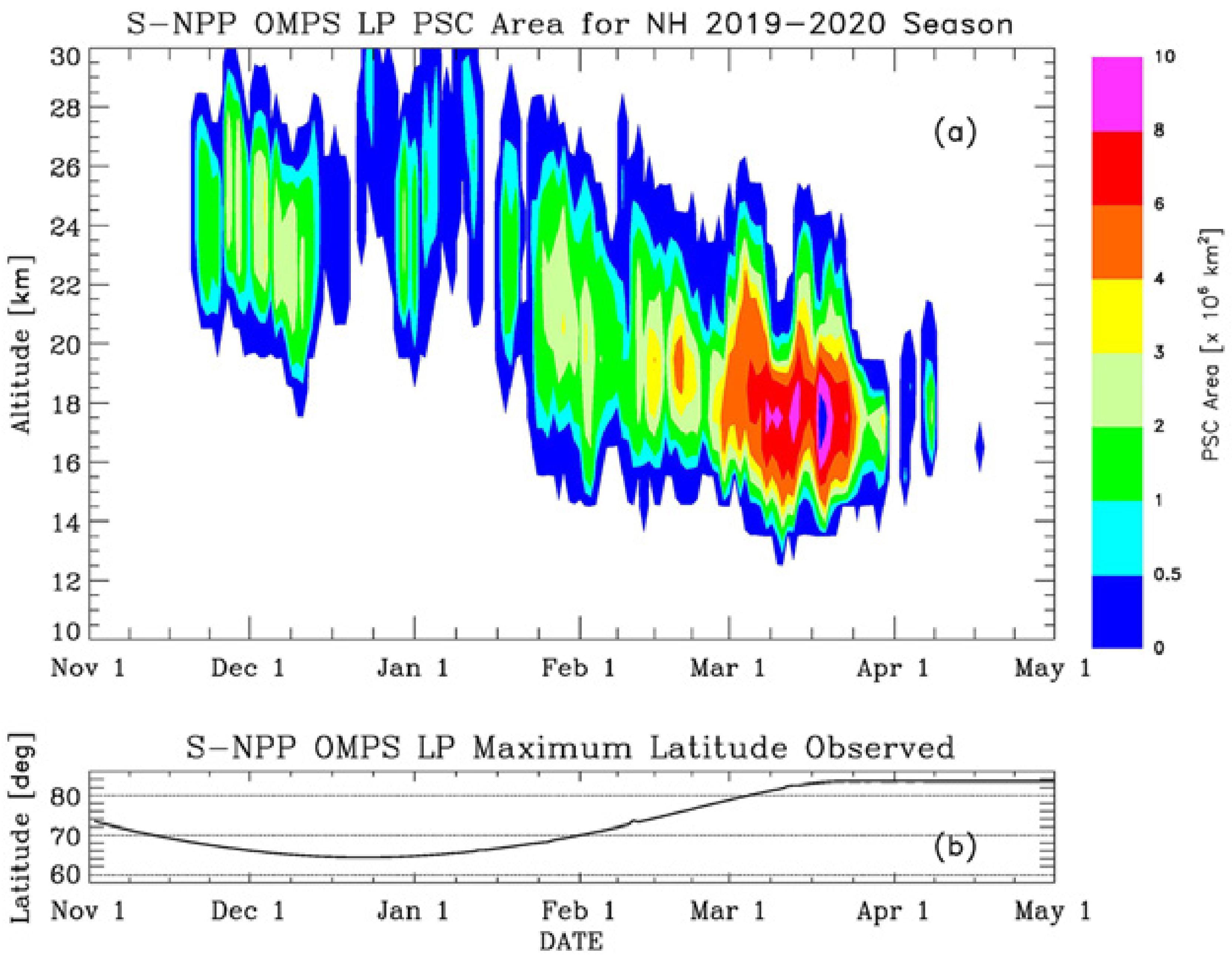
Why the dramatic difference? The 2019 Antarctic ozone hole, the smallest observed since the late 1980s, was the result of abnormally warm stratospheric temperatures that weakened the polar vortex and significantly limited ozone losses in September and October. Conversely, in 2020, persistently cold temperatures and a strong polar vortex led to the formation of a deep and wide ozone hole that covered most of Antarctica. The 2020 ozone hole was also the longest-lasting on record.

OMPS maintains the decades-long observation of the Antarctic ozone hole, providing scientists with the data necessary to study trends. The graph above shows the size (in millions square kilometers and million square miles) of Antarctic ozone holes dating back to 1979. Continuation of these data is critical for monitoring Antarctic ozone hole recovery over the coming decades.

Arctic Ozone Depletion

When talking about the ozone hole, Antarctica is generally implied. But the polar stratospheric clouds that accelerate seasonal ozone depletion above Antarctica can also form in the Arctic. The difference is that polar stratospheric clouds only develop at temperatures below about -78°C (-108°F), and while that kind of extreme cold in the stratosphere is common in Antarctica, it is rare in the Arctic. To date, only three Arctic winters have been marked with significant ozone losses, occurring during the winters of 1996-1997, 2010-2011, and 2019-2020. All three were associated with an extremely strong and cold polar vortex and an unusual abundance of polar stratospheric clouds.

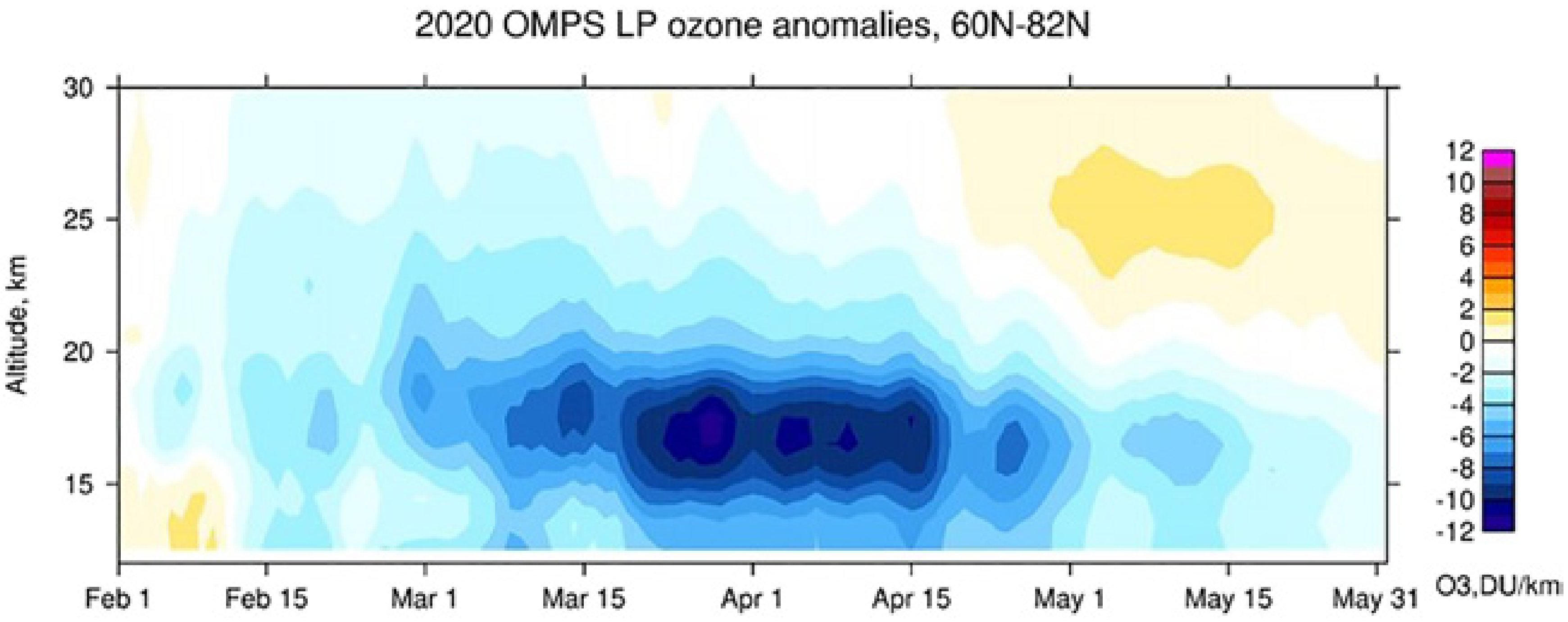
The most recent Arctic ozone depletion in 2019-2020 was the largest since 1979 when the satellite record began. "Because temperatures were very cold and the vortex was very stable, that resulted in a frequent occurrence of polar stratospheric



Top: OMPS LP polar stratospheric cloud (PSC) area as a function of altitude during the Northern Hemisphere 2019-2020 winter season, including all layers with temperature (T) < TPSC up to 7 km below the cloud detection altitude. Bottom: Maximum latitude observed by OMPS LP during the Northern Hemisphere 2019-2020 winter season. Source: DeLand et al. 2020.

clouds in March and the beginning of April 2020," Dr. Kramarova notes. It was a record high occurrence of polar stratospheric clouds in the OMPS LP record, which, as a result, produced substantial ozone depletion over the Arctic.

"Using [OMPS] LP data, we can plot the frequency of these stratospheric clouds over the season," says Dr. Kramarova—information that helps scientists visualize the evolution of meteorological conditions within the vortex. The plot above shows the time dependence of the area of polar stratospheric clouds for the 2019-2020 Arctic winter as calculated by OMPS LP. Cloud area dramatically increases in March to a maximum size of 10 million square kilometers between about 17 km to 19 km in altitude, as indicated in pink.



OMPS LP lower stratospheric ozone depletion between 60°N and 82°N during February to May 2020 (in DU/km). Differences are calculated relative to the LP average concentration observed during the period 2012–2019 for the same months and latitude range. Source: DeLand et al. 2020.

Around the same time, "ozone between 15 and 20 kilometers dropped by about 30 to 50 percent," Dr. Kramarova points out. Anomalies in stratospheric ozone concentration from OMPS LP relative to the 2012–2019 average are shown in the plot on the previous page between 60°N and 82°N. The dark blue color indicates that ozone concentration was -8 to -12 DU/km below the climatological mean, far less than typical values of 14 to 22 DU/km in the region.

STUDYING CHANGES IN GLOBAL CIRCULATION AND COMPOSITION

"Ozone is a tracer gas," says Dr. Kramarova. The relatively long lifetime of ozone (weeks to months below the ozone peak that occurs around 32 km) makes the gas suitable for tracing how air flows from one region to another. Ozone can be used to study changes in global circulation and composition caused by climate change or short-scale weather patterns. For example, the Quasi-Biennial Oscillation (QBO) drives ozone distribution in the tropics. "Ozone anomalies reproduce [the] QBO signal," Dr. Kramarova explains. "In the tropics, we can look at ozone anomalies when we subtract the seasonal cycle" to better understand the QBO.

Quasi-Biennial Oscillation

The Quasi-Biennial Oscillation (QBO) is the regular variation of winds that blow high above the equator. Strong winds in the lower to middle tropical stratosphere travel in a belt around the planet. About every 14 months, these winds reverse direction—a full QBO cycle takes roughly 28 months. The QBO has been a consistent characteristic of the tropical stratosphere since observations began in 1953.

The QBO plays a crucial role in influencing weather patterns and climate variability, as it can affect the behavior of the jet streams and the distribution of stratospheric ozone.

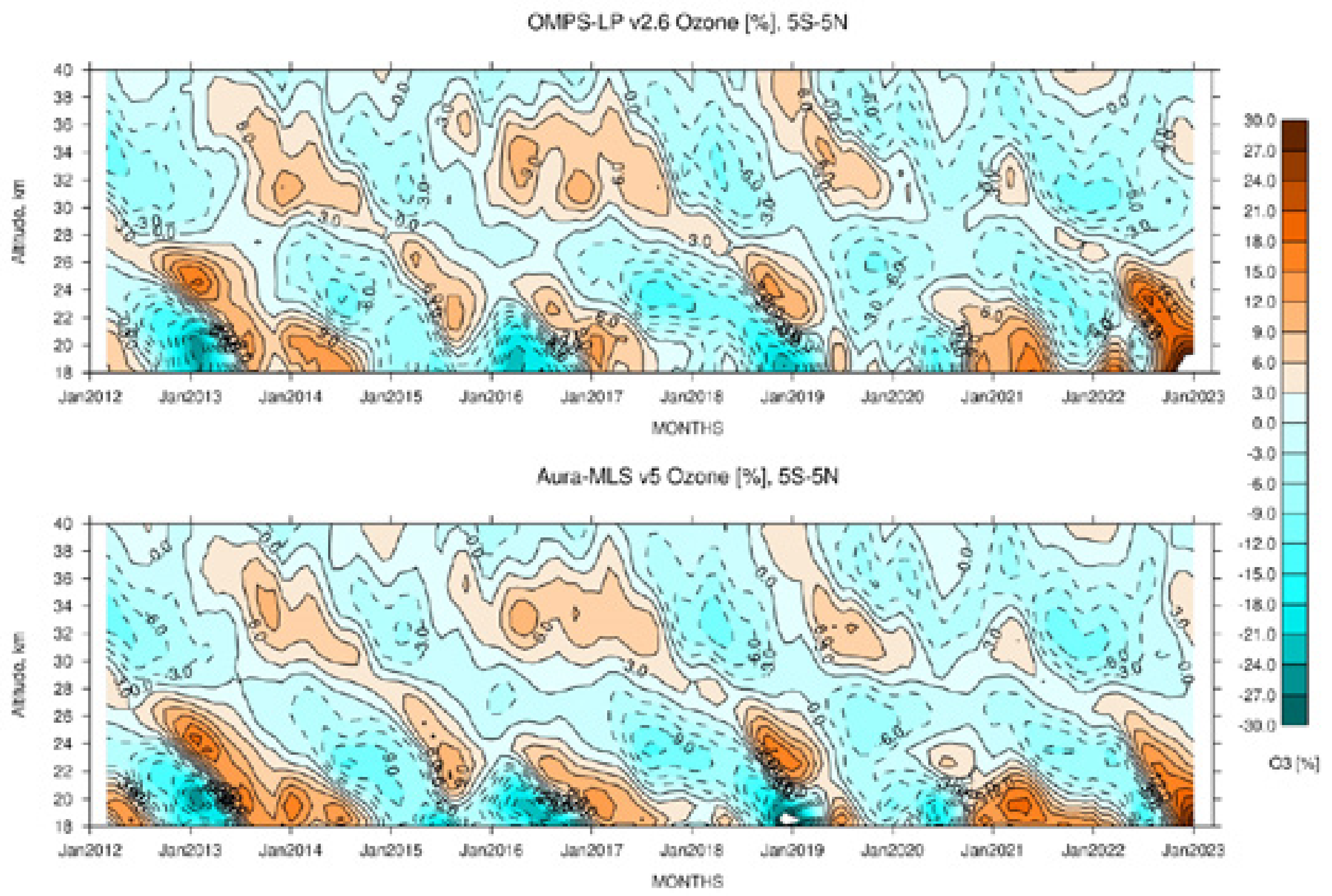
Source: *www.metoffice.gov.uk*

The QBO is typically predictable, but in late 2015 an unprecedented disruption of its cycle began to develop that was associated with unusually strong tropical atmospheric wave activity. The QBO disruption led to a significant decrease in global ozone distribution in the lower tropical stratosphere in 2016, from early spring to late autumn.

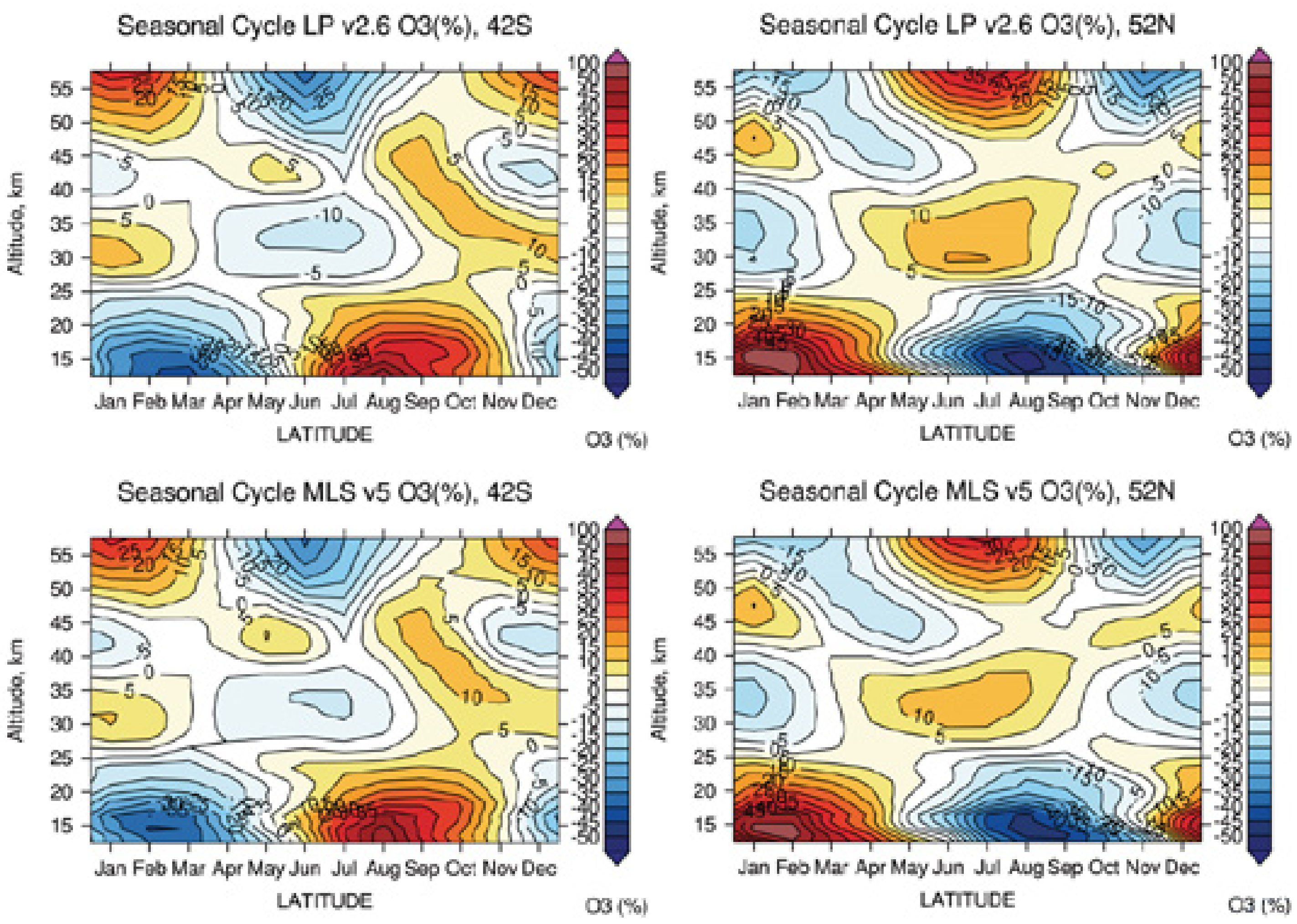
The plots on the following page show the vertical distribution of tropical ozone (from 18 to 40 km in altitude) over time (January 2012 to January 2023), as measured by OMPS LP version 2.6 (the new retrieval algorithm) and Aura MLS. Positive anomalies in stratospheric equatorial ozone over ~50-30 hPa (or ~20-25 km) in May 2016 to September of 2016 are associated with the disrupted 2015-2016 QBO.[3] "You can see that LP can reproduce the same structure and the same vertical descent of [the] QBO signal in ozone as Aura MLS following the changes in the tropical circulation," Dr. Kramarova says. "This is important for assimilation purposes because ozone provides additional information about global transport in assimilation systems."

The comparison between OMPS LP and Aura MLS provides confidence that the algorithmic changes in OMPS LP version 2.6 did not negatively affect performance.

Ozone participates in many atmospheric chemistry cycles, making it a valuable tracer gas for understanding global circulation. Global ozone variability captured by OMPS LP is shown in the four plots above. Here, the seasonal patterns of ozone from OMPS LP version 2.6 (top) and Aura MLS (bottom) are shown for two latitudes, 42°S (left) and 52°N (right). "The high resolution observations [from OMPS LP and Aura MLS] allow us to look at how the seasonal cycle [of ozone] changes as a function of altitude," says Dr. Kramarova, noting that "the seasonal cycle agrees very well between LP and MLS." OMPS LP enables scientists to study potential links between ozone and the variability and sensitivity of the global climate system.



De-seasonalized ozone anomalies (in %) over the equatorial latitudes (5°S to 5°N) from OMPS LP version 2.6 (top) and Aura MLS version 5 (bottom). The instruments had very similar responses in ozone to an anomalous QBO event in late 2015 and 2016.



Seasonal ozone cycles (shown in % from the annual mean) derived from OMPS LP version 2.6 (top row) and Aura MLS version 5 (bottom row) as functions of month and altitude for 42°S (left) and 52°N (right).

WHAT LIES AHEAD

Limb profilers like OMPS LP allow scientists to study various atmospheric components, such as ozone, aerosols, and cloud heights, with high precision. This information is crucial for climate monitoring and comprehension of ozone depletion, and for understanding the dynamics of the Earth's atmosphere. As technology advances and satellite missions expand, satellite limb profilers are poised to play an increasingly vital role in the overall improvement of atmospheric science and its applications.

Continuation of ozone observations with OMPS onboard NOAA-21, launched in 2022, and future JPSS-3 and JPSS-4 missions is important to ensure reliable long-term datasets of global ozone. These data already significantly contribute to the advancement of climate research by helping researchers study the link between ozone and global circulation patterns and refine global climate models. The future of OMPS and similar ozone instruments is one of continued innovation and essential contributions to environmental protection, human health, and climate science. ✦

STORY SOURCE

The information in this article is based, in part, on the June 21, 2023, LEO Science Seminar titled, "Version 2.6 Ozone Profile Record from Suomi NPP OMPS Limb Profiler," presented by Dr. Natalya Kramarova, Research Scientist, NASA Goddard Space Flight Center (GSFC) Atmospheric Chemistry and Dynamics Lab, with contributions from Dr. Philippe Xu of Science Applications International Corporation (SAIC), Dr. Jungbin Mok of Science Systems and Applications, Inc. (SSAI), Dr. P.K. Bhartia of NASA GSFC (emeritus), Leslie Moy of SSAI, Dr. Glen Jaross of NASA GSFC, Stacey Frith of SSAI, Dr. Jerald Ziemke of Morgan State University, Drs. Sean Davis and Yue Jia of NOAA Chemical Sciences Laboratory (CSL) in Boulder, CO, and NASA's Ozone Mapping and Profiler Suite (OMPS) Science Investigator-led Processing System (SIPS).

FOOTNOTES

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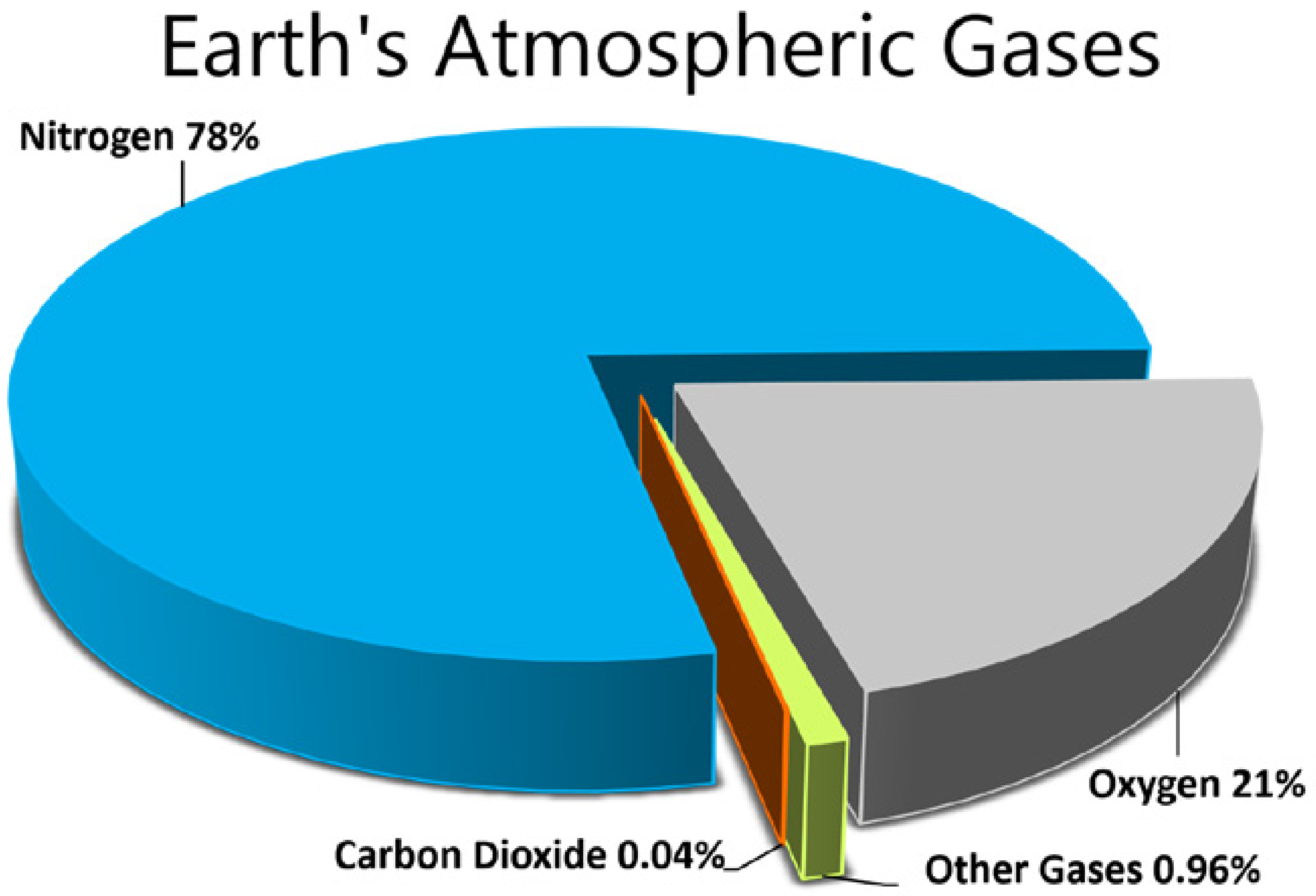
FEATURE 7

Assimilating JPSS Trace Gas Measurements Into an Air Quality Modeling System

Wildfire smoke from Canada hits Minneapolis on May 18, 2023, prompting air quality warnings. Source: Canadian Wildfire Smoke in Minneapolis. Credit: Chad Davis, licensed under the Creative Commons Attribution 2.0 Generic license (no changes).

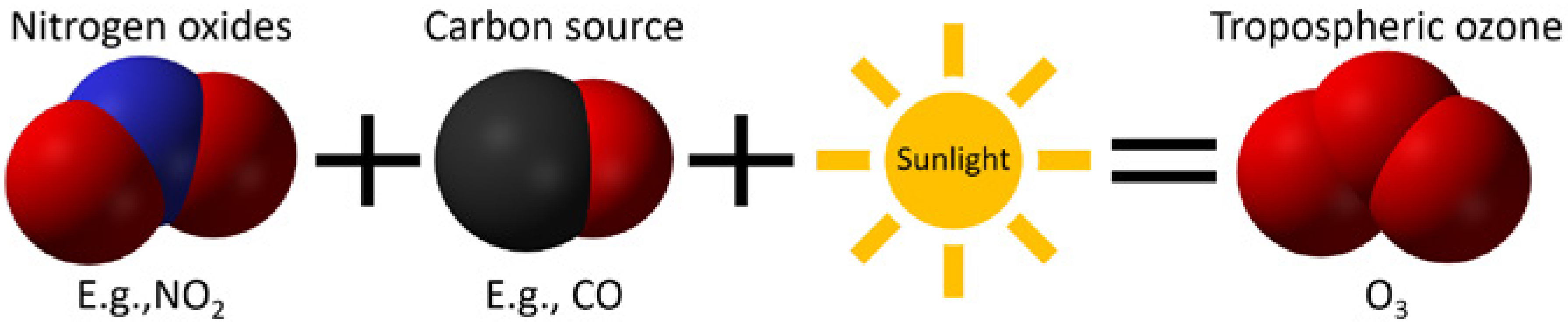


The Earth's atmosphere is made up of a cocktail of gases, mostly nitrogen (around 78%) and oxygen (around 21%). The rest are trace gases, each making up less than 1% by volume of the atmosphere. Hundreds of trace gases exist, produced through natural processes like photosynthesis and volcanic eruptions, and through anthropogenic processes like the burning of fossil fuels and management of livestock manure, among others.

Trace gases are essential for life. Carbon dioxide, methane, nitrous oxide, water vapor, and ozone, for instance, help keep the Earth warm and protected by absorbing radiation from the Sun. But despite their relatively minor abundance in the atmosphere, many trace gases play a significant role in air quality and climate change.

Take ozone, for example: Stratospheric ozone is critical for blocking harmful ultraviolet radiation from the Sun. But tropospheric ozone—often thought of as ground-level ozone—is formed through chemical reactions with other pollutants, is unhealthy to humans and the environment, and is the main ingredient in smog. It's a similar story for other trace gases. Carbon monoxide, for instance, is a precursor to ozone and one of six major air pollutants regulated by the U.S. Environmental Protection Agency (USEPA). It interferes with the destruction of methane in the stratosphere—a potent greenhouse gas—and, as a component of wildfire smoke, contributes to ozone formation.

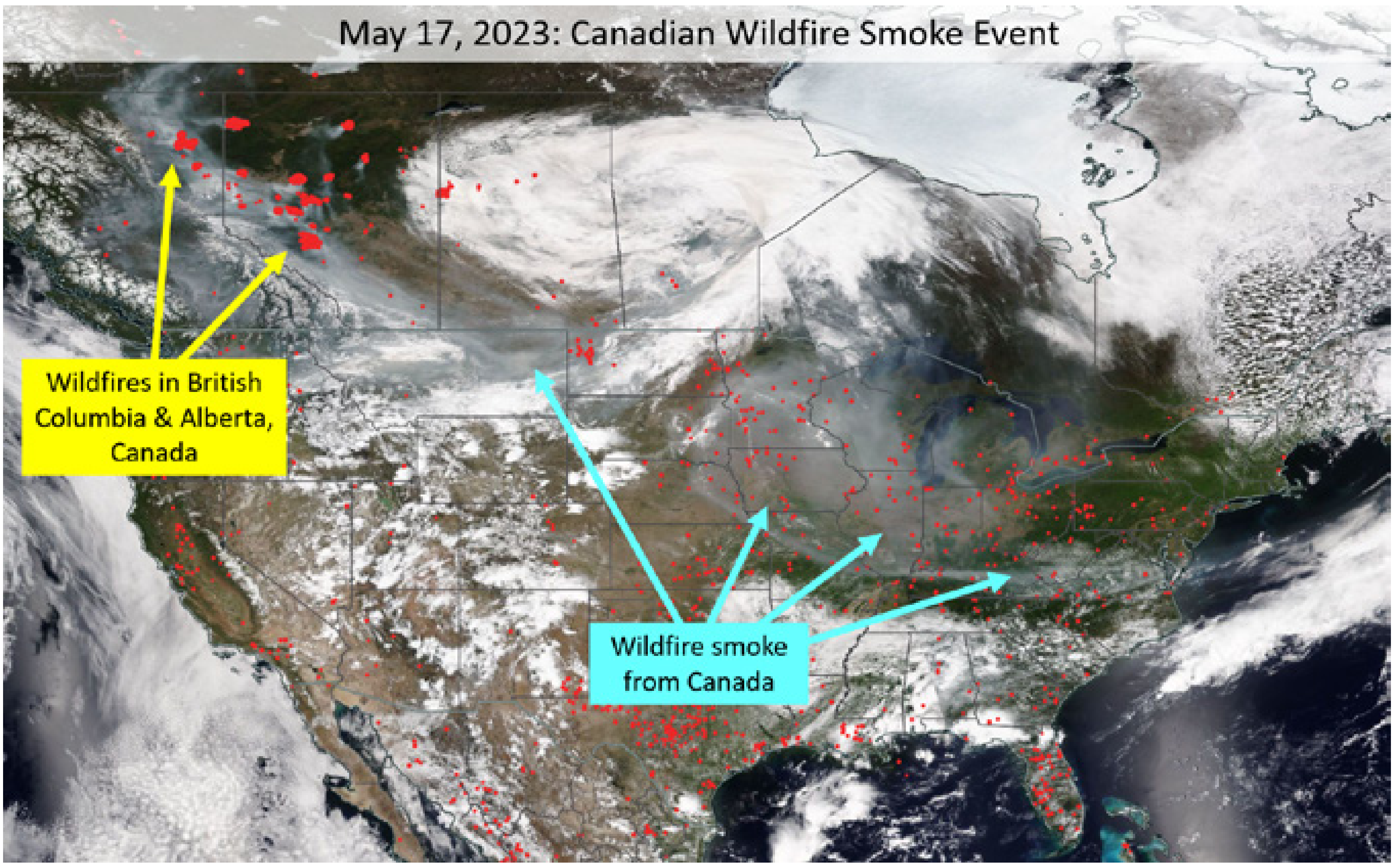
Wildfires emit many trace gases that are ozone precursors—carbon monoxide, methane, nitrogen oxides, and others—making fires "quite relevant for air quality for both ozone and particulates," says Dr. R. Bradley Pierce, Director of the Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison. And because wildfire smoke can travel hundreds and even thousands of miles from its



Ozone precursors like nitrogen dioxide (NO2) and carbon monoxide (CO) combine and photochemically react with sunlight to produce surface-level (tropospheric) ozone.

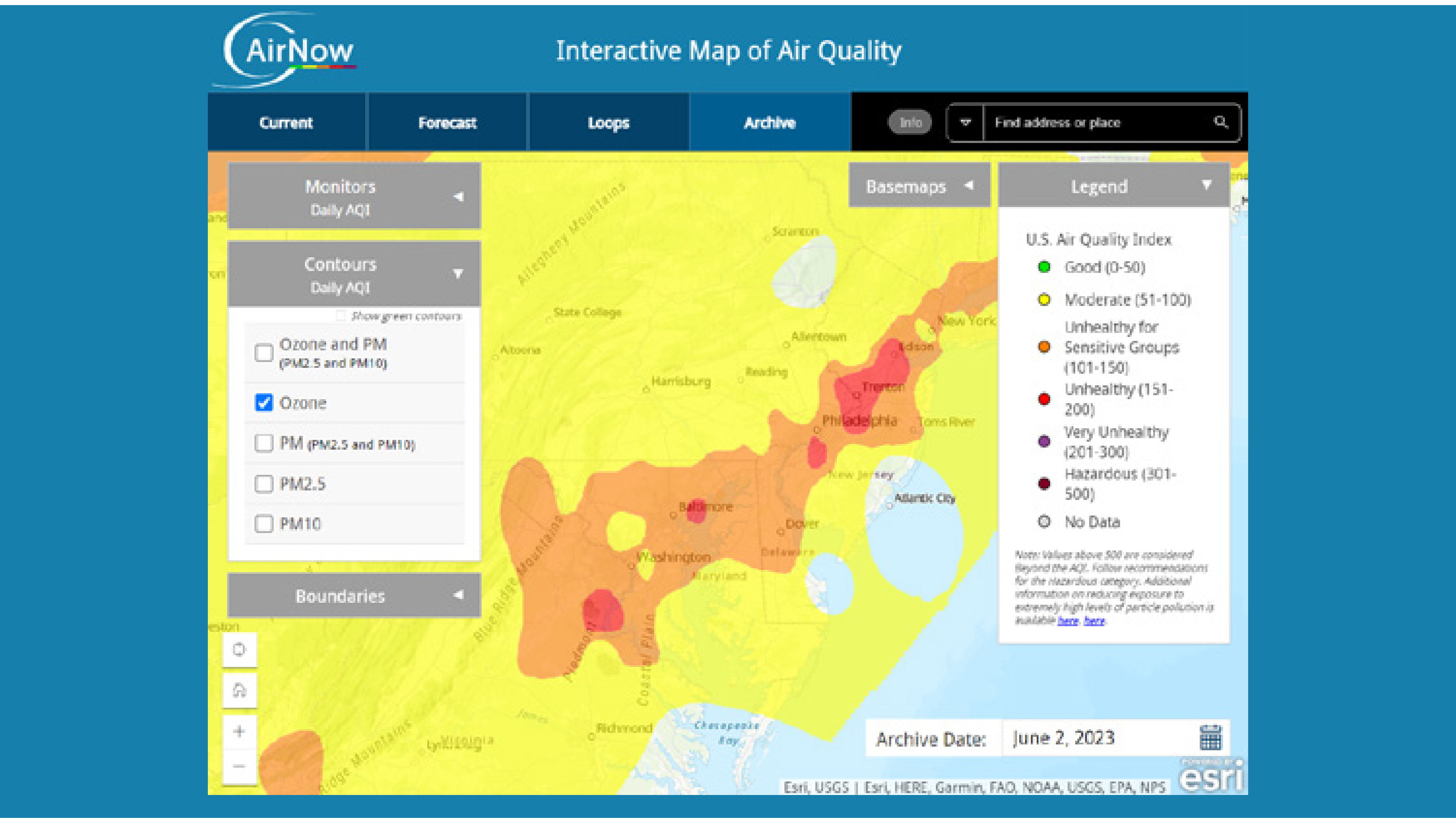
source, the impacts to air quality are often felt around the globe. This phenomenon can be seen on the following page in an image from May 17, 2023, taken by the JPSS Visible Infrared Imager-Radiometer Suite (VIIRS). Here, smoke originating from British Columbia and Alberta, Canada wildfires (red dots) can be seen moving down and across the Upper Midwest of the U.S. and reaching the East Coast.

"This is the kind of large-scale pollution event that we need to be paying attention to," says Dr. Pierce. Significant smoke events produce ozone through photochemical reactions, and contribute substantially to poor air quality far from the source. For example, on June 2, 2023, the air quality index (AQI) for ozone in parts of Illinois, Pennsylvania, and New Jersey spiked to "red" status—unhealthy for everyone—because of the Western Canadian wildfires noted above.



This May 17, 2023, image from NOAA-20 VIIRS shows smoke from wildfires in British Columbia and Alberta, Canada. The smoke traveled southeast across the Upper Midwest of the United States, eventually reaching the East Coast. Red dots indicate active fires from the Suomi NPP/NOAA-20 VIIRS Fire and Thermal Anomalies product. Source: NASA WorldView.

Surface-level pollutants at unhealthy levels can trigger chest pain, coughing, throat irritation, and congestion in even the healthiest of individuals, and are especially dangerous to those with asthma and other lung and heart conditions. In fact, asthma-related hospital visits were 17% higher than normal across the U.S. during



Air Quality Index (AQI) values for ozone for the Northeast U.S. on June 2. 2023. Source:

the 2023 Canadian smoke events, and even higher in New York and New Jersey, which saw a 46% increase in smoke-related emergency room traffic.

It's not only human health impacts that are worrisome: The economic cost of wildfire smoke can be great. One recent study suggests a 13% loss in earnings linked to drifting smoke plumes, noting that "wildfire smoke exposure leads to statistically and economically significant losses in labor income, employment, and labor force participation"[1] because of lingering health impacts and other issues that reduce worker productivity, lead to premature mortality, and decrease tourism, among other impacts. Another study estimates the value of health impacts from short-term smoke exposure in the continental U.S. at around $79 billion per year (CPI-adjusted).[2] Statistics like these drive home the importance of accurate air quality forecasting so that timely alerts can be issued, and steps can be taken to lessen exposure.

Researchers and air quality forecasters rely on Earth system models that assimilate trace gas measurements from satellite instruments to simulate atmospheric chemistry and predict large scale pollution events. One of these is the Real-time Air Quality Modeling System (RAQMS), a chemistry and aerosol analysis and forecast system that has provided real-time predictions of global air quality since 2012. At the May 2023 LEO Science Seminar, Dr. Pierce, Principal Investigator of RAQMS, gave an overview of the system and shared recent assimilation experiments using JPSS data and other work in support of the transition of RAQMS to NOAA operational status.

A woman wears an N95 mask to protect against inhaling wildfire smoke. Source: U.S. Fire Administration/FEMA.

MEASURING TRACE GASES FROM SPACE

For decades, satellite data have been used in public health applications like air quality forecasting and monitoring as a complement to ground-based or near-surface measurements. The latter, while very precise, are spatially and temporally sparse because they are limited to sampling within a specific geographic area at a specific time. Satellites, on the other hand, provide continuous (and in many cases, global) monitoring. More complete spatial and temporal coverage allows scientists to characterize the long-range transport of air pollutants, and helps improve air quality model simulations—all important for filling gaps in ground-based data. Two instruments that are used to measure and monitor atmospheric ozone and other trace gases are the Ozone Mapping and Profiling Suite (OMPS) and Cross-track Infrared Sounder (CrIS) onboard JPSS satellites.

Clockwise from top left: Ambient surface air sampling unit (source: CARB), balloon launch of an ozonesonde (source: NOAA GML), sampling ports on aircraft (source: NOAA GML).

OMPS is a hyperspectral instrument with high vertical resolution that tracks concentrations of ozone, other trace gases, and aerosols in the atmosphere. OMPS measures atmospheric ozone in two ways: by mapping total ozone over the globe

OMPS: A Hyperspectral Instrument

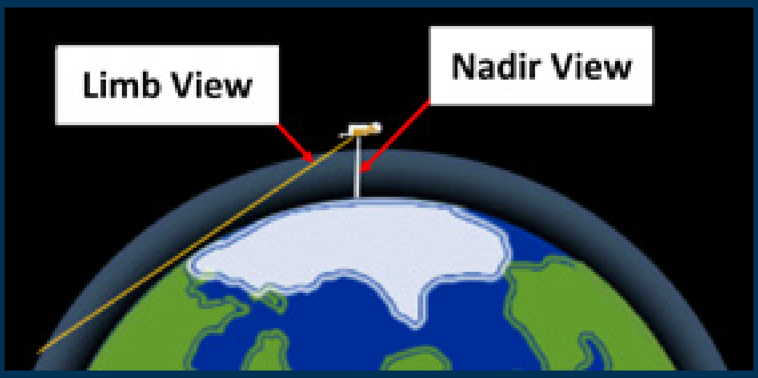
The Ozone Mapping and Profiler Suite (OMPS) consists of three spectrometers that measure the concentration of ozone in the Earth's atmosphere.

- **Nadir Mapper (NM)** – A nadir-viewing sensor that maps total ozone concentration over the globe daily.
- **Nadir Profiler (NP)** – A nadir-viewing sensor that measures the vertical distribution of ozone in the stratosphere less than daily.
- **Limb Profiler (LP)** – A limb-viewing sensor that measures the vertical distribution of ozone in the lower stratosphere and troposphere less than daily. OMPS-LP is only on Suomi-NPP and NOAA-21 satellites.

Nadir vs. Limb

Nadir-viewing sensors are pointed toward the Earth's surface, meaning they look straight down. Because of their viewing position, they provide good horizontal coverage.

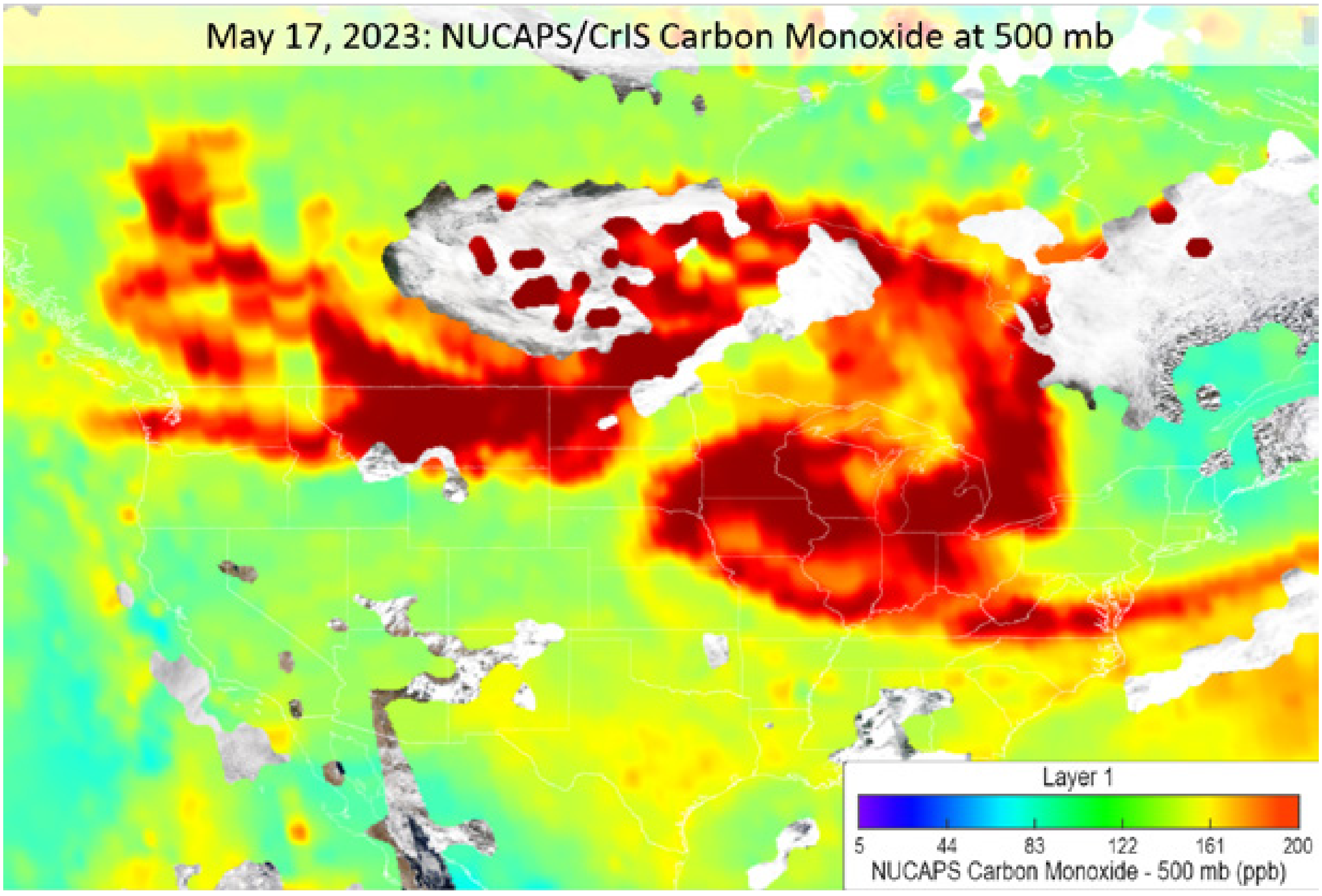
Limb-viewing sensors are pointed at an angle, meaning that they look through the halo that surrounds the Earth. They feature good vertical resolution and a strong signal.



using the Nadir Mapper (NM), and by probing the atmosphere vertically to collect precise measurements at different altitudes with the Nadir Profiler (NP) and the Limb Profiler (LP). Combining nadir-viewing and limb-viewing perspectives enhances the ability of OMPS to measure the vertical structure of ozone, which is important in understanding how ozone and other trace gases react in the atmosphere.

CrIS is a hyperspectral infrared (IR) sounding instrument that primarily provides vertical profiles of atmospheric temperature and moisture for severe weather forecasting. But CrIS can also profile certain trace gases thanks to its ability to measure in the IR spectral region at very high spectral resolution; for instance, carbon monoxide molecules absorb IR radiation making them visible to CrIS. These profiles, called soundings, provide details about how trace gas concentrations and other conditions change with altitude, which enables the detection, tracking, and monitoring of greenhouse gases and emissions from wildfires that impact air quality. These data are delivered to users as NOAA Unique Combined Atmospheric Processing System (NUCAPS) products (NUCAPS is NOAA's operational algorithm for real-time processing of satellite soundings).

An example from NUCAPS of carbon monoxide concentrations at 500 millibars (the middle atmosphere, roughly 5,000 to 6,000 meters above sea level) is shown below for May 17, 2023. Note how well the areas of high carbon monoxide (red) match up to the May 17, 2023, Canadian wildfire smoke plume in the previously shown VIIRS image.



With support from the Office of Low Earth Orbit Observations (LEO) Proving Ground and Risk Reduction (PGRR) program, Dr. Pierce and his team at SSEC have been developing capabilities for assimilating JPSS atmospheric composition and aerosol products, like those derived from OMPS and CrIS. Their objective is to improve air quality prediction through better representation of atmospheric trace gas concentrations in anticipation of transitioning RAQMS to NOAA operational status.

IMPROVING AIR QUALITY PREDICTION THROUGH CHEMICAL DATA ASSIMILATION

Chemical Data Assimilation

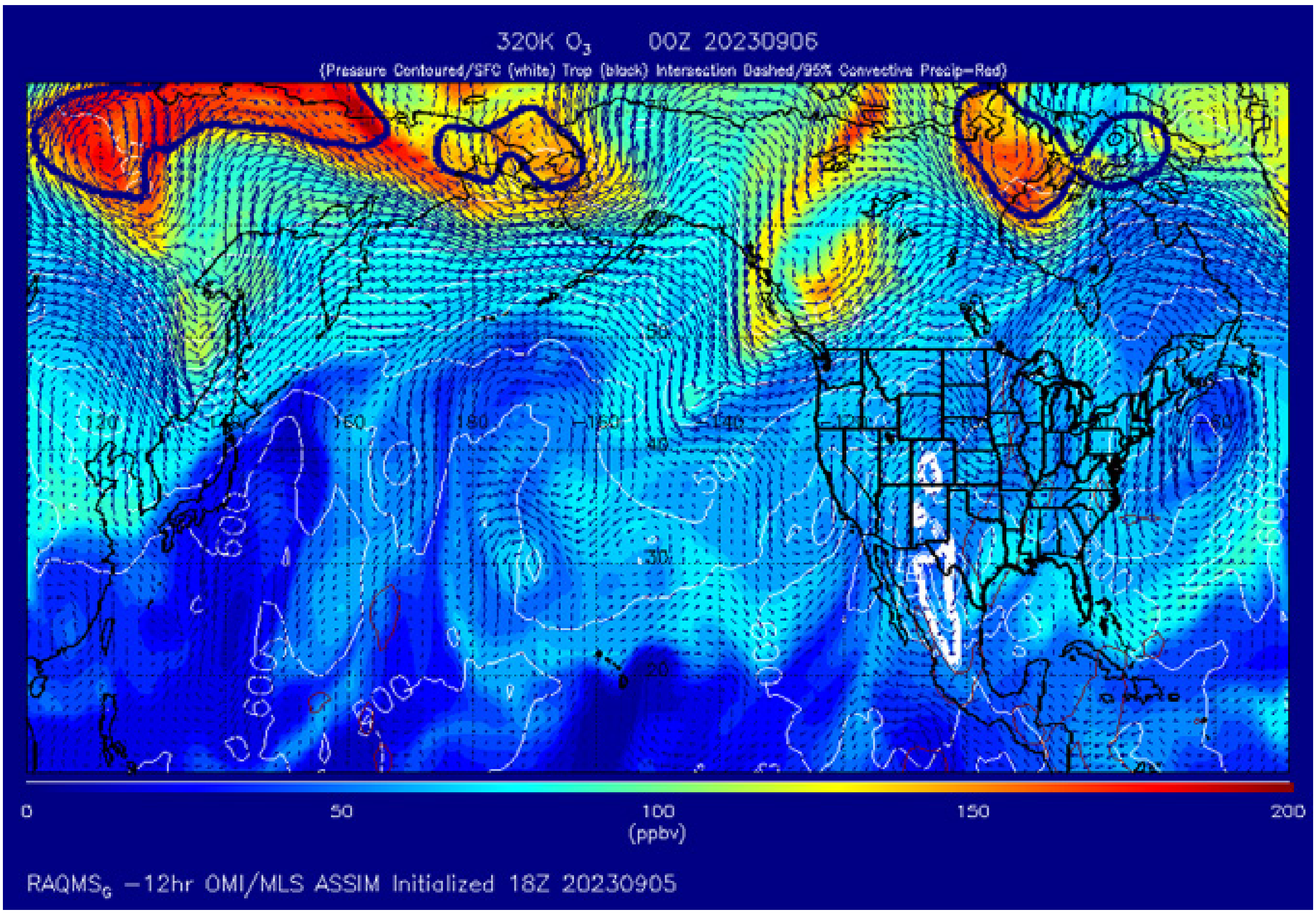
Chemical data assimilation is the process by which models use measurements to produce an optimal representation of the chemical composition of the atmosphere—essentially a reality check to guide the model.

In the case of RAQMS, atmospheric measurements of trace gases and aerosols retrieved from satellite instruments (OMPS, CrIS, etc.) are blended with model predictions to constrain other model data, such as long-range pollution transport and global emissions inventories. The purpose is to improve regional air quality forecasts.

On April 25, 2002, Congress passed the Energy Policy Act of 2002, which directs the U.S. Secretary of Commerce, through NOAA, to "establish a program to provide operational air quality forecasts and warnings for specific regions" of the U.S. In response, Dr. Pierce—at the time a physical scientist at NASA Langley Research Center—along with others, undertook the challenge of broadening the use of space-based atmospheric chemical composition data in global air quality forecasts through chemical data assimilation, with the overarching goal of improving regional air quality prediction. The result was RAQMS, a chemistry and aerosol analysis and forecast system that can predict the global and regional distribution of atmospheric aerosols and trace gases—ozone and ozone precursors—at 1x1 degree resolution.

For many years, the SSEC team has been developing capabilities to assimilate satellite-based atmospheric measurements into the RAQMS modeling system. The idea is that satellite observations bring simulations closer to reality. The intended result is improved model performance and better estimates of the vertical distribution of atmospheric pollutants—information that supports regional air quality forecasting and situational awareness for NWS Incident Meteorologists providing aid at wildfire locations.

At the top of the next page is an example of the type of improved analysis that can be achieved with data assimilation. Shown here is a RAQMS chemical analysis for ozone. Data from the Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) onboard the NASA Aura satellite are assimilated in the model to constrain ozone. This analysis shows large-scale transport of lower stratospheric high ozone air into the upper troposphere. Colors indicate ozone concentrations (parts per billion by volume, ppbv) between 400 and 600 millibars (mb), roughly corresponding to an altitude of 4,200 to 7,200 meters. A detailed explanation is provided in the caption.

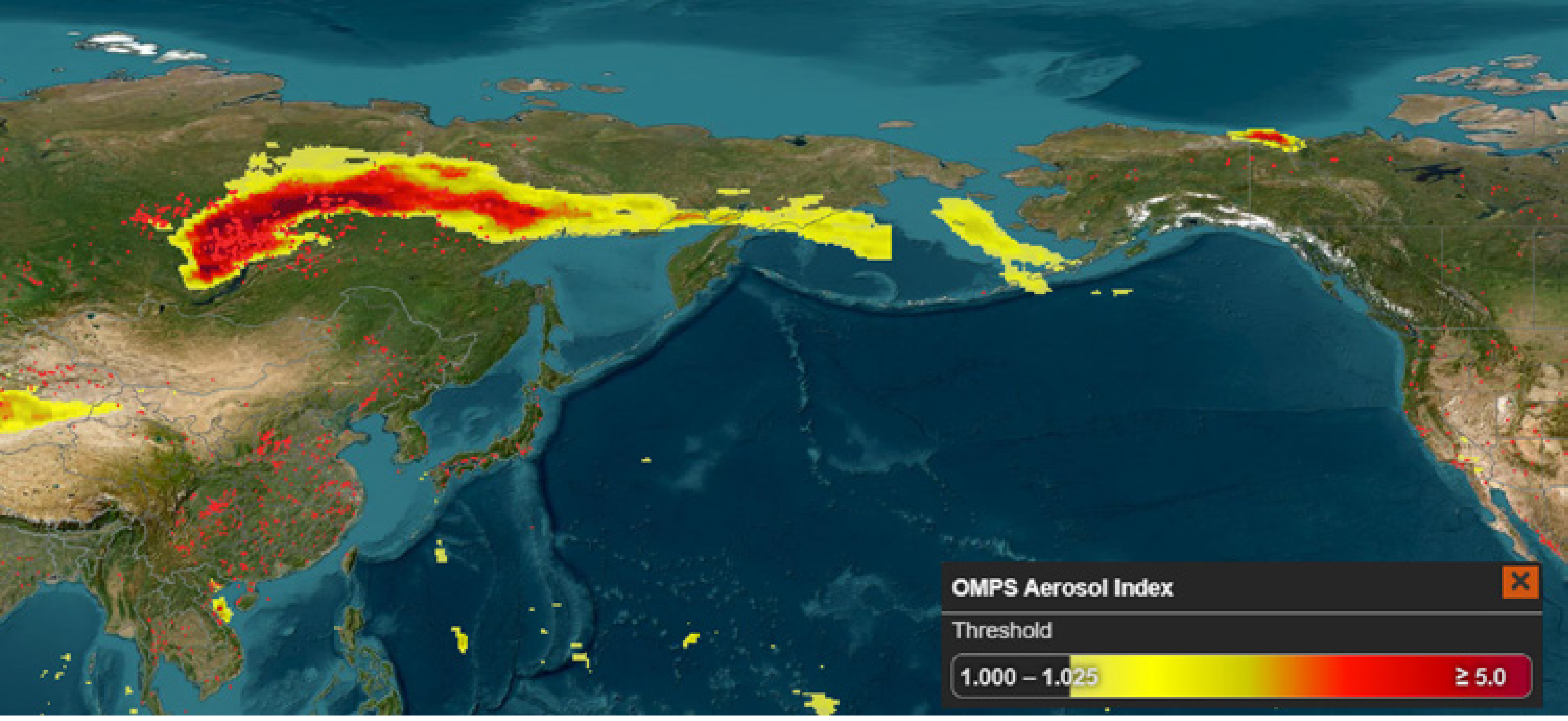


An example of a RAQMS chemical analysis for ozone (O3) on the 320K isentropic surface (between 400-600mb) assimilated with measurements from the NASA Aura Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS). This analysis is valid at 00Z on September 6, 2023, and shows large-scale transport of lower stratospheric high ozone air into the upper troposphere. Colors indicate ozone concentrations (ppbv) with the pressure of the 320K isentropic surface indicated by white contours (mb). The thick blue contours show where the 320K isentropic surface intersects the tropopause while the thick white lines show where the 320K isentropic surface intersects the ground. The red contours enclose the regions with 6-hour accumulated convective precipitation. The contour is equal to the precipitation amount which is in the upper 95th percentile of the convective precipitation over the North American Sector. Source: http://raqms-ops.ssec.wisc.edu/.

CONSTRAINING THE IMPACT OF LONG-RANGE POLLUTANT TRANSPORT ON RAQMS

Biomass burning—the burning of vegetation from wildfires and other sources—contributes to uncertainty in air quality forecast models, in part because biomass burning emissions can impact regional air quality thousands of miles from the emission source. Pollutants pulled up into higher altitudes can encounter strong winds, leading to rapid transport across oceans and continents. One example of this phenomenon occurred during the summer of 2019 when emissions from hundreds of Siberian wildfires caused elevated levels of aerosols and trace gases in Alaska, shown in the OMPS Aerosol Index visualization below.

Recently, Dr. Pierce began a series of experiments to assess the impact of assimilated JPSS data on emission estimates within an updated version of RAQMS called UFS-RAQMS (the RAQMS unified chemical mechanism was incorporated into the NOAA Unified Forecasting System, an emerging unified modeling system that will be the source system for future NOAA operational numerical weather prediction applications). Within UFS-RAQMS, long-range transport of biomass burning emissions (like from Siberian wildfires) is accounted for with data from the Blended Global Biomass Burning Emissions Product (GBBEPx). GBBEPx estimates



The transport of aerosols from Siberia to Alaska are seen in this data visualization from the OMPS Aerosol Index on July 27, 2019. The aerosols were the result of biomass burning from wildfires across Siberia, indicated by red dots. Source: NASA Fire Information for Resource Management System (FIRMS).

daily global biomass burning emissions with blended fire observations from VIIRS onboard Suomi NPP and the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua satellites. But when predicting regional air quality, regional emissions need to be distinguished from emissions transported from far away.

Using the 2019 Siberian wildfires as a test case, Dr. Pierce and his team performed retrospective forecast experiments for July 15 through September 30, 2019, to evaluate whether assimilating satellite retrievals of atmospheric carbon monoxide could correct biases in global carbon monoxide concentrations associated with the GBBEPx emissions within UFS-RAQMS. “What we’re hoping to do with this assimilation experiment is improve our background prediction by constraining the carbon monoxide that’s being transported in from Siberia,” says Dr. Pierce. In other words, remove the bias in background concentrations of carbon monoxide—bias from long-range pollutant transport—to better represent regional air quality.

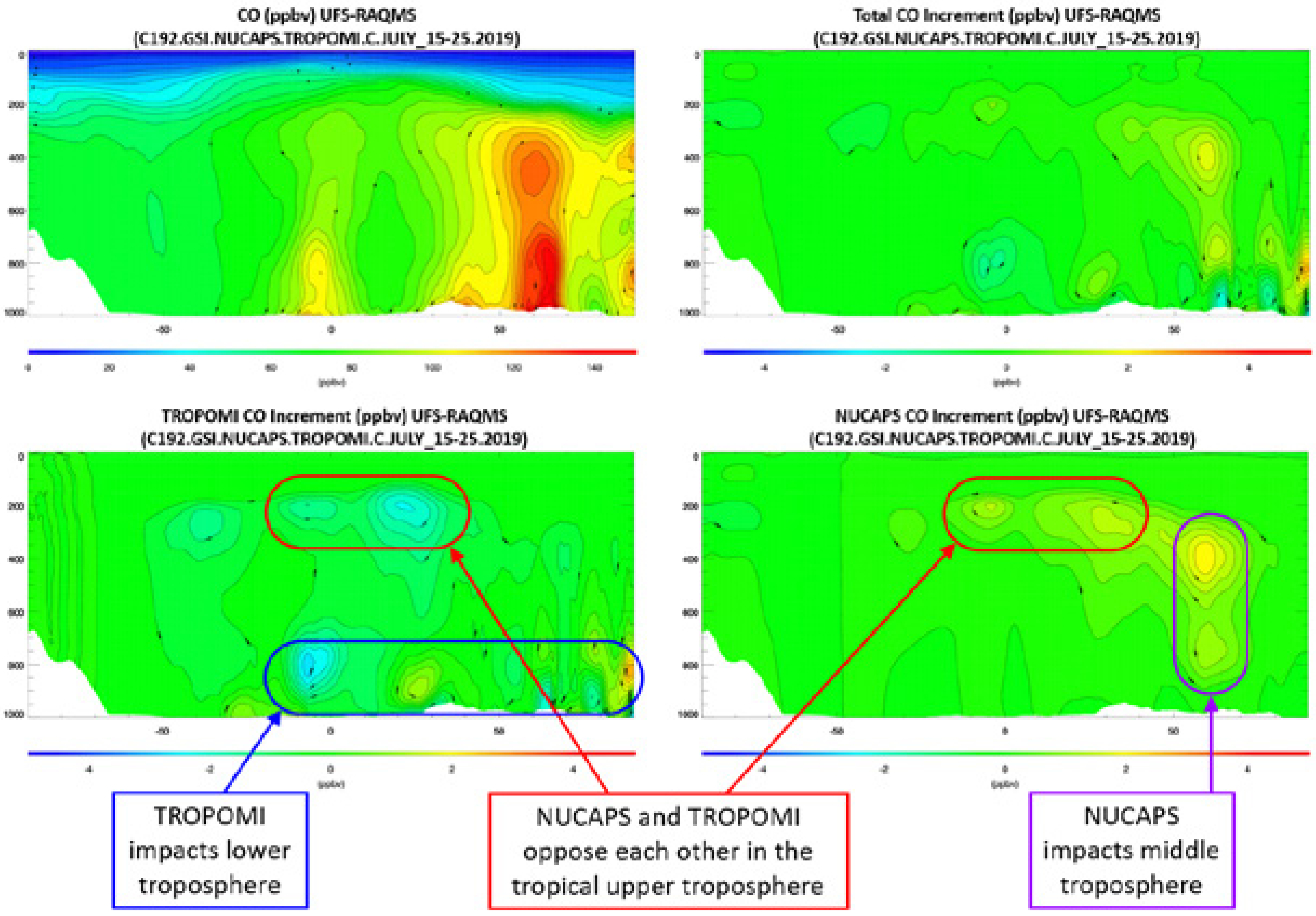
The experiments involved assimilating carbon monoxide column retrievals from NUCAPS/CrIS and the European Space Agency (ESA) TROPOspheric Monitoring Instrument (TROPOMI) within UFS-RAQMS. “The reason that we’re doing this,” Dr. Pierce explains, “is that the thermal IR carbon monoxide retrieval [from NUCAPS] is really only sensitive to mid-tropospheric carbon monoxide, while the TROPOMI shortwave IR is sensitive to the total column carbon monoxide.” By combining observations from these two instruments, he says, “we’re hoping to improve constraints on the lower troposphere.”

What is bias?

The term **bias** broadly includes any error that is systematic and can be corrected, rather than random errors that cannot be corrected due to their randomness.

Below are results from the NUCAPS/TROPOMI assimilation experiment for July 15-25, 2019, when Siberian wildfires were at their peak. The top left plot shows zonal mean analyzed carbon monoxide where an enhancement in the carbon monoxide column is seen around 50 to 60 degrees north latitude (in red), which is linked to biomass burning in Siberia. The top right is the total carbon monoxide analysis increment, and the bottom plots are TROPOMI (left) and NUCAPS (right) carbon monoxide analysis increments.

These results indicate that NUCAPS and TROPOMI oppose each other in the tropical upper troposphere (circled in red), "so that's something we need to try and minimize because that means that the satellite carbon monoxide retrievals are opposing each other in the analysis system when we try to constrain UFS-RAQMS with these measurements," Dr. Pierce points out. "But you can see TROPOMI is making adjustments in the lower tropical troposphere that NUCAPS is not, and this extends all the way into the higher latitudes where TROPOMI is having its largest impact down near the surface in the boundary layer [circled in blue] and NUCAPS is having its largest impact in the middle troposphere [circled in purple]."



Results from the UFS-RAQMS July 15-25, 2019, NUCAPS/TROPOMI data assimilation experiment. Top left: zonal mean analyzed carbon monoxide. Top right: total carbon monoxide analysis increment. Bottom left: TROPOMI carbon monoxide analysis increment. Bottom right: NUCAPS carbon monoxide analysis increment.

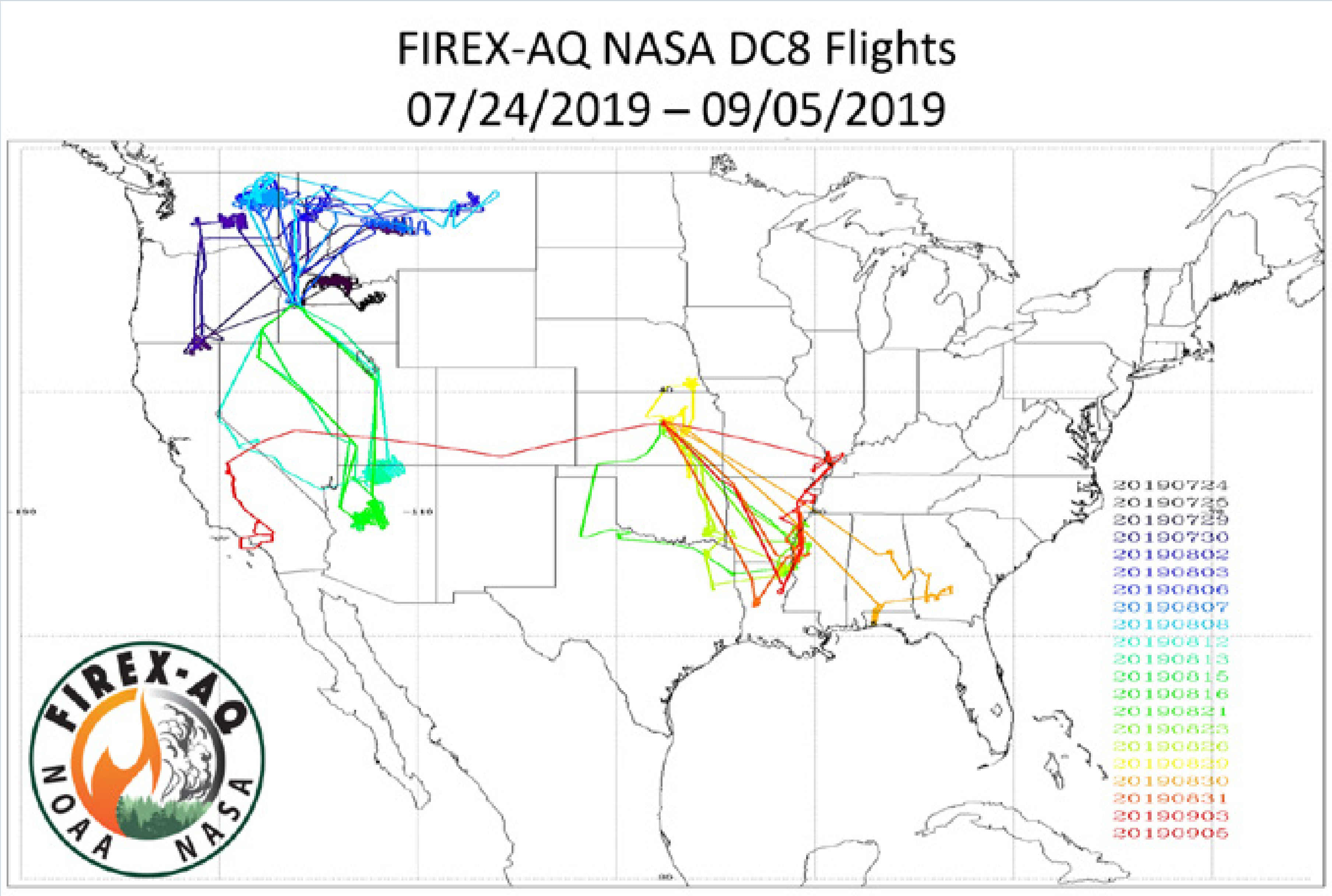
The key takeaway, according to Dr. Pierce, is that "we're getting additional information and additional constraints on the overall carbon monoxide column by combining TROPOMI, which is providing constraints in the lower troposphere, and NUCAPS, which is providing constraints in the upper troposphere." This emphasizes the importance of combining observations from multiple satellite sensors to leverage the strengths of each and reduce uncertainties associated with either retrieval.

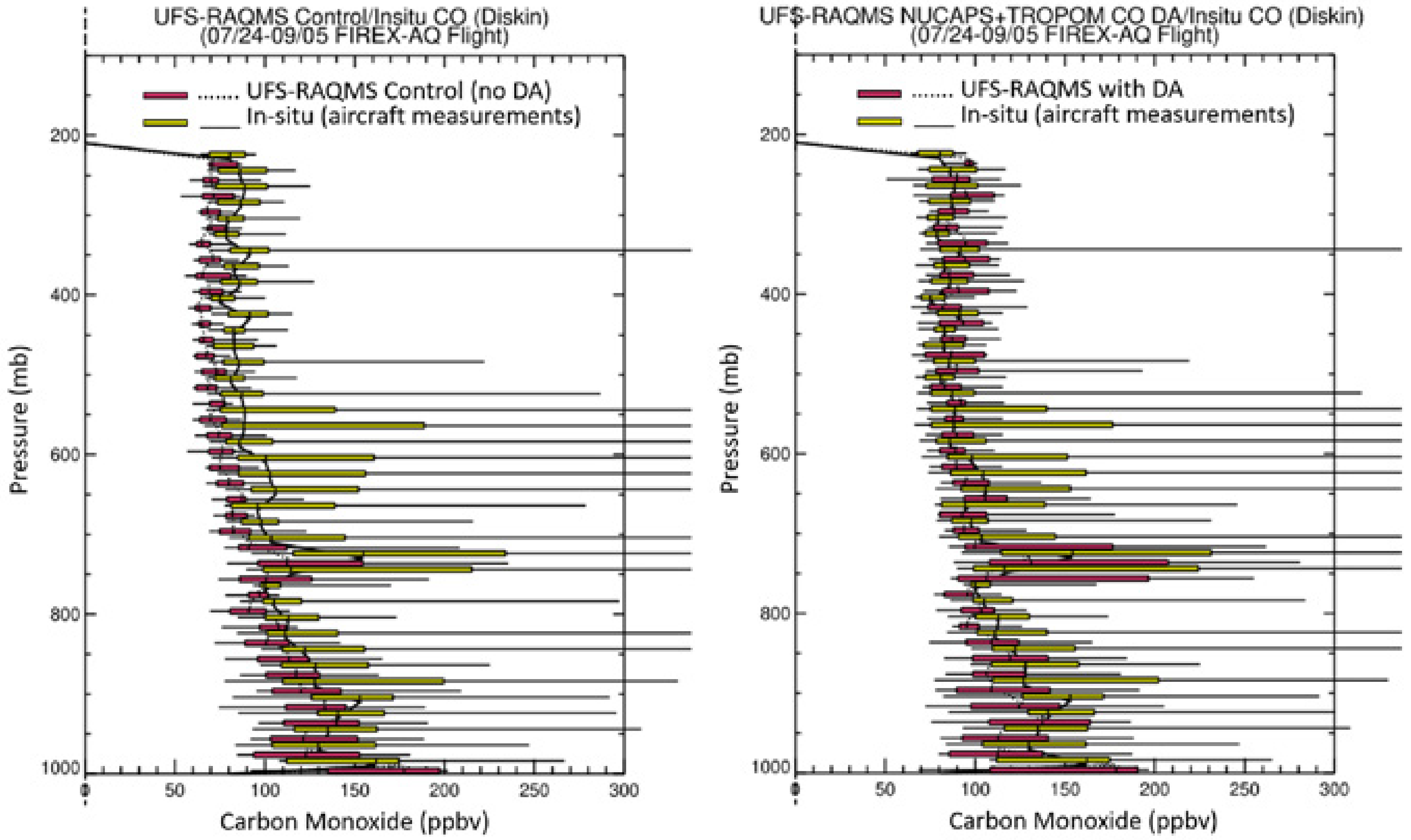
Verifying Assimilation Experiments With FIREX-AQ Observations

Verifying results is fundamental to any assimilation experiment. The test case above happened to coincide with the 2019 Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) field campaign, providing a unique opportunity for Dr. Pierce to evaluate the success of his team's experiments. FIREX-AQ airborne in situ data was collected between July 24 and September 5, 2019, throughout the Western-Central U.S. using sensors onboard a NASA DC8 aircraft that measured trace gases and aerosols emitted by active fires along the routes shown in the map (inset).

2019 FIREX-AQ Field Campaign

FIREX-AQ, a program jointly led by NOAA and NASA, provides comprehensive observations about fire emissions for better forecasting and for improving satellite sensors that measure and monitor trace gases and aerosols. Throughout the summer of 2019, FIREX-AQ observations were collected from hundreds of ground and airborne instruments throughout the Western-Central U.S. Airplanes carrying a multitude of instruments flew over fires to measure emissions, characterize conditions relating to smoke plumes, and follow plumes downwind to understand chemical transformation and air quality impacts. These data can be used with confidence to evaluate measurements from satellite sensors.





Left: Comparison of the carbon monoxide concentrations at different pressure levels from the UFS-RAQMS control with no data assimilation (red bars) and FIREX-AQ airborne measurements (yellow bars). Right: Comparison of the carbon monoxide concentrations at different pressure levels from the UFS-RAQMS assimilated with NUCAPS and TROPOMI (red bars) and FIREX-AQ (yellow bars). The profiles in these "bar and whisker" plots show the median UFS-RAQMS (dashed) and FIREX-AQ airborne measurements (solid) carbon monoxide mixing ratios (ppbv). The bars show the upper 75% and lower 25% of the model and measurements and the whiskers show the upper 95% and lower 5% of the carbon monoxide distribution within each 20mb pressure bin.

Above, the "bar and whisker" plot on the left compares the control experiment (UFS-RAQMS without data assimilation) and all the aircraft carbon monoxide measurements from FIREX-AQ. The coarse resolution of the UFS-RAQMS model (red bars) does not capture the range of very high carbon monoxide concentrations from Siberian biomass burning (seen around 600 millibars) that are captured by the FIREX-AQ aircraft sensors (yellow bars). The hope is that assimilating hyperspectral, high resolution satellite data within UFS-RAQMS will reduce the median bias in carbon monoxide concentrations and improve the range of variability within the wildfire plumes.

Looking at the plot on the right, assimilating NUCAPS and TROPOMI within UFS-RAQMS removes the median bias (dashed and solid lines) very effectively. Here, the variability in the assimilation experiment (red bars) compares well with FIREX-AQ measurements (yellow bars). "In this case," Dr. Pierce explains, "you can see that we're not underestimating the variance, we're actually improving the variance somewhat, and that is largely because we spent a significant amount of time considering how to deal with cloud clearing within the NUCAPS retrieval."

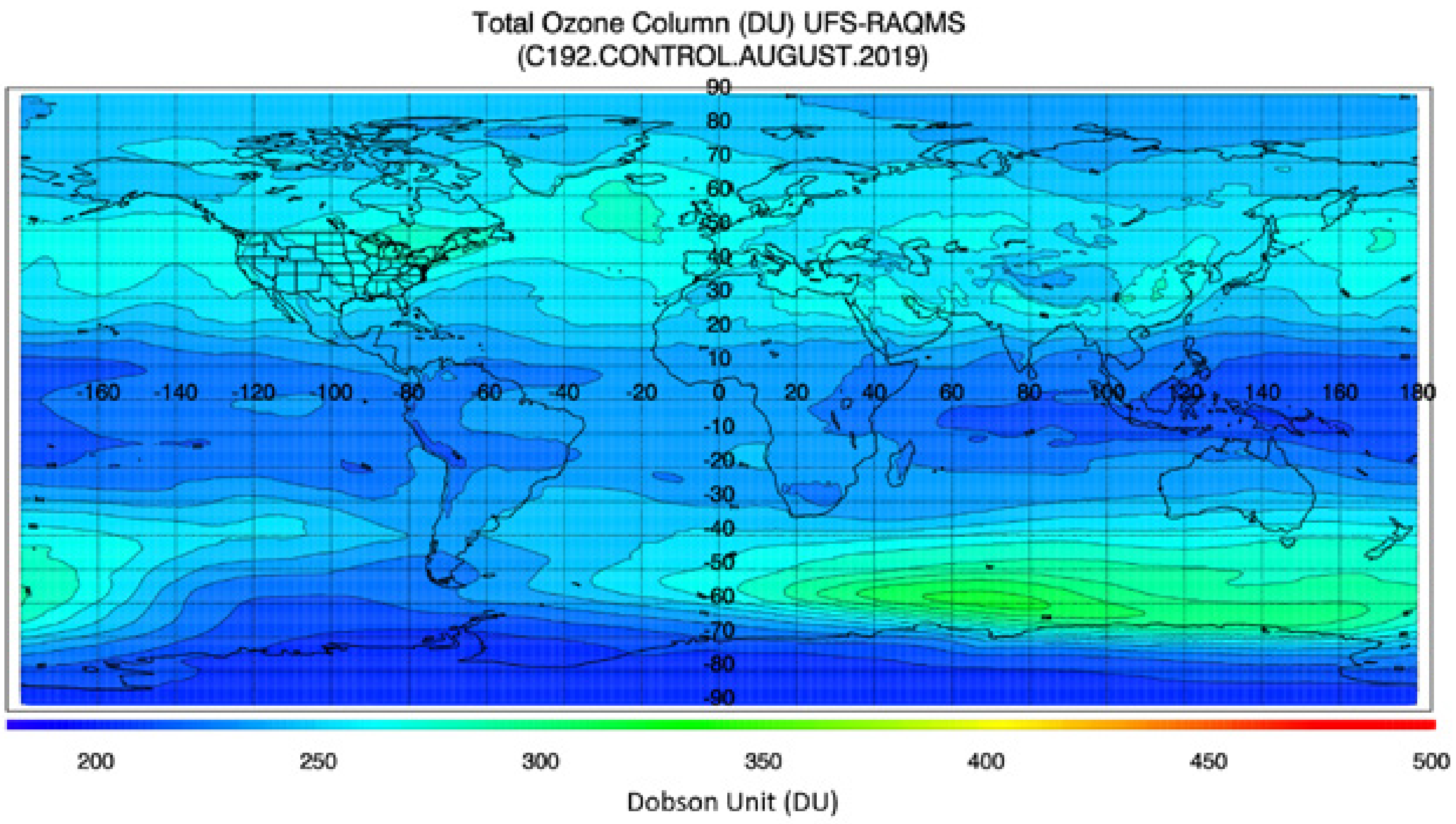
The assimilation experiment to constrain the long-range transport of biomass burning emissions from Siberia effectively improved agreement with the median background carbon monoxide concentration and enhanced sensitivity in the boundary layer near the surface. Combining NUCAPS and TROPOMI data, concludes Dr. Pierce, "leads to increases in carbon monoxide concentrations over Siberian, Alaskan, and Canadian wildfires leading to higher background carbon monoxide during FIREX-AQ and improved agreement with in-situ carbon monoxide measurements."

Assessing Bias From the Assimilation of OMPS Ozone Profiles

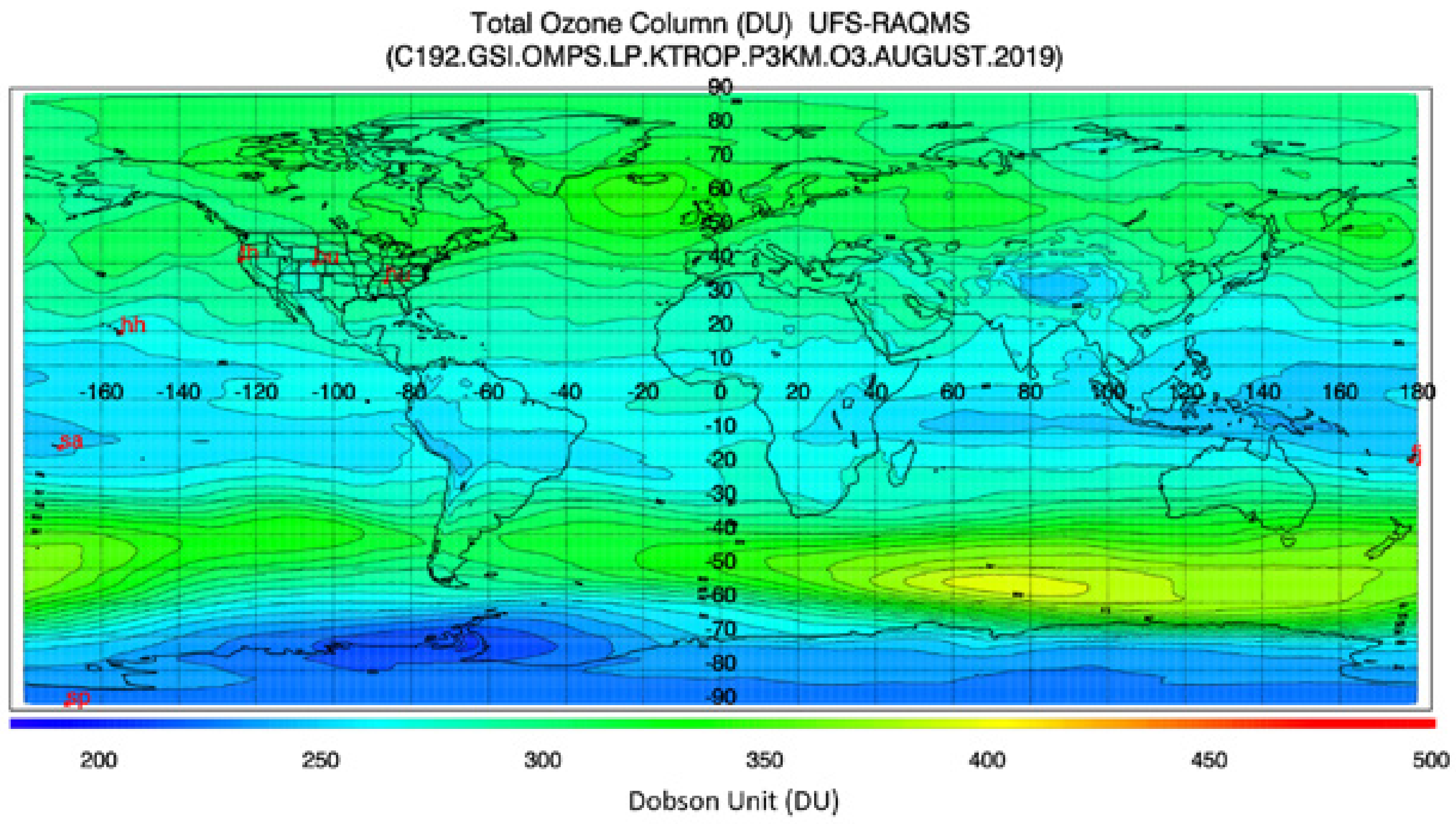
Assimilating satellite observations is valuable to constrain model uncertainty and improve estimates of the atmospheric state. Through experiments like the one described above, SSEC has shown that "improving global air quality forecasts through chemical data assimilation [of satellite data] improves regional air quality prediction, particularly through influence of lateral boundary conditions," says Dr. Pierce. That's not to say, though, that model predictions are not influenced by the biases of the satellite observations used. In fact, in a recent experiment, Dr. Pierce and his colleagues found that uncertainties in satellite-based constrained estimates of nitrogen oxide emissions produced with an inverse model were attributed to biases in satellite retrievals.[3] While satellite observations provide a unique opportunity for continuously measuring global air pollutants, they also can introduce uncertainty because of retrieval noise, cloud contamination, instrument bias, or other issues.

For that reason, Dr. Pierce and his team performed assimilation experiments to assess the bias of ozone retrievals from the OMPS Limb Profiler (LP) and OMPS Nadir Mapper (NM) within UFS-RAQMS, and to determine where in the atmospheric column can be best constrained with OMPS data. The OMPS experiments built off previous work performed at SSEC—a chemical reanalysis that assimilated ozone profiles from Aura's MLS and OMI to constrain global ozone and served as the framework of RAQMS.

The image below shows total ozone column amounts (in Dobson units, a unit of measurement of the amount of a trace gas in a vertical column through the Earth's atmosphere) for August 2019 from the control experiment (UFS-RAQMS with no data assimilation), followed below by total ozone column amounts from assimilating OMPS LP and OMPS NM within UFS-RAQMS. Comparing the two, "you can see there are significant increases in the [total ozone] column by assimilating these two satellite retrievals," says Dr. Pierce, as indicated by the greens and yellows.

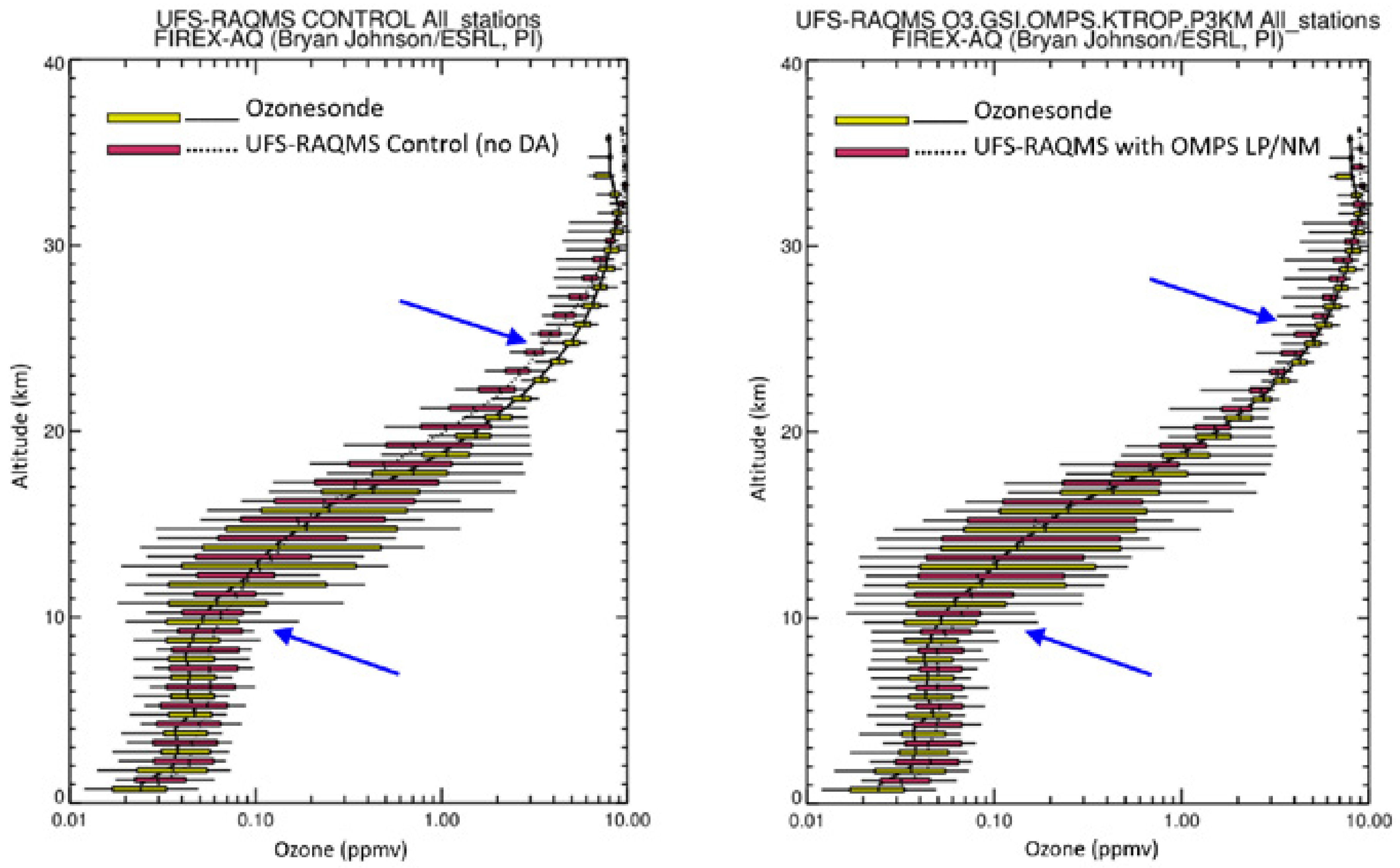


Total ozone column from the UFS-RAQMS control (no data assimilation) for August 2019.



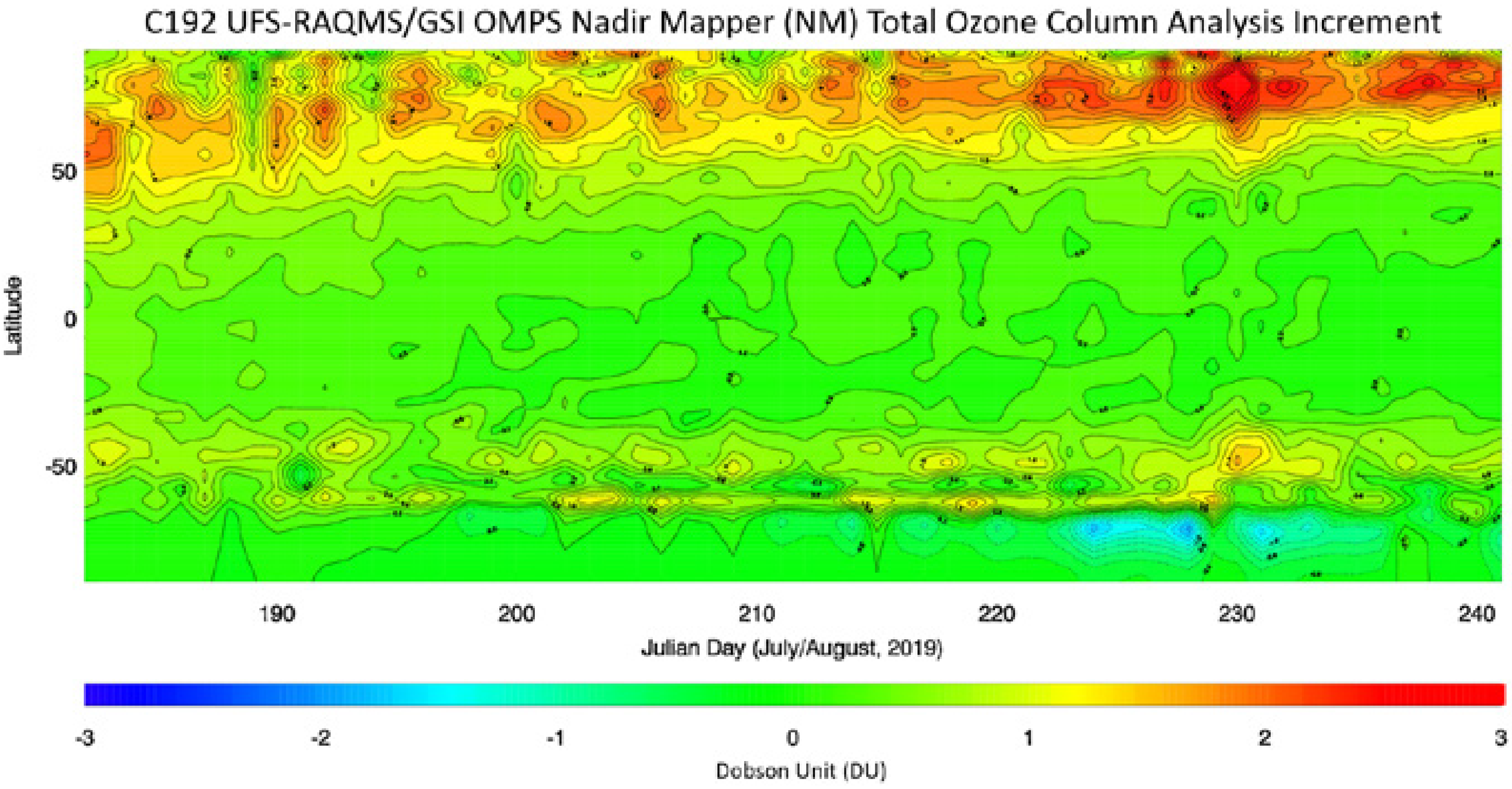
Total ozone column from UFS-RAQMS assimilated with OMPS LP and OMPS NM observations for August 2019.

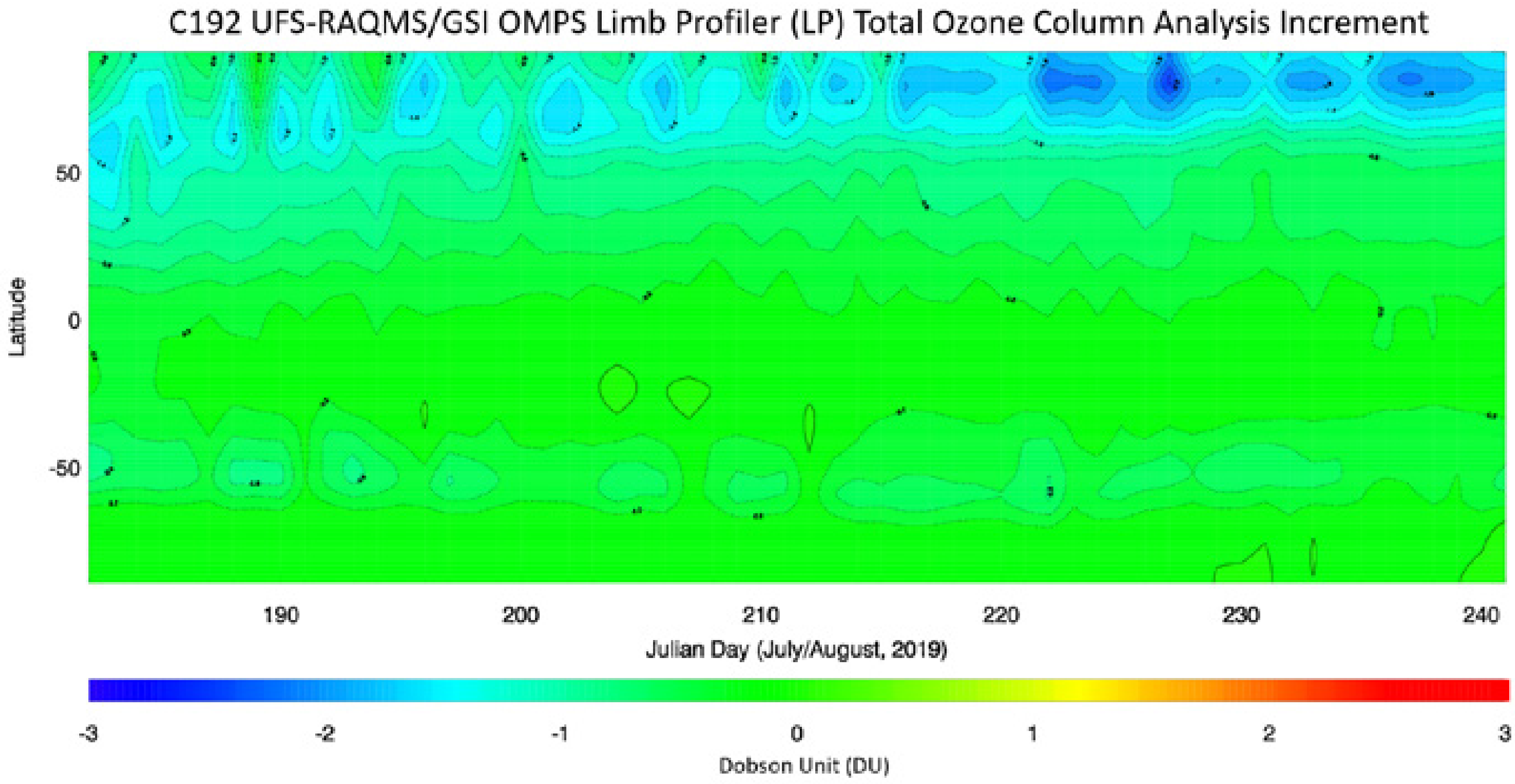
To verify that the observed column ozone enhancement is real and not a model artifact, the analysis was compared to ozonesonde data collected during the 2019 FIREX-AQ campaign time period (ozonesondes are balloon-borne instruments capable of taking ozone measurements from the surface to about 35 km in altitude). Without data assimilation (below left), UFS-RAQMS (red) significantly underestimates ozone in the stratosphere. But "by assimilating OMPS we reduced that bias to essentially zero [below right, red]," says Dr. Pierce. The median agreement in the troposphere and representation of ozone variance also improved through data assimilation. "All in all, the OMPS LP and NM can be effectively used in the same way that we've used MLS and OMI in the past," he concludes.



Left: Comparison of the ozone concentrations (ppmv) at different pressure levels from the UFS-RAQMS control with no data assimilation (red bars) and ozonesonde measurements (yellow bars). Right: Comparison of the ozone concentrations at different pressure levels from the UFS-RAQMS assimilated with OMPS LP and NM (red bars) and ozonesonde measurements (yellow bars). The profiles in these "bar and whisker" plots show the median UFS-RAQMS (dashed) and ozonesonde measurements (solid) ozone mixing ratios (ppmv). The bars show the upper 75% and lower 25% of the model and measurements and the whiskers show the upper 95% and lower 5% of the carbon monoxide distribution within each 20mb pressure bin.

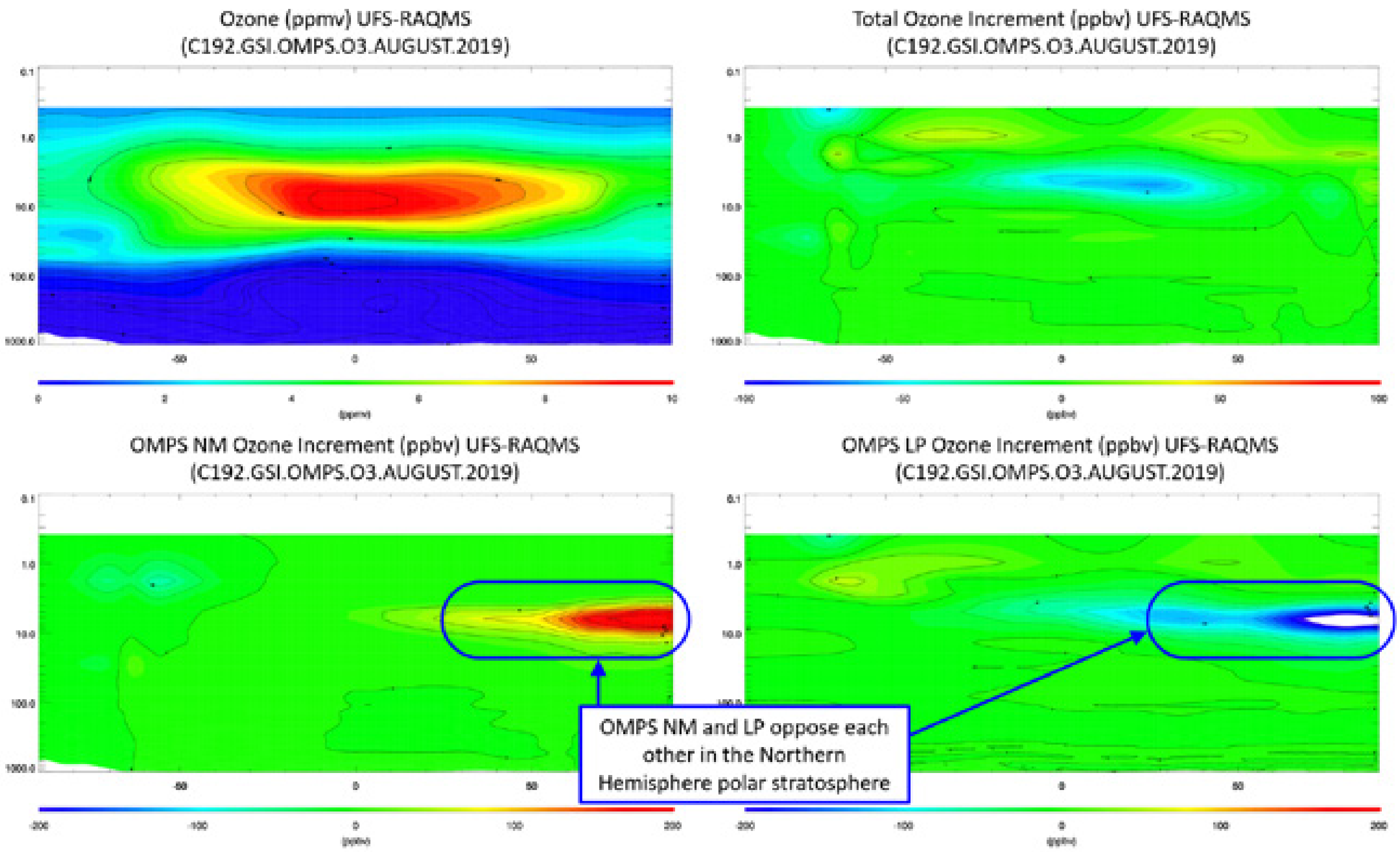
There are, however, some subtleties. Below are two time series plots for July 2019 through August 2019 with the total ozone column analysis increment along the x-axis and latitude along the y-axis. In the top plot, assimilating OMPS NM results in a largely positive analysis increment (indicated by red) that is restricted to the polar region above 50 degrees north latitude. But assimilating OMPS LP produces a largely negative analysis increment (blue) in the same polar region (bottom plot). In other words, OMPS NM and OMPS LP oppose each other in the polar region of the Northern Hemisphere. “This is something we try to avoid,” notes Dr. Pierce.





Top: Total ozone column analysis increment for UFS-RAQMS assimilated with OMPS Nadir Mapper (NM) ozone retrievals. Bottom: Total ozone column analysis increment for UFS-RAQMS assimilated with OMPS Limb Profiler (LP) ozone retrievals.

Talking a closer look, below are atmospheric cross sections for August 2019 with latitude along the x-axis and pressure level on the y-axis. Simulated ozone distribution reveals peak concentrations in the stratosphere, indicated by red in the top left plot. The top right plot shows the overall total ozone analysis increments combining retrievals from OMPS NM and OMPS LP within UFS-RAQMS. The bottom plots separate the analysis increments—left for OMPS NM and right for OMPS LP.



"You can see that right near the ozone peak in the stratosphere in the Northern Hemisphere we have a pretty large positive adjustment by the [OMPS] NM [bottom left, red] and a large negative adjustment by the [OMPS] LP [bottom right, blue]," Dr. Pierce points out. "This suggests that we need to consider bias correction of the LP to get rid of the opposing impacts in the middle stratosphere."

Evaluating the consistency between OMPS NM and OMPS LP instruments for the same parameter—ozone—proved useful for Dr. Pierce in determining the need for further adjustments, but also in deciding where in the atmosphere that model-based global ozone should be constrained with OMPS data. "In the end, we're assimilating down to the tropopause plus three kilometers because of larger errors and uncertainty in OMPS LP retrievals near the tropopause [where the troposphere and stratosphere meet]," he explains. Experiments like this support global air quality by improving air quality prediction models such as RAQMS, which are important for understanding the role stratospheric ozone plays on stratospheric warming—a key to understanding seasonal-to-subseasonal forecasting.

THE PATH FORWARD

Measuring trace gases in the atmosphere is essential for improving air quality prediction, protecting human health and ecosystems, understanding climate, and informing decisions ranging from daily firefighting planning to long-term environmental policy. By incorporating trace gas data into air quality models, forecasters, emergency managers, and others can more accurately predict air quality fluctuations, issue timely warnings, and recommend appropriate measures to protect public health. Furthermore, with improved information about air quality conditions, the public can make informed decisions on days with high pollution levels, such as limiting outdoor activities, closing windows and doors, wearing protective N95 masks, and using air purifiers.

New chemical data assimilation capabilities, like those being developed at SSEC, and the increasing volume of satellite-based atmospheric chemical composition data, have opened the door to improved modeling and a better understanding of the role that trace gases play in climate change dynamics. SSEC's experiments have shown that these objectives are achievable in RAQMS through assimilation of satellite data to constrain sources of model uncertainty and by combining measurements from different instrument systems, such as NUCAPS and TROPOMI. These approaches have enabled better estimates of the vertical distribution of atmospheric pollutants.

Experiments are ongoing at SSEC to enhance capabilities for assimilating JPSS data products and to transition this skill to NOAA's Earth System Research Laboratories for pre-operational testing. With the RAQMS unified chemical module already part of the Unified Forecasting System, RAQMS trace gas chemistry is poised for seamless integration into the operational Global Ensemble Forecast System-Aerosols atmospheric composition model.

JPSS satellites will provide observations from OMPS and CrIS to the 2040s, extending the long-term record of many atmospheric trace gases, including ozone, carbon monoxide, nitrogen dioxide, and others. As next generation polar satellites are launched, like the JPSS follow-on Near Earth Orbit Network, new sensors with enhanced capabilities will come online, providing scientists with a wealth of increasingly precise and comprehensive information about atmospheric composition. These satellites will play a pivotal role in our ongoing efforts to improve air quality forecasting, protect public health, and create cleaner and healthier living environments. ✦

STORY SOURCE

The information in this article is based, in part, on the May 19, 2023, LEO Science Seminar, "Data Assimilation of Trace Gases" presented by Dr. R. Bradley Pierce, Director, Space Science and Engineering Center (SSEC), University of Wisconsin-Madison.

FOOTNOTES

1 Borgschulte, M. Molitor, D., and Zou E.Y. (2022). Air Pollution and the Labor Market: Evidence from Wildfire Smoke. The Review of Economics and Statistics, 1-46. https://doi.org/10.1162/rest_a_01243

2 Fann, N., Alman, B., Broome, R.A., et al. (2018). The health impacts and economic value of wildland fire episodes in the U.S.: 2008-2012. Sci Total Environ., 610-611: 802-809. https://doi.org/10.1016/j.scitotenv.2017.08.024

3 East, J.D., Henderson, B.H., Napelenok, S.L., Koplitz, S.N., et al. (2022). Inferring and evaluating satellite-based constraints on NOx emissions estimates in air quality simulations. Atmos. Chem. Phys., 22(24), 15981-16001.

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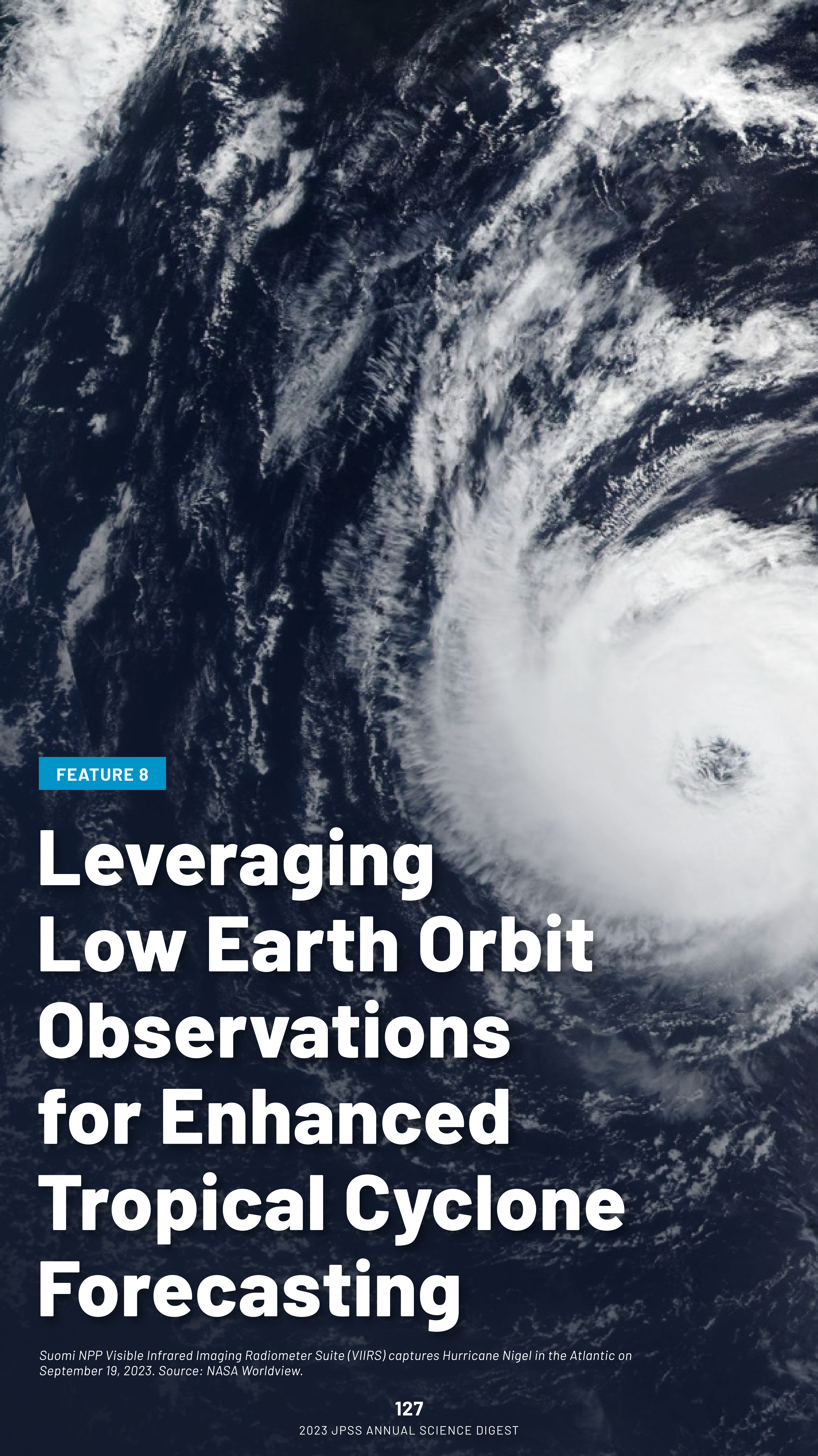
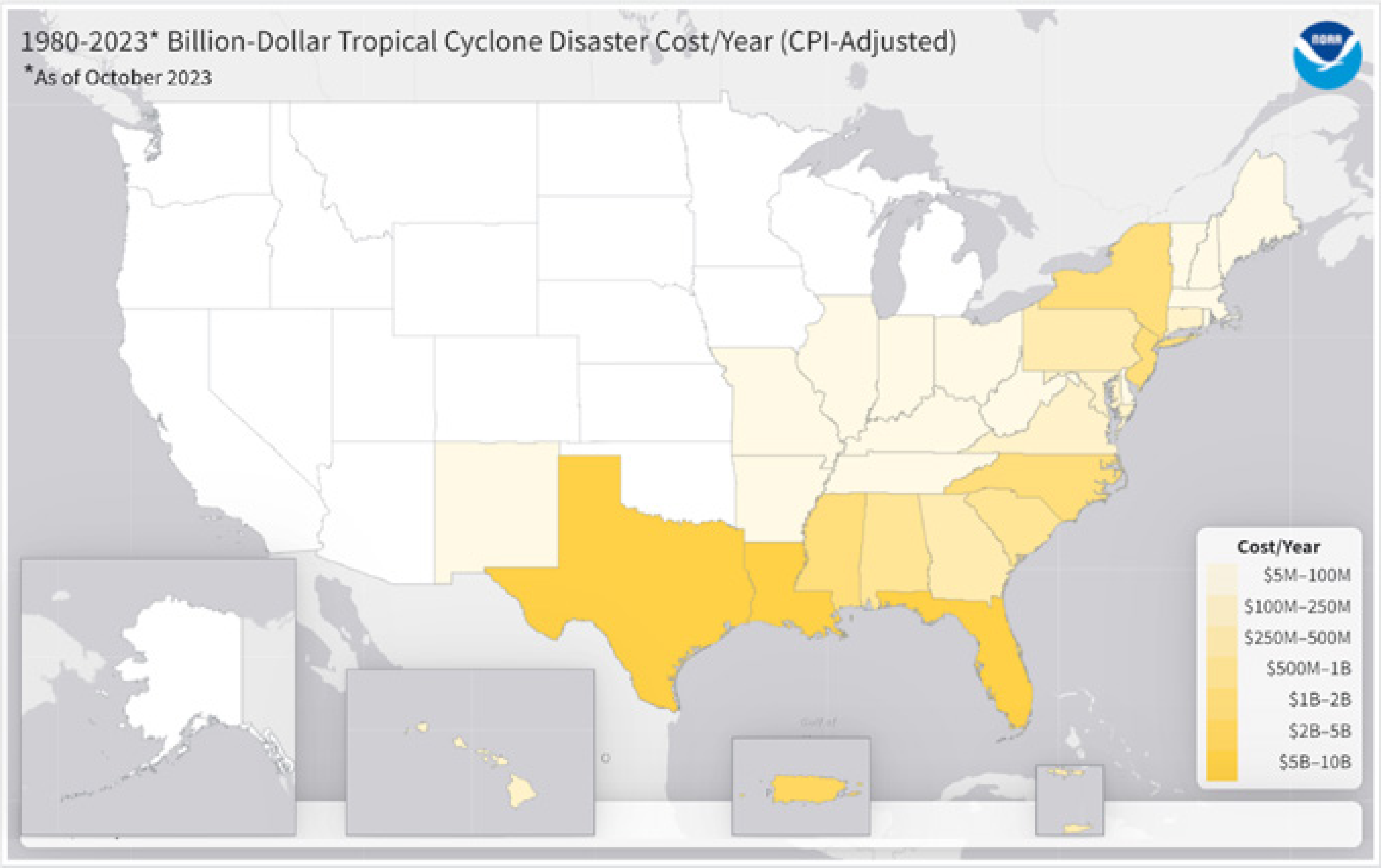


FEATURE 8

Leveraging Low Earth Orbit Observations for Enhanced Tropical Cyclone Forecasting

Suomi NPP Visible Infrared Imaging Radiometer Suite (VIIRS) captures Hurricane Nigel in the Atlantic on September 19, 2023. Source: NASA Worldview.



Billion-dollar tropical cyclone disaster cost/year from 1980 through October 2023 (CPI-Adjusted) for the United States and its territories. Note that the map reflects a summation of billion-dollar events for each state affected (i.e., it does not mean that each state shown suffered at least $1 billion in losses for each event). Source: NOAA National Centers for Environmental Information.

Tropical cyclones have significant and often devastating impacts on the lives of Americans. These intense weather systems can cause widespread damage through powerful winds, heavy rainfall, and storm surges. Coastal regions are particularly vulnerable, with the potential for severe flooding, extensive property damage, and loss of life. But the impacts of tropical cyclones extend beyond immediate destruction, as they can disrupt critical infrastructure, displace communities, and lead to significant economic losses.

"Of all billion-dollar disaster events, tropical cyclones are the most costly of all, even though they don't occur quite as often as severe storms," says Monica Bozeman, physical scientist and project manager at the National Weather Service Office of Central Processing. Since 1980, there have been 61 tropical cyclone events with losses exceeding $1 billion in the United States[1], and climate change has raised concerns about increased frequency and severity of these events in the future.

Studying and understanding tropical cyclones is vital for safeguarding the well-being of Americans and protecting the economy. Early storm warnings play a crucial role in timely evacuations and preparedness efforts, saving lives and property. Within the NOAA NESDIS Office of Low Earth Orbit Observations (LEO), the Hurricanes & Tropical Storms Initiative—part of the LEO Proving Ground Risk Reduction (PGRR) program—serves as a bridge connecting scientists and operational forecasters at the National Weather Service (NWS) with Joint Polar Satellite System (JPSS) data products that are tailored to the observation of tropical cyclones. "The objective of the initiative," explains Bozeman, who also serves as its facilitator, "is to improve tropical cyclone

What is the Proving Ground?

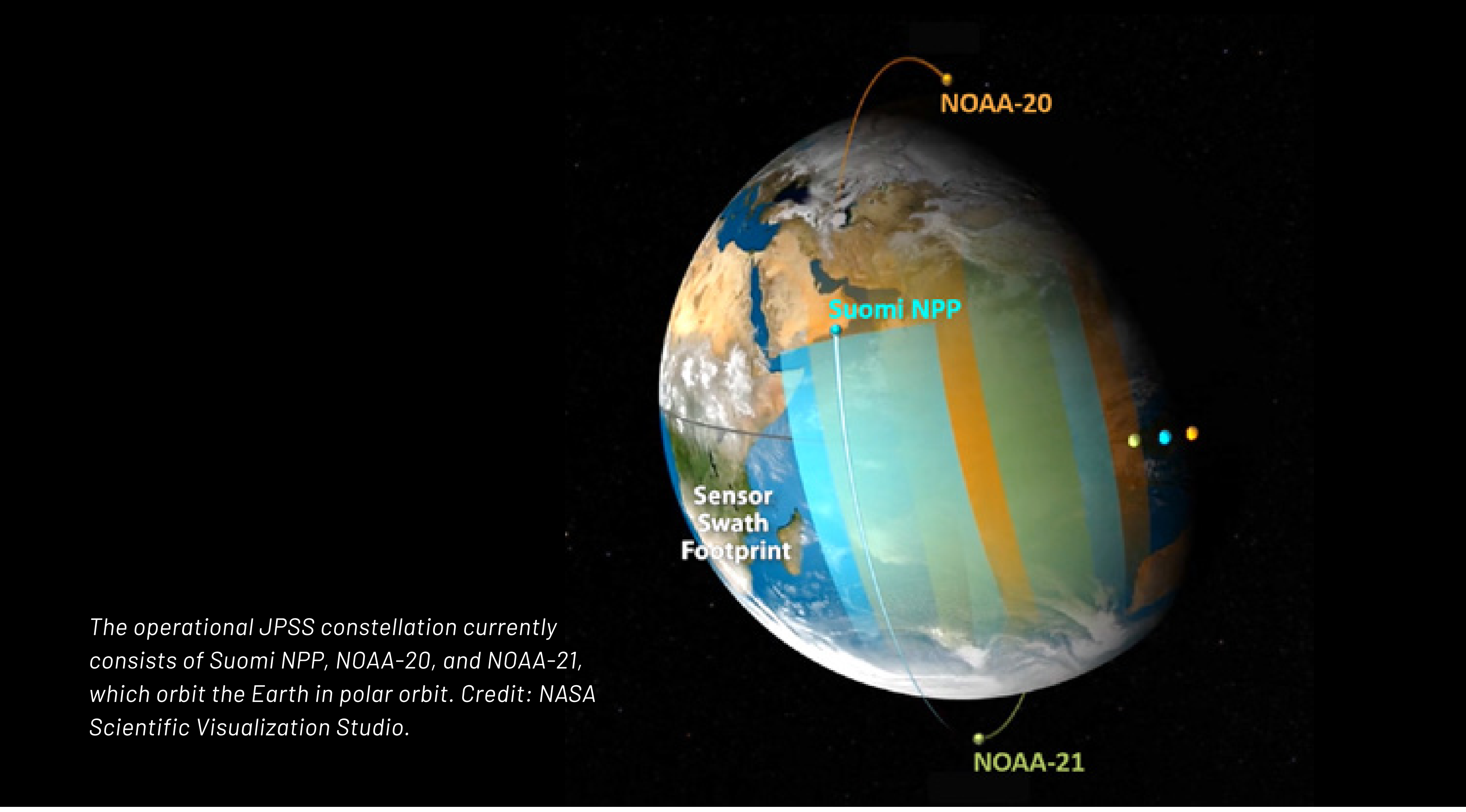
The Proving Ground Risk Reduction (PGRR) program is an effort to improve NOAA services through optimizing the use of satellite data along with other sources of data and information. Currently, eleven PGRR initiatives across various topics are managed by the Office of Low Earth Orbit Observations (LEO). Each initiative is made up of a team of developers and users working together to improve an application in a testbed environment, providing assessments of utility from the users and feedback to the developers.

Source: NOAA NESDIS

Aerial imagery from NOAA's National Geodetic Survey of damage in the Times Square district of Fort Myers Beach, Florida, after Category 4 Hurricane Ian struck the area in September 2022. Hurricane Ian is the third-costliest weather disaster to affect the United States, costing $116.3 billion and 152 lives. Source: NOAA News & Features; NOAA National Centers for Environmental Information.

analysis and forecasting specifically using the JPSS product suite and getting more of that data into operations to see where it can help with the existing tools that the forecasters have."

Having more data will help meteorologists better predict the strength and path of these dangerous storms. "We need to keep working to reduce damage and deaths," Bozeman asserts, noting that "JPSS continues a critical microwave sounding capability for characterizing tropical cyclones that can only be observed in detail via satellite." In its current funding cycle, the Hurricane & Tropical Storms Initiative supports three projects that aim to improve the use of JPSS imager and sounder data for tropical cyclone analysis and forecasting. At the July LEO Science Seminar, Bozeman provided an overview of the applications of polar-orbiting satellite data in tropical cyclone operations, followed by a deep dive into each of the Hurricane & Tropical Storms Initiative projects and their path to operations.



The operational JPSS constellation currently consists of Suomi NPP, NOAA-20, and NOAA-21, which orbit the Earth in polar orbit. Credit: NASA Scientific Visualization Studio.

THE IMPORTANCE OF SATELLITE DATA IN TROPICAL CYCLONE ANALYSIS AND FORECASTING

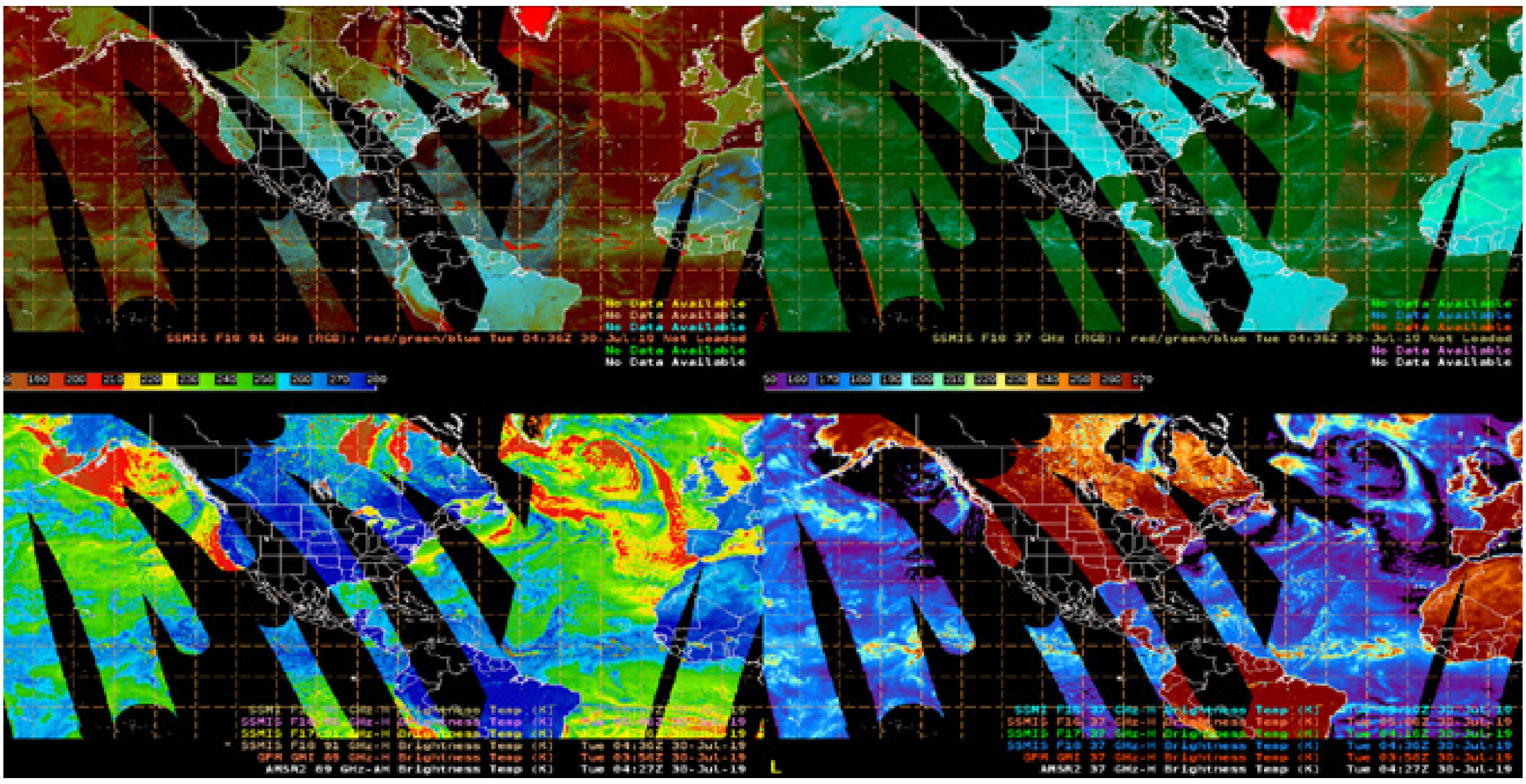
Most tropical cyclones spend the majority of their lifecycle in remote regions of the ocean where very little in situ data is available. Observation stations are primarily located on land, with radar and buoy measurements concentrated near coastal zones, leaving gaps in the monitoring network. Ship reports are also scarce given that ships steer clear of tropical cyclones for safety reasons, and aircraft reconnaissance primarily targets storms that pose a threat to land. While these in situ data sources are valuable, environmental satellites provide a complementary top-down perspective for storms developing in data-sparse oceans.

JPSS and other polar-orbiting satellites circle the Earth in low Earth orbit (an altitude of around 2,000 kilometers or less), traveling from the North Pole to the South Pole and back again as the Earth rotates beneath them. This low orbit allows them to capture a global perspective of the Earth's weather and climate, observing both polar and equatorial regions multiple times per day. Three JPSS satellites are currently operational—Suomi NPP, NOAA-20, and NOAA-21—each crossing the equator 14 times daily and providing full global coverage twice a day.

Conversely, geostationary satellites, like NOAA's Geostationary Operational Environmental Satellites (GOES), provide a complementary perspective to polar-orbiting satellites. Geostationary satellites orbit the Earth at a much higher altitude than polar-orbiting satellites, remaining fixed above a specific point on the equator. This stationary position enables them to deliver continuous, real-time monitoring of rapidly developing severe weather events. Together, these two types of satellites offer critical information to meteorologists and scientists for monitoring and predicting weather patterns, tracking climate change, and improving the understanding of the Earth's complex environmental systems.

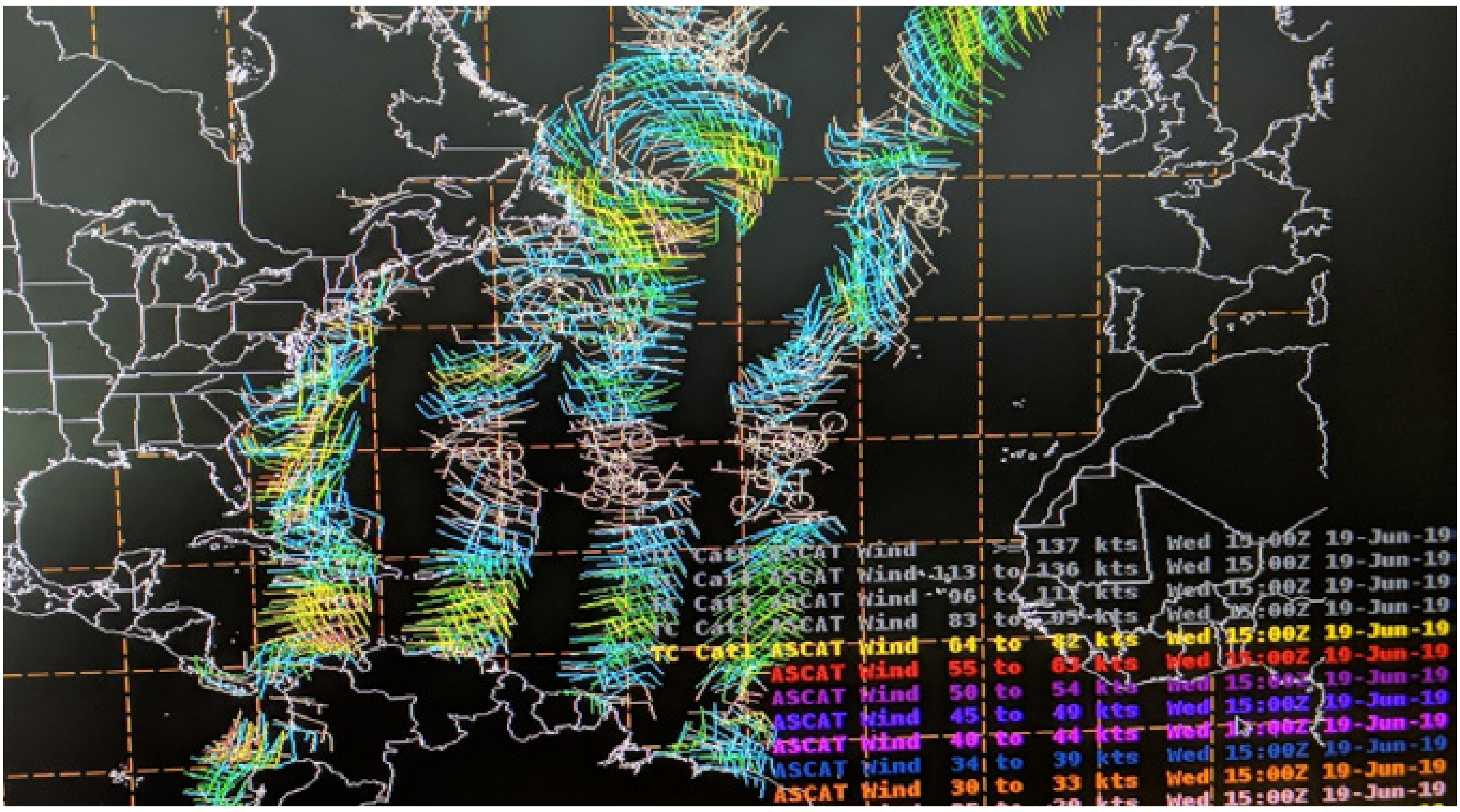
Using Low Earth Orbit Observations in the Operational Setting

In tropical cyclone operations, meteorologists at forecasting centers, including the National Hurricane Center, Central Pacific Hurricane Center, and the Joint Typhoon Warning Center, use data derived from JPSS and other polar-orbiting satellites to better understand cyclone characteristics and predict storm track and intensity. Microwave sounding instruments ("sounders") provide significant information about atmospheric properties that influence severe weather, and can "see" through clouds because they observe the Earth in the microwave portion of the electromagnetic spectrum (most clouds are transparent at microwave wavelengths). For instance, data from the JPSS Advanced Technology Microwave Sounder (ATMS), the Advanced Microwave Sounding Unit (AMSU) onboard NOAA-19, and EUMETSAT's MetOp satellites are critical for analyzing the internal structure of tropical cyclones to gain insights into their organization and development. Polar-orbiting microwave data, scatterometry, visible and infrared imagery from the JPSS Visible Infrared Imaging Radiometer Suite (VIIRS) and ProxyVis imagery (discussed below)—along with data from geostationary satellites—also assist with center fixing within the Automated Tropical Cyclone Forecast (ATCF) system. Center fixing, a critical first step in tropical cyclone forecasting, helps to precisely locate a storm's center, which is essential for tracking and trajectory predictions.



Example low Earth orbit observations as viewed in the Advanced Weather Interactive Processing System (AWIPS). Data visualization of satellite-based microwave data from the Special Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager Sounder (SSMIS) onboard the Defense Meteorological Satellite Program (DMSP) satellite, NASA's Global Precipitation Measurement (GPM) Microwave Imager (GMI), and the Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the JAXA GCOM-W1 satellite.

"Scatterometers are a really big deal" for analyzing tropical cyclone genesis and estimating maximum sustained winds, says Bozeman. Instruments, such as the Advanced Scatterometer (ASCAT) onboard MetOp satellites operated by EUMETSAT, measure wind speed and direction over the surface of the oceans (an example of ASCAT in AWIPS, the NWS weather forecasting data and display



Example low Earth orbit observations as viewed in the Advanced Weather Interactive Processing System (AWIPS). ASCAT wind data in the Advanced Weather Interactive Processing System (AWIPS).

system, is shown above). Operational forecasters also rely on altimeters that fly in polar orbit to estimate wave height for marine forecasting and ocean heat content for predicting intensity.

Avoiding a "Sunrise Surprise"

Another operational forecasting product that exploits polar-orbiting satellite data is ProxyVis. Developed at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, ProxyVis helps meteorologists track tropical cyclones at night to avoid what forecasters call a "sunrise surprise"—unanticipated changes in a storm's path that can occur overnight.

Full-disk ProxyVis imagery for the Western Hemisphere on October 12, 2023, at 16:50:20 UTC. Source: RAMMB/CIRA SLIDER.

The ProxyVis product is a nighttime proxy for visible imagery. Visible imagery generally requires sunlight to "see" (no sunlight means no image), so the amount of information available to forecasters at night is significantly limited. ProxyVis combines a selection of infrared channels from VIIRS that closely match the infrared channels currently available on geostationary satellites to mimic daytime visible imagery at night. The product was trained to reproduce nighttime imagery from the VIIRS Day/Night Band that can detect extremely low levels of visible light at night, a capability unique to the VIIRS sensor. ProxyVis algorithms, when applied to geostationary satellite data, produce visible-like full-disk nighttime imagery at the high temporal resolution needed to monitor short-term changes that can occur during the night in low-level oceanic clouds. "This product was a huge help once it got into operations," Bozeman emphasizes.

The use of polar-orbiting satellite-derived products at operational forecasting centers underscores the significance of low Earth orbit observations in advancing the science of tropical cyclone monitoring and forecasting. These data enhance forecasters' ability to predict how a storm may develop and evolve, helping authorities and the public make informed decisions in the face of these powerful weather events. Through the LEO PGRR program and other testbeds, fresh capabilities are continuously being developed for collecting, processing, and analyzing low Earth orbit observations tailored to tropical cyclone forecasting.

CURRENT HURRICANE & TROPICAL STORMS INITIATIVE PROJECTS

The LEO PGRR program aims to maximize the benefits and performance of low Earth orbit data, algorithms, and products in support of both operations and research. The program includes eleven initiatives, each consisting of collaborative teams composed of product developers and users. These teams work together in a testing environment to improve and evaluate applications, offering valuable feedback to the developers to further refine their functionality.

LEO PGRR Initiatives

- Hurricanes & Tropical Storms
- Fire & Smoke
- Sounding Applications
- Numerical Weather Prediction Impact Studies & Critical Weather Applications
- Aviation Weather
- Ocean & Coastal
- Arctic
- Volcanic Hazards
- River Ice & Flooding
- Hydrology
- Training

The Hurricane & Tropical Storms Initiative currently supports three research projects, described below, to enhance the use of JPSS imager and sounder data for tropical cyclone analysis and forecasting. These projects involve improving low Earth orbit data processing for tropical cyclone centered views in the operational setting, developing a deep learning model to predict two-dimensional (2D) wind structure from ATMS soundings, and using ATMS retrievals to help diagnose extratropical transitions in real time.

Improvements to Near-Real Time GeoIPS® Low Earth Orbit Data Processing

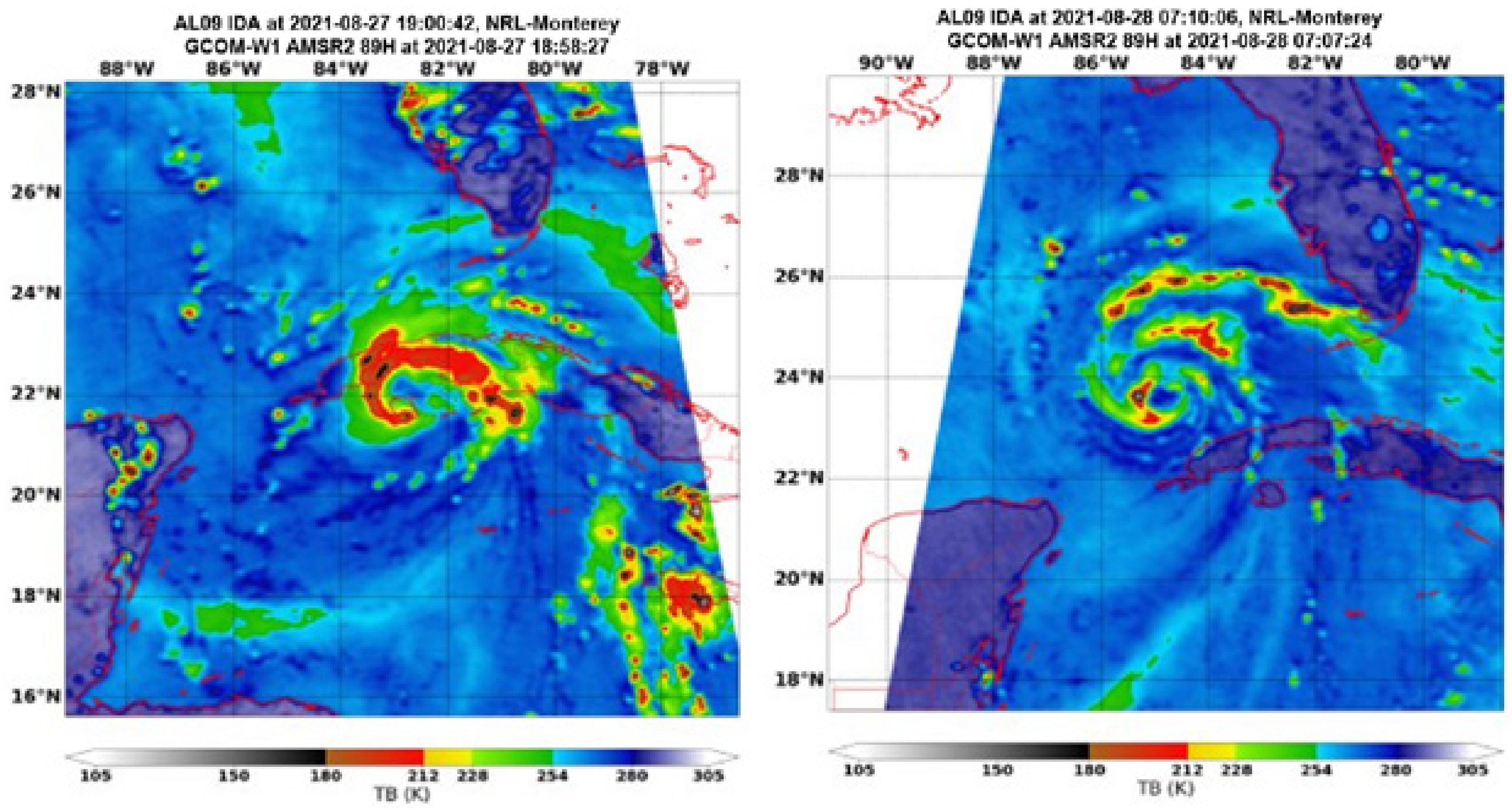
Project
Improvements to Near-Real Time GeoIPS® LEO Data Processing

Organization
Naval Research Laboratory

Principal Investigator
Christopher Selman

By the end of 2025, the NOAA National Centers for Environmental Prediction (NCEP) is expected to migrate to AWIPS II, the weather forecasting display and analysis package used by NWS Weather Forecasting Offices (WFOs) across the U.S. "The implications are huge," says Bozeman. "[NCEP] has their own system so they don't have the easiest capability to talk back and forth with the WFOs and leverage tools that are written on or for AWIPS II for collaboration. This [transition] will mean that NCEP and the WFOs will be on the same platform." In anticipation of this shift, the Naval Research Laboratory (NRL) is enhancing their Geo-located Information Processing System (GeoIPS®) to improve data latency and display options so that forecasters can access low Earth orbit observations from polar-orbiting satellites more quickly and effortlessly in AWIPS II.

GeoIPS® is a Python-based open-source data processing and display system developed by NRL to accommodate the next generation of weather satellites. It offers a versatile framework for applying advanced processing algorithms to a diverse range of environmental datasets from geostationary and polar-orbiting satellite sensors, numerical weather prediction (NWP) model outputs,



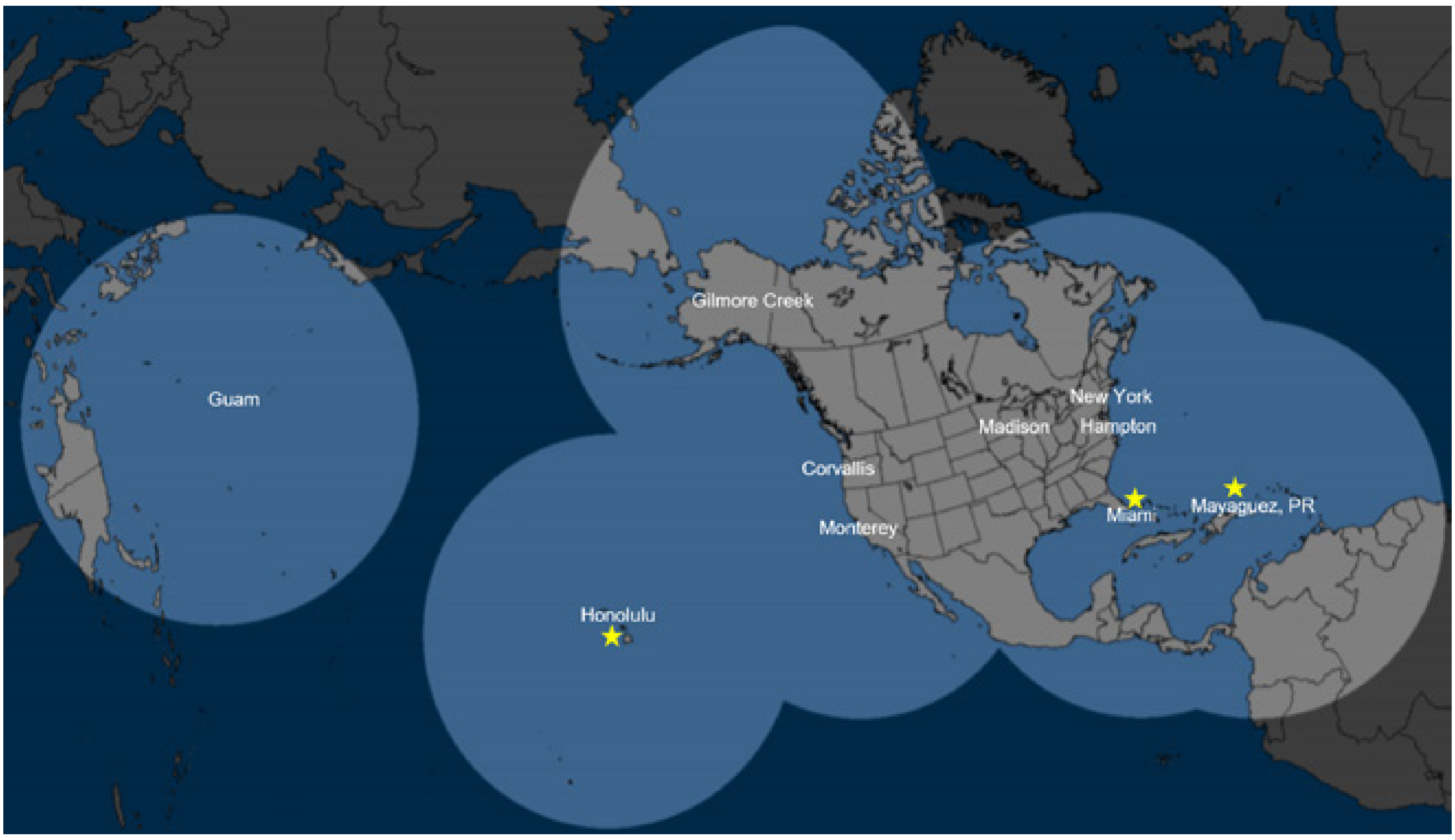
Tropical cyclone centered views developed with the help of GeoIPS® show microwave data from Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the JAXA GCOM-W1 satellite for Hurricane Ida in August 2021.

in situ observations, and other sources. The system streamlines the transition from research to operational use, offering the flexibility to integrate future advancements and technological developments while enhancing efficiency.

GeoIPS® was tested on National Hurricane Center infrastructure, where it was used to preprocess polar-orbiting microwave sounder data for producing tropical cyclone centered imagery (see examples below). The centered view saves time when visualizing satellite data because it centers the storm in the image—"you don't have to move [the image] around, find the storm in the swath, or do any zooming," which is time consuming for forecasters, Bozeman asserts.

Getting low Earth orbit observations into GeoIPS® for preprocessing in a timely manner can be a challenge. One common issue is data latency—the time from satellite data acquisition to user availability. To get data faster, the NRL team, led by Christopher Selman, is retrieving microwave soundings through three Direct Broadcast Network[2] locations in Miami, Puerto Rico, and Honolulu. As of now, they are ingesting and processing data from several polar-orbiting sensors including ATMS, AMSU, the Microwave Humidity Sounder (MHS) onboard NOAA-19 and MetOp satellites, and the Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the JAXA GCOM-W1 satellite.

Direct Broadcast offers a substantial speed advantage over NOAA's Production Distribution and Access (PDA) system, the NESDIS enterprise distribution system for near-real time JPSS data—and in the context of tropical cyclones where time is of the essence every minute can be crucial. But "while Direct Broadcast gets there much faster, there are some issues you have to deal with," Bozeman warns. There can be missing data, artifacts, or inaccuracies in geolocation, for instance. "But overall, the Direct Broadcast imagery is pretty good."



Direct Broadcast receiving stations in the U.S. Yellow stars indicate sites where NRL is retrieving data: Miami, Puerto Rico, and Honolulu.

AWIPS2-DB Plugin Sample Products

Sample Products	AMSR2 Channels	Purpose
19 GHz, H. pol. 19H-19V (19D)	7, 8	Atm. Liquid water emission D Maximizes ocean/atmosphere signal
37 GHz, H. pol. 37D	11, 12	Atm. Liquid water emission D maximizes ocean/atmosphere signal
89 GHz-A, H. pol. 89D	13, 14	Higher res than 19 or 37GHz, but more dominated by ice scattering
Color37 RGB	11, 12	Boundary layer thermodynamics
Color89 RGB	13, 14	Boundary layer thermodynamics
Low-Level RGB	7, 8, 11, 12, 13, 14	Low-level circulation
Hydrometeor RGB	7, 8, 13, 14	Vertical liquid/ice distribution

Generating low Earth orbit data that is compatible with AWIPS II using GeoIPS® presents another unique problem. While a plugin is available for microwave imagery display, it requires reconfiguration to make it suitable for displaying low Earth orbit observations because it was developed specifically for GOES geostationary satellites. Considering this challenge, the NRL team is working on a solution they call the AWIPS2-DB plugin. The plugin works with GeoIPS® to produce AWIPS II-compatible tropical cyclone centered microwave sounding imagery from polar-orbiting satellites for the entire swath without the need to reconfigure files or reproject the data. The AWIPS2-DB plugin also allows for the creation of derived products like red-green-blue or "RGB" composite imagery. As of now, the team has produced several products beneficial to forecasters, a sample of which is shown in the table. An open source version of the AWIPS2-DB plugin is expected in late 2023.

For preprocessing, "GeoIPS® can slice and dice your data however it's needed and then produce the output for AWIPS II compatible imagery," says Bozeman. The base version is compatible with about 20 satellites, and the NRL team continues to add features and incorporate indices and innovative science algorithms with an eye on expanding GeoIPS® to more operational settings.

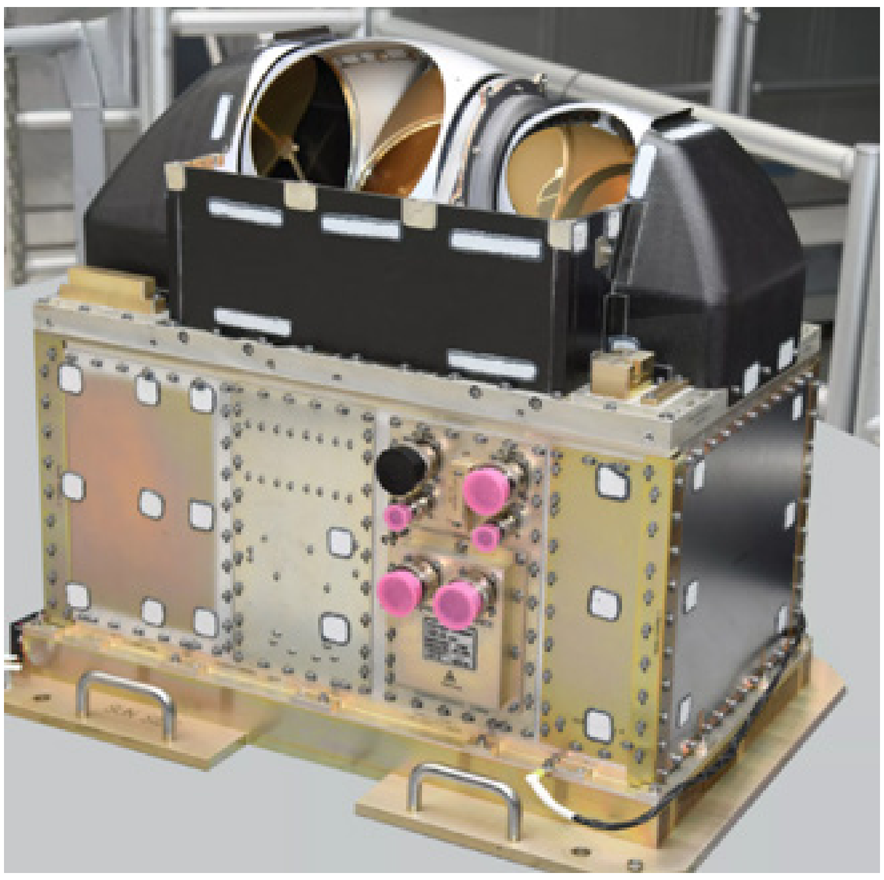
Direct Integration of JPSS Observations into Tropical Cyclone Surface Wind Structure Retrievals Using Deep Learning

Project
Direct Integration of JPSS Observations into Tropical Cyclone Surface Wind Structure Retrievals Using Deep Learning

Organization
Cooperative Institute for Meteorological Satellite Studies

Principal Investigator
Dr. Anthony Wimmers

ATMS is a 22-channel scanning microwave sounder (a type of radiometer) that flies on JPSS satellites in low Earth orbit and is the successor to the AMSU and MHS microwave sounders onboard previous NOAA missions. It observes the Earth in the microwave part of the electromagnetic spectrum, allowing it to view inside and beneath clouds associated with severe weather. This capability enables forecasters to produce imagery within tropical cyclones to better understand their dynamics and provide improved predictions. But forecasters need information about tropical cyclone structure—like the radius of maximum winds—for a more complete picture of the storm wind field. While ATMS imagery shows these features quite well, wind structure is hard to quantify.



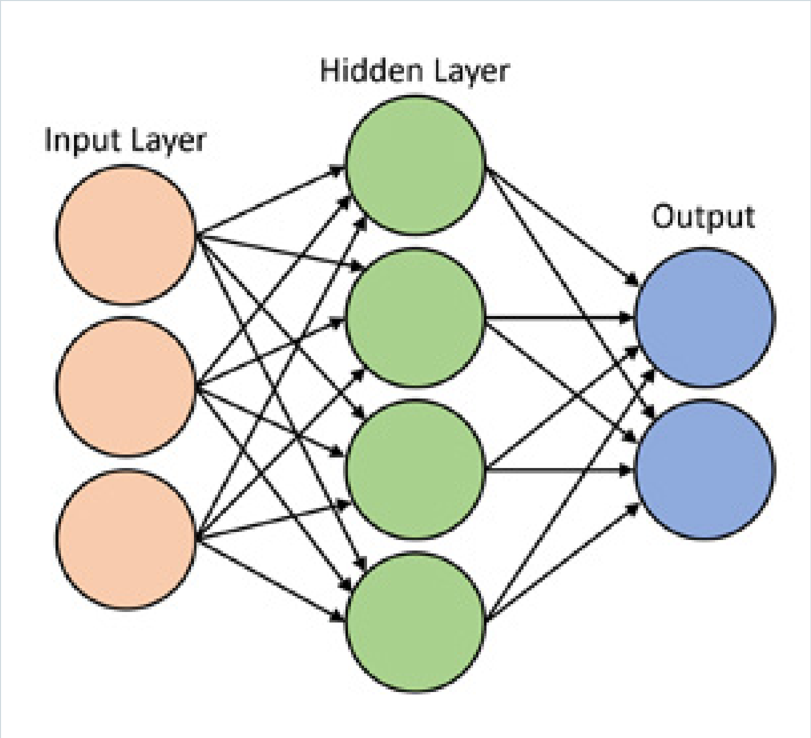
The ATMS instrument onboard JPSS satellites.

Maximum sustained surface wind is a standard operational measure of tropical cyclone intensity and is closely linked to storm-related losses. Improving the estimation of intensity and wind structure should lead to more effective storm warnings and fewer lives lost. In response, the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison is exploring the use of a deep learning model to predict 2D winds from ATMS data.

Deep learning is a subset of machine learning that uses artificial neural networks with multiple layers to automatically learn and extract patterns, features, and representations from data. It has been particularly successful for image and speech recognition, natural language processing, and various forms of predictive modeling.

Demystifying Deep Learning

Deep learning is a subset of machine learning that uses artificial neural networks designed to mimic how humans think and learn. Deep learning models use training data to improve their ability to make predictions or perform specific tasks. Training data helps the model learn patterns and relationships between the input data (input variables that the model will use to make predictions) and the target data (also called labels, target data are the correct answers or outcomes associated with the input data). The model continually adjusts its internal parameters to minimize the difference between its predictions and the target data. This iterative process allows the model to improve its performance over time, and continues until the model reaches an acceptable level of performance.



A simplified schematic of an artificial neural network.

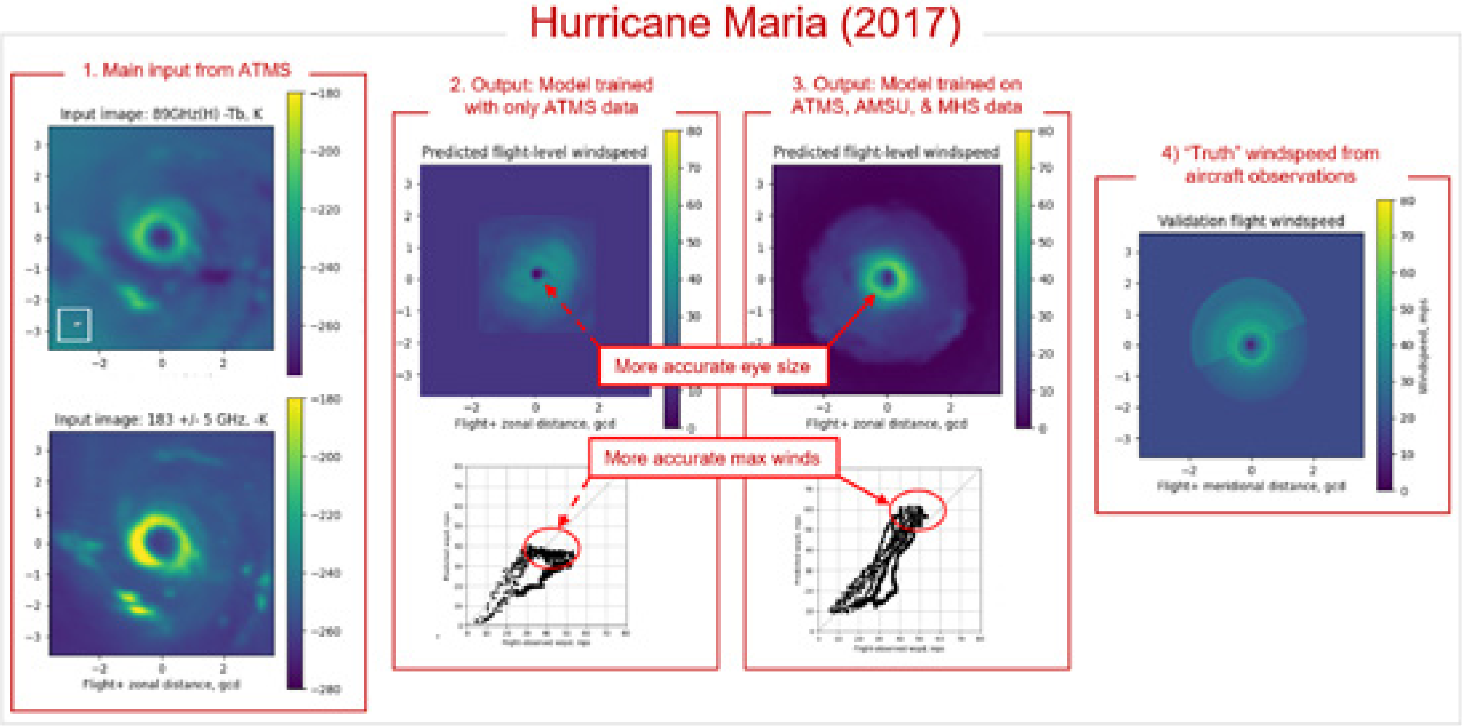
Deep learning models rely on large amounts of training data to teach them to make accurate predictions or classifications. At CIMSS, Dr. Anthony Wimmers, Principal Investigator, and his team trained a proof-of-concept ATMS-only deep learning model using hundreds of ATMS soundings of tropical cyclones that coincided with high-accuracy aircraft observations ("truth" data). The results showed that the method worked but more training data was needed to improve accuracy.

Having first launched on Suomi NPP in October 2011, the ATMS sensor record of operations is relatively short. To acquire more training data, the CIMSS team compiled more than 26,000 additional tropical cyclone centered images from AMSU and MHS sensors (from ATMS-matching channels) dating back to 1998. "This required a lot of quality control of the data," Bozeman notes, "[which] is always important in machine learning."

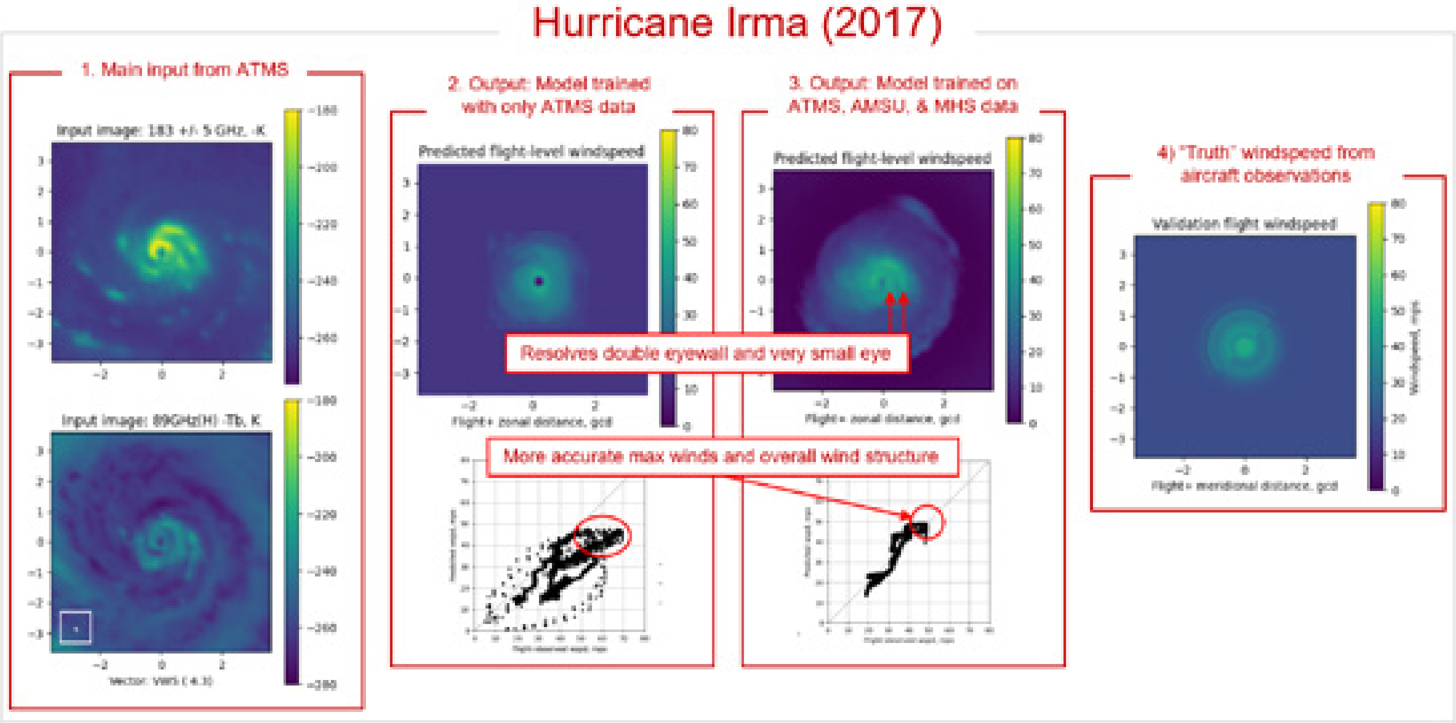
The enhanced model (enhanced with more training data) performed well with very promising outcomes. Looking at validation results for Hurricane Maria (next page, top image), the deep learning model trained on ATMS, AMSU, and MHS data (number 3 in the example) provided a more accurate eye size and more accurate maximum winds.

For Hurricane Irma (bottom image), the model resolves the double eyewall and very small eye, and provides more accurate maximum winds and overall wind structure. Note that both scatterplots show the model versus measured winds along the validation flight transects (not shown).

Hurricane Maria (2017)



Hurricane Irma (2017)



Bozeman indicated that a more thorough analysis is forthcoming, but these two instances already demonstrate the new model's strong performance. "With deep learning methods, we can go beyond normal [tropical cyclone] intensity nowcasting and begin to estimate 2D wind structure," she notes. This is important because tropical cyclone structure plays a critical role in accurately predicting a storm's behavior, potential impacts on affected areas, and getting reliable and timely information to the public. Research at CIMSS continues, with plans to make better use of ~55 GHz temperature channels, produce more comprehensive accuracy statistics, and conduct a flight-level to surface-level conversion so that the model is valid at the surface.

Use of JPSS Instrument Suite to Improve Operational Tropical Cyclone Structure and Intensity Analysis and Forecasts

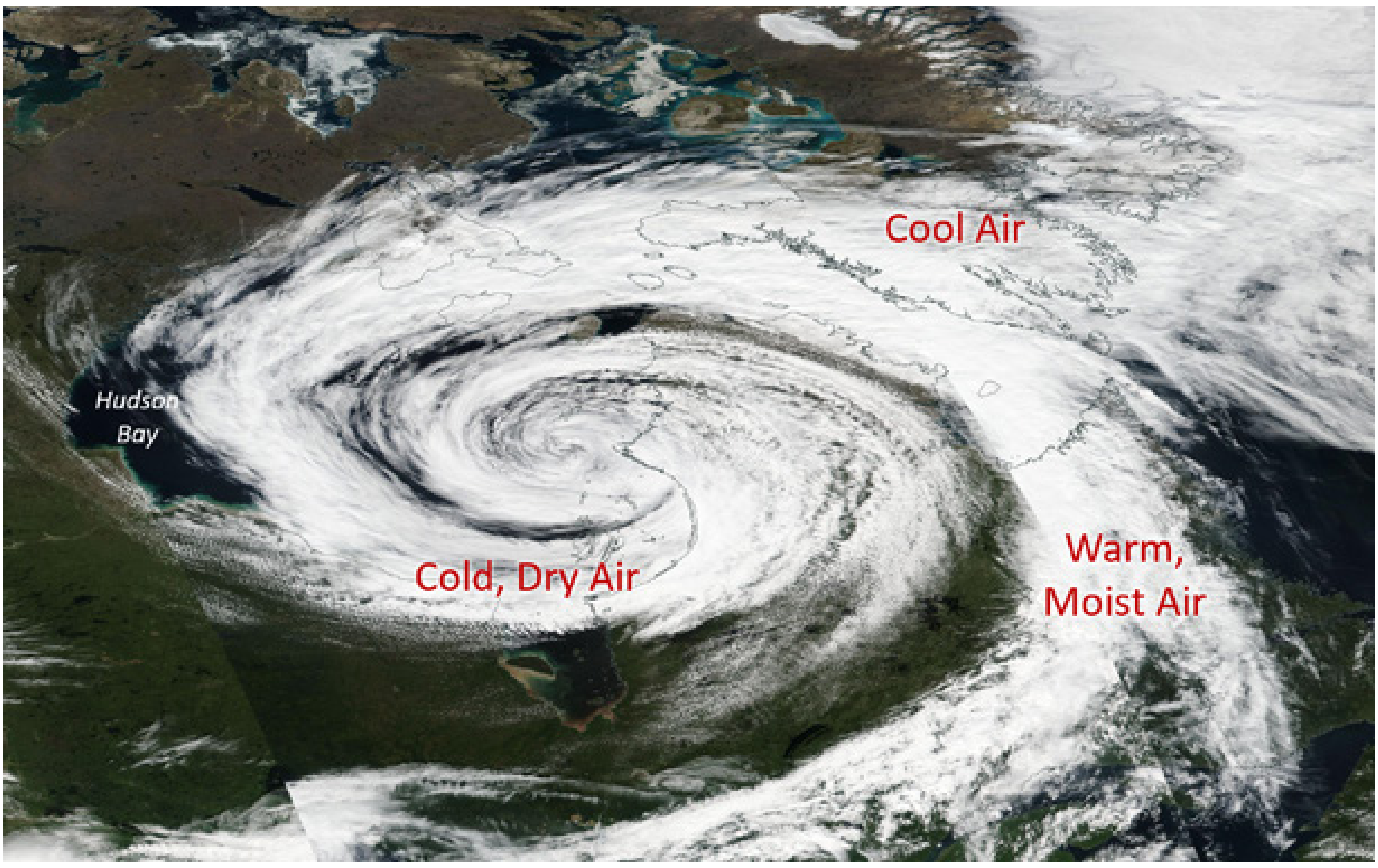
Project
Use of JPSS Instrument Suite to Improve Operational Tropical Cyclone Structure and Intensity Analysis and Forecasts

Organization
Cooperative Institute for Research in the Atmosphere

Principal Investigator
Galina Chirokova

Extratropical transition refers to the complex transformation of a tropical cyclone into an extratropical cyclone. It is a crucial process in meteorology, typically occurring when a tropical cyclone moves poleward out of the tropics and encounters westerly winds prevalent in the mid-latitudes between 30° and 60° latitude. This transition can bring about substantial changes in a cyclone's structure and behavior as it loses its warm core (as a tropical cyclone) and becomes a cold core system (extratropical cyclone), often leading to the formation of or connection with nearby fronts and troughs. These changes can cause the system to become larger and alter its track, sometimes making it harder to predict its future intensity and path.

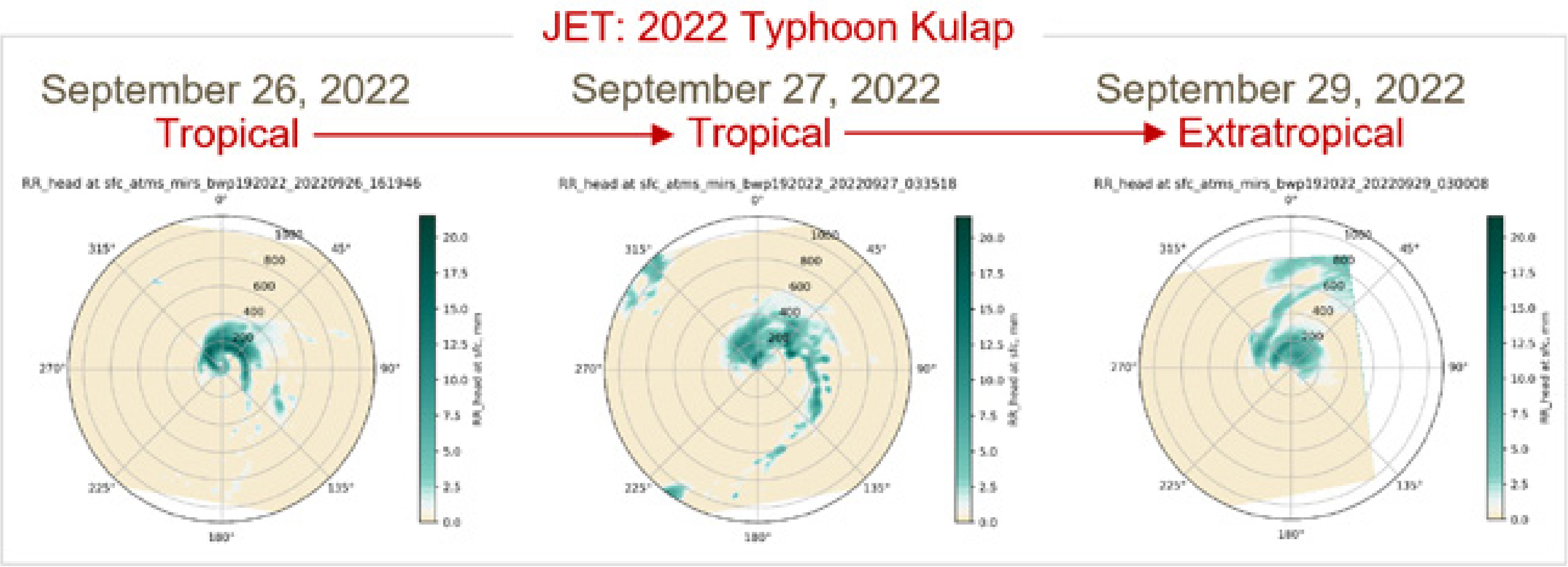
"On average," says Bozeman, "[there are] about 15 tropical storms to extratropical cyclone transitions per year in all global basins." Extratropical cyclones are responsible for most of the extreme weather in the mid-latitudes, home to more than fifty percent of the world's population. They can produce heavy rainfall, strong winds, storm surge, and severe thunderstorms, making it crucial for meteorologists to monitor and predict extratropical transitions for effective weather forecasting and preparedness. "[Extratropical] transition is also important for interagency coordination and handoff," says Bozeman. But diagnosing and forecasting the transition from a warm core to a cold core system, or vice versa, remains a challenge.

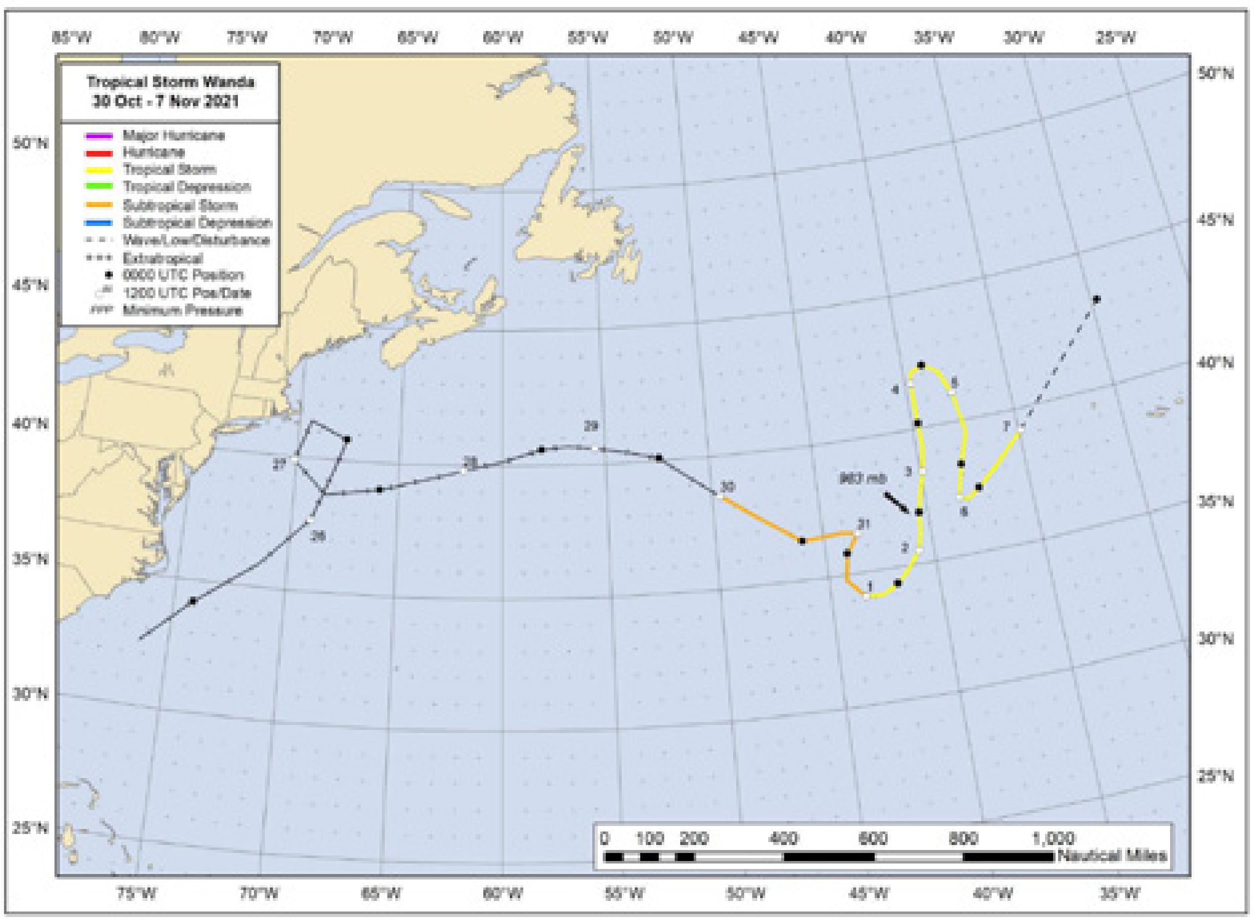


Suomi NPP Visible Infrared Imaging Radiometer Suite (VIIRS) captures a mature extratropical cyclone over Hudson Bay on August 10, 2016. Extratropical cyclones are fueled by interactions between masses of cold and warm air. Mature extratropical cyclones often feature comma-shaped cloud patterns, like the one seen here, that are the product of conveyor belt circulation—airstreams that transport warm, moist air northward, cool air westward, and cold, dry air counterclockwise around a low-pressure system. Credit: NASA Earth Observatory.

Galina Chirokova leads a team at the Cooperative Institute for Research in the Atmosphere (CIRA) that is using ATMS-MiRS retrievals to help forecasters diagnose extratropical transitions (MiRS is a satellite retrieval algorithm that makes it possible to reconstruct the 3D structure of a storm with ATMS data). CIRA's JPSS Extratropical Transition (JET) application provides forecasters with information to help them recognize extratropical transitions using a real-time imagery display that shows ATMS-based time series plots. CIRA is also developing a machine learning classification model (JET Class, which stands for **J**PSS **E**xtratropical **T**ransition **Class**ification) to diagnose storm type in real-time using information from JPSS data.

Two examples that use ATMS-MiRS microwave data to identify the extratropical transition of a cyclone are shown on the following page. The first shows post-processed ATMS-MiRS rain rate plotted on a cylindrical grid for Typhoon Kulap in 2022. The precipitation pattern becomes more asymmetrical as the cyclone transitions from tropical (left plot) to extratropical (right plot), with precipitation mostly confined to the north as cold air cuts off the rising motion to the west and south.

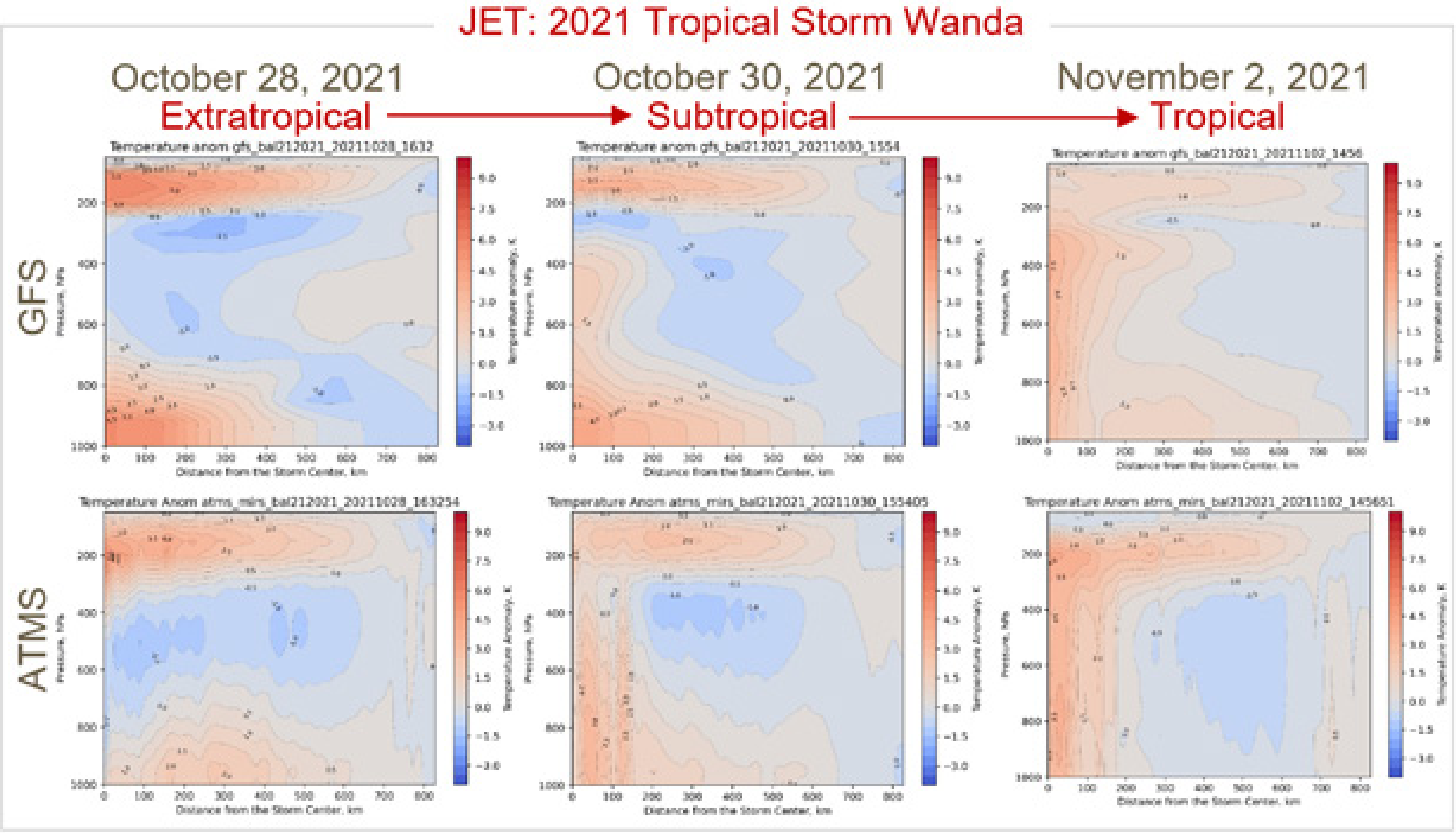




Best track positions for Wanda, October 30 to November 7, 2021. Tracks during the extratropical stage are partially based on analyses from the NOAA Ocean Prediction Center and the NOAA Weather Prediction Center. Source: National Hurricane Center.

The second example, Tropical Storm Wanda, was a curious case. This erratic and powerful nor'easter started as a cold core extratropical cyclone, bringing hurricane-force winds, heavy rainfall, and flooding to parts of New England in late October 2021 that left more than 600,000 people without power. Later, the system became a subtropical cyclone and moved away from the U.S., eventually undergoing a transition to a warm core tropical storm over the open waters of the north Atlantic Ocean (track shown above). "This is rather unusual," Bozeman explains. "More often, storms start as tropical and transition to [extratropical] as they move to high latitudes."

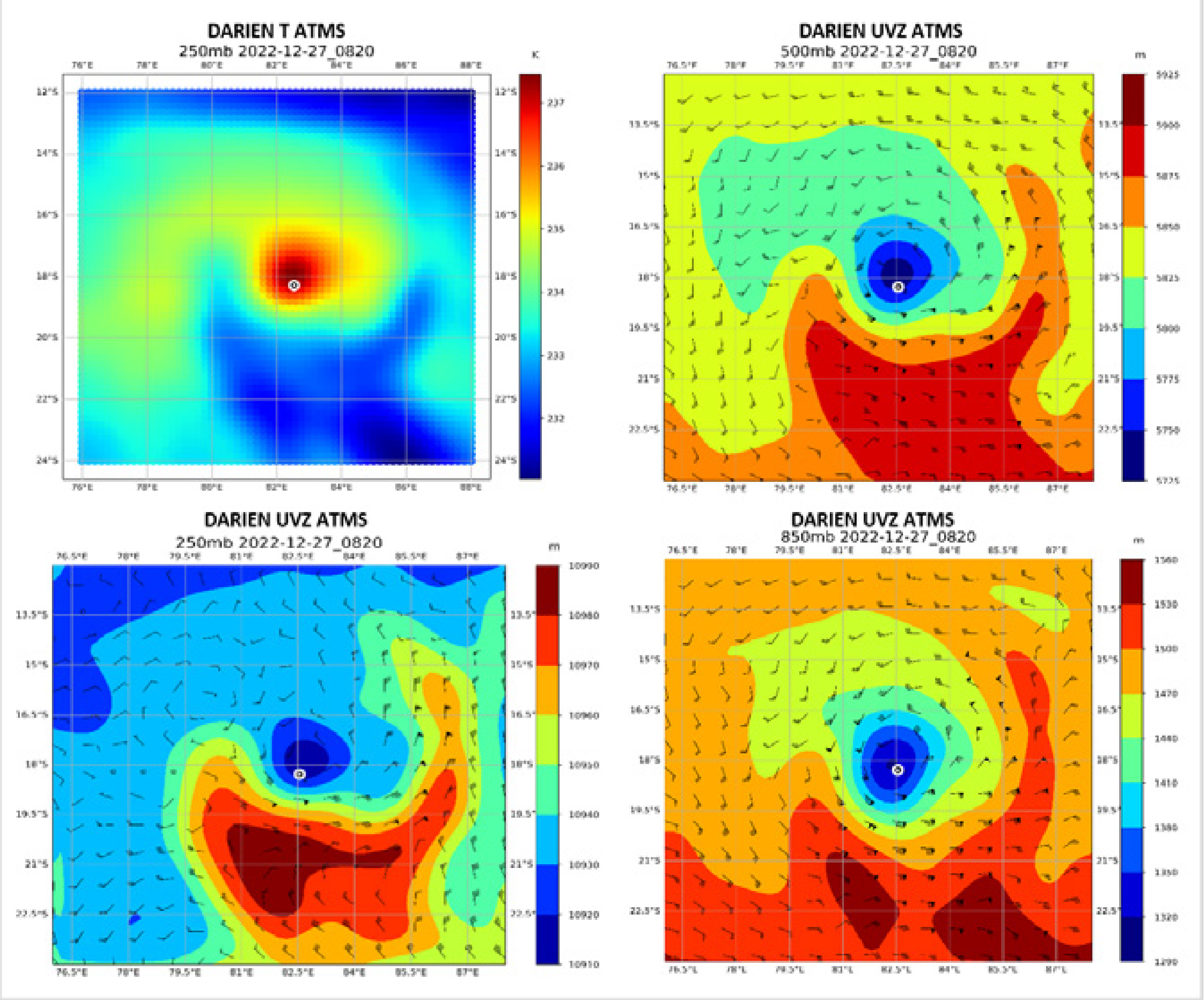
Below is ATMS-MiRS microwave data (bottom row) and Global Forecast System (GFS) model output (top row) collocated with Tropical Storm Wanda, produced using the CIRA JET application. These plots illustrate the difference in timing and location of the cyclone's shift from a cold core to warm core system. As the storm transitions from extratropical to tropical (left to right), cold core temperatures (darker blue) begin to decrease as there is a shift to warmer temperatures, shown in light blue and orange-red colors in the plots on the right. "This is why ATMS is important for bringing in more data to identify the core temperature and, therefore, the storm type," affirms Bozeman.



Forecasting tropical cyclone intensity, particularly rapid intensification, is also a challenge. In 2004, CIRA developed the Hurricane Intensity and Structure Algorithm (HISA) to estimate cyclone intensity and structure using microwave temperature profiles from AMSU onboard NOAA-15 and -16 satellites. The HISA system has since undergone several updates, and operational versions now include temperature and Cloud Liquid Water retrievals from microwave sounders on seven polar-orbiting satellites, including ATMS on Suomi NPP and sounders on MetOp satellites. Additionally, efforts are underway to adapt HISA to work with NOAA-20 ATMS-MiRS retrievals.

HISA provides gradient wind data as a function of height and distance from the tropical cyclone center, 3D horizontal winds, geopotential height (the height above sea level of a pressure level), and temperature—data that are especially helpful when radar and aircraft reconnaissance are not available. These data are used as inputs for CIRA's JET application and to provide tropical cyclone intensity estimates. A demonstration is shown below for Tropical Cyclone Darien in the Indian Ocean on December 27, 2022. These plots generated with HISA show temperature at 250mb (top left) and geopotential height and horizontal winds at 500mb (top right), 850mb (bottom right), and 250mb (bottom left).

HISA: 2022 Tropical Cyclone Darien

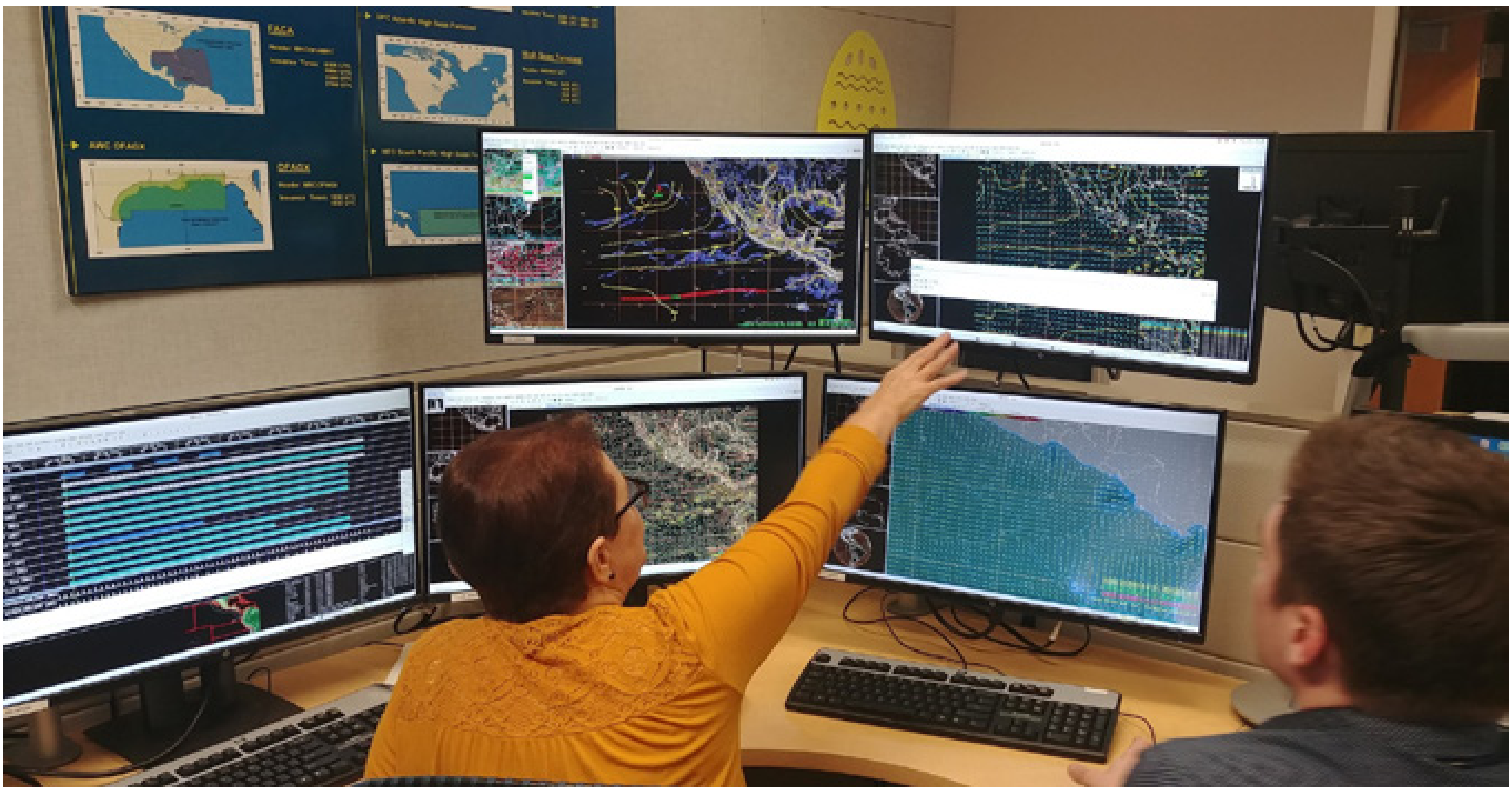


These and other new applications being developed at CIRA will enhance the precision of storm location, intensity, and structural forecasts. Tropical cyclone tools are available through CIRA, where operational collaborators and forecasters at institutions like the National Hurricane Center, Weather Prediction Center, Joint Typhoon Warning Center, and others can assess them and provide valuable feedback. After successful evaluation, the products can then be considered for integration into NOAA's forecasting operations.

THE PATH TO OPERATIONS

Forecaster feedback is essential for fine tuning algorithms, products, and datasets to meet the needs of the forecasting community. Bozeman notes that NRL, CIMSS, and CIRA have plans to make their tools available via web browser to forecasters at the NWS National Hurricane Center and Central Pacific Hurricane Center and the Navy's Joint Typhoon Warning Center. Some products will also be available in the National Hurricane Center's Hurricanes & Ocean Testbed, which includes a cloud platform that can display experimental products in AWIPS II without interfering with their operational AWIPS II systems. This will enable inter-office testing and forecaster engagement, and give NRL, CIMSS, and CIRA the ability to host product demonstrations. Additionally, it will establish a crucial feedback loop between product developers and users, a vital component for iterative improvements throughout the development process.

As of now, JPSS data continues to be added to AWIPS II, and NRL, CIMSS, and CIRA are leveraging relationships with the NWS AWIPS Program Office and Office of Central Processing, as well as the Total Operational Weather Readiness - Satellites (TOWR-S) group, for their AWIPS expertise to enable the processing of low Earth orbit data in more AWIPS II-friendly formats.



Gladys Rubio, a meteorologist with the Tropical Analysis and Forecast Branch of NOAA's National Hurricane Center in Miami, Florida, works with the latest AWIPS display during testing phases.

IN CONCLUSION

The tropical cyclone applications being developed by NRL, CIMSS, and CIRA using low Earth orbit observations and advanced data analysis techniques will significantly contribute to improved tracking and forecasting of tropical cyclones. Their innovative tools provide meteorologists with real-time, high-quality data, helping to enhance the accuracy of tropical cyclone predictions. Organizations like these are essential in strengthening the scientific foundation for tropical cyclone research and bolstering our capacity to mitigate the impact of these extreme weather events.

The benefits of using JPSS and other low Earth orbit observations in tropical cyclone operations are substantial. Microwave sounders and other polar-orbiting satellite sensors supply vital data on atmospheric processes and conditions that influence cyclone formation, intensification, structure, and movement. This information is instrumental in operational settings for issuing timely and accurate storm warnings, enabling informed decisions about evacuations and resource allocation, and facilitating efficient coordination and response efforts during and after a cyclone's impact. Such data can also enhance the precision of cyclone tracking, contributing to better community preparedness. As more polar-orbiting satellites are launched in the coming decades, the data record for microwave sounders like ATMS will expand, leading to continued improvements in the early detection of cyclone formation and intensification. ✦

STORY SOURCE

The information in this article is based, in part, on the July 17, 2023, LEO Science Seminar titled "Tropical Cyclone Analysis and Forecast Improvements Using JPSS Data and Products" presented by Monica Bozeman, JPSS PGRR Tropical Cyclones Initiative Facilitator, NWS Office of Central Processing, Silver Spring, MD, with contributions from Dr. Anthony Wimmers and Derrick Hernon (Cooperative Institute for Meteorological Satellite Studies (CIMSS)/University of Wisconsin – Madison), Galina Chirokova, Dr. Yijie Zhu and Dr. Mark DeMaria (Cooperative Institute for Research in the Atmosphere (CIRA)/Colorado State University), Dr. John Knaff and Dr. Chris Slocum (NOAA NESDIS), and Chris Selman and Dr. Justin Bobak (U.S. Naval Research Laboratory).

FOOTNOTES

1 As of October 2023.

2 The Direct Broadcast Network is a worldwide network of local receiving stations that allows for real-time acquisition and rapid delivery of polar-orbiting satellite data to the global user community.

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FEATURE 9

Revealing the Night Sky:

Using VIIRS Data to Detect and Characterize Natural Gas Flares

Flares burn at sunset in the Bakken oil and gas fields in North Dakota. Photo: J. Peischl, NOAA/CIRES.

A flare stack at a wellhead. Source: South Coast Air Quality Management District.

Flaring—the controlled burn of natural gas that is a byproduct of the oil extraction process—has been occurring since modern oil drilling began in the mid-1800s. Flaring remains popular to this day at onshore and offshore oil fields as a relatively safe way to depressurize equipment and handle unpredictable and significant pressure changes that can occur when extracting oil from wells. But the practice is detrimental and environmentally damaging, adversely affecting the climate and posing risks to human health by emitting significant quantities of methane, a potent greenhouse gas, along with other harmful pollutants.

Efforts to reduce emissions from gas flares require monitoring and measurement capabilities that can be challenging for some producers due to the high costs involved or the impracticality of monitoring in remote or inaccessible locations where many oil and gas wells are situated. Furthermore, relying on reported data to estimate gas flare volume is problematic due to inconsistent reporting practices both within the U.S. and globally, different estimation methods, reporting errors, political instability, and other factors that undermine its reliability.

Satellites offer a global perspective that circumvents several of these limitations, and have played a crucial role in monitoring flares since as early as 1978. By using different spectral bands, satellite sensors can identify and analyze the characteristics of individual gas flares, such as intensity, duration, and location. This capability enables researchers, industry, and regulators to assess the environmental impact of gas flaring, track compliance with regulations, and develop strategies to reduce emissions. As a cost-effective and scalable solution, satellite monitoring allows for frequent and widespread observations that contribute to a better understanding of the global impact of natural gas flaring on the atmosphere and climate.

A range of methods to detect and measure radiant emissions from gas flares using satellite observations have been published, including an algorithm that uses nighttime imagery from the JPSS Visible Infrared Imaging Radiometer Suite (VIIRS) called VIIRS Nightfire. The product was developed by Dr. Christopher Elvidge and others at the Earth Observation Group at the Colorado School of Mines in collaboration with NOAA. At the August LEO Science Seminar, Dr. Elvidge, a Senior Research Associate and Director of the Earth Observation Group, talked about the benefits of VIIRS nighttime imagery, and provided an overview of VIIRS Nightfire capabilities and the group's ongoing efforts to enhance the product.

THE IMPLICATIONS OF NATURAL GAS FLARING

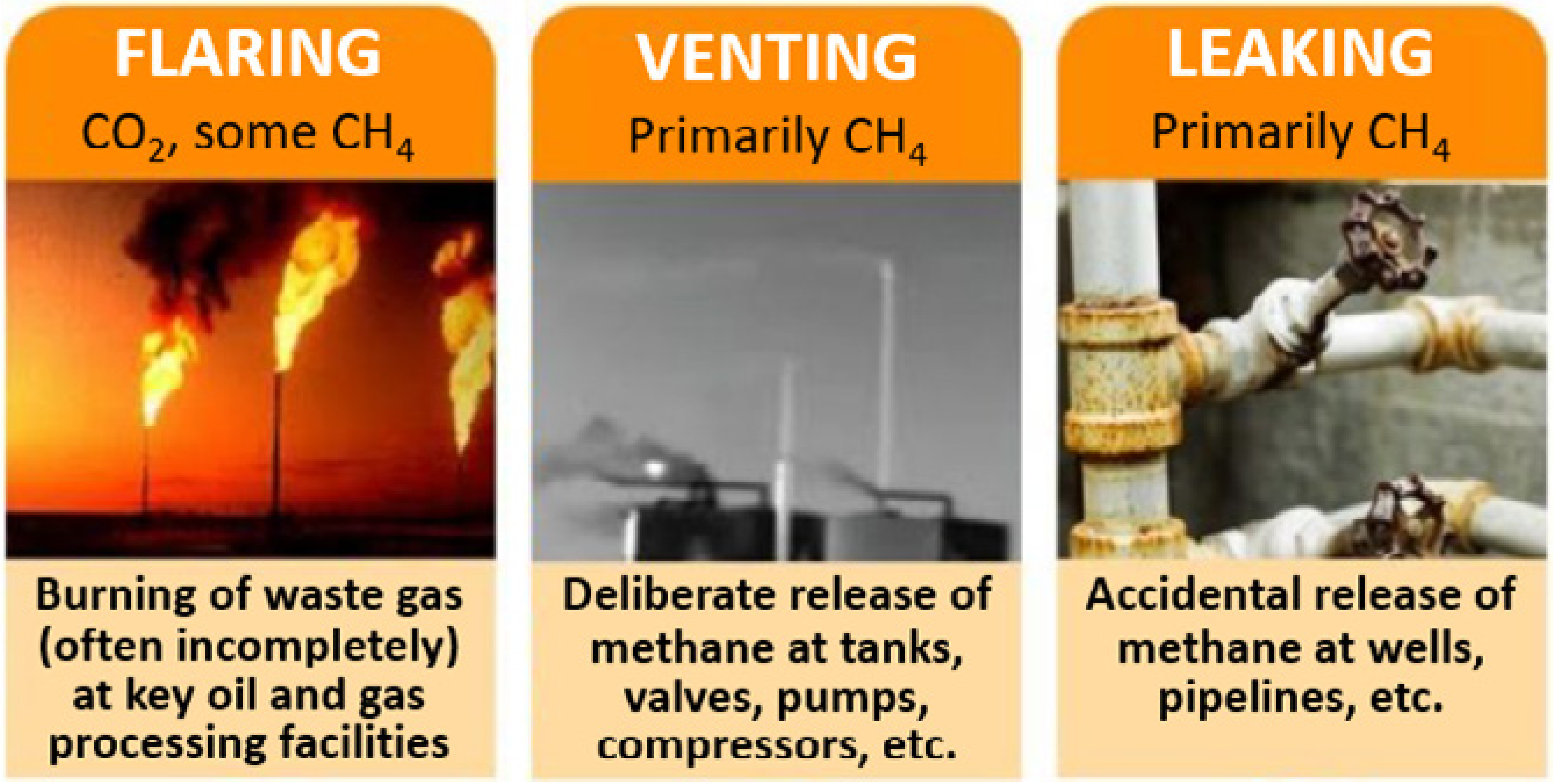
Well operators burn natural gas, composed mostly of methane (70 to 90%), at the wellhead through a flare stack. The gas is ignited at the top of the stack, and the combustion process converts the methane and other hydrocarbons into mostly carbon dioxide and water vapor. A portion of unburned methane is also released to the atmosphere. The amount of methane emitted largely depends on the methane destruction efficiency of the flare. Incomplete combustion can also lead to the release of other pollutants, such as black carbon, sooty black material that is a component of fine particulate matter (PM2.5) air pollution.

Around 10,000 flares at oil production sites around the world burn roughly 140 billion cubic meters (bcm) of natural gas annually. Current estimations indicate this volume results in the generation of more than 350 million metric tons of carbon dioxide equivalent (CO_2e) emissions each year, of which about 12% is unburned methane. But this calculation assumes optimal operating conditions where flares are always lit, function correctly, and achieve a methane destruction efficiency of 98%—the generally assumed rate among industry and government. However, reality often falls short of ideals. There is growing evidence that 98% may be an overestimation because of issues like aging infrastructure, equipment malfunction, leaky valves, wind, and gas impurities, which contribute to incomplete combustion and extinguished flames.

CO_2 equivalent

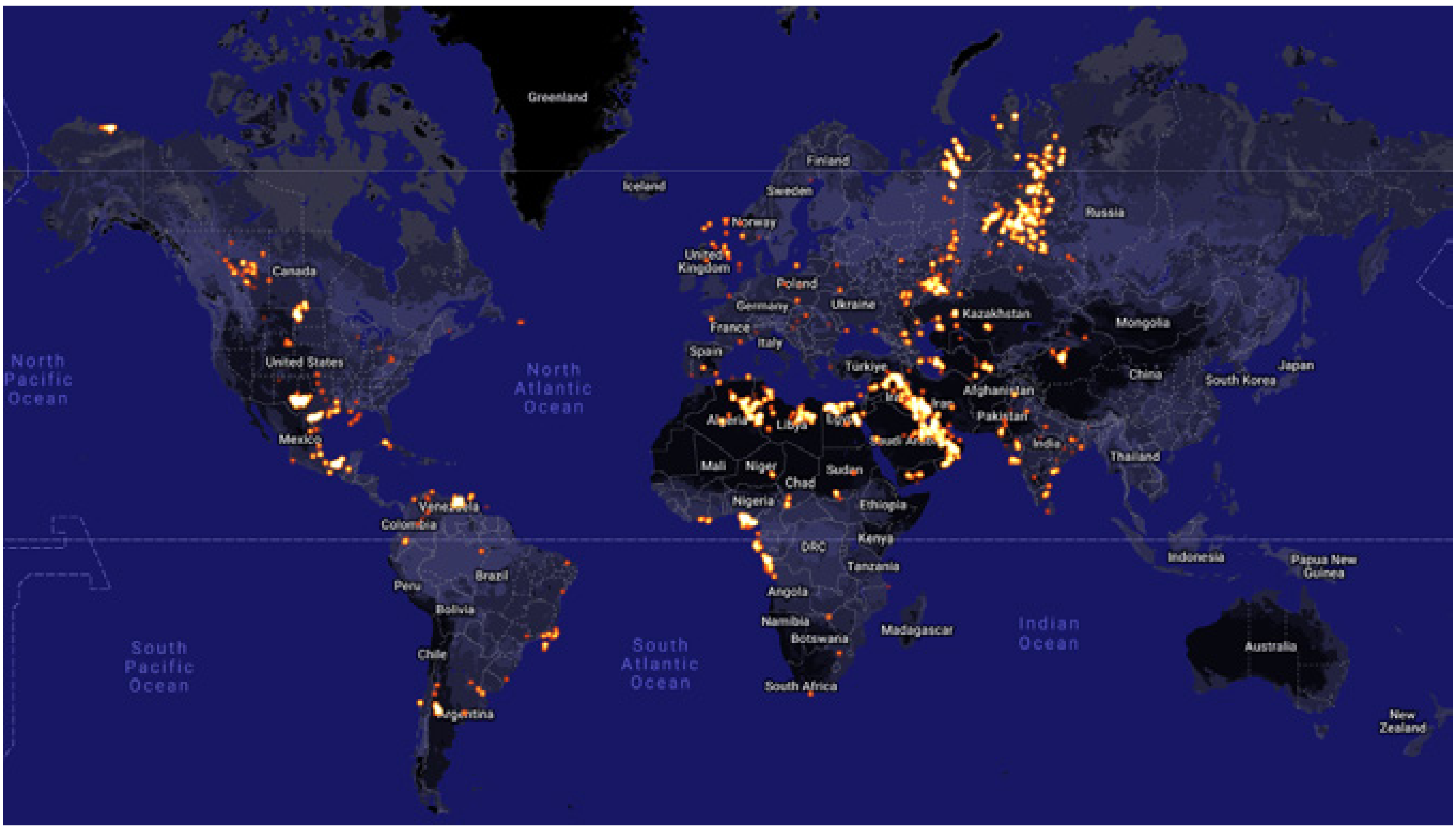
Carbon dioxide equivalent or CO_2e is the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas. It is a way to express the total impact of various greenhouse gases on the climate by equating them to the amount of carbon dioxide that would have the same warming effect.

Sources of Greenhouse Gas Emissions From Oil and Gas Operations



Source: FlareIntel

Several recent studies report effective methane destruction efficiencies in the 87 to 97% range based on direct measurements.[1] One example: Plant *et al.* discovered through airborne sampling of over 300 flares in major U.S. oil-producing regions that natural gas flaring only effectively destroys 91.1% of methane on average, suggesting that methane emissions from such flaring may be up to five times higher than previously thought. Furthermore, the Environmental Defense Fund recently found that about 10% of flares in the Permian Basin—the highest producing oil field in the U.S.—were consistently malfunctioning or unlit and venting methane directly to the atmosphere.[2]



Satellite-detected natural gas flares on March 15, 2023. This map was made using VIIRS Nightfire nightly data produced by the Earth Observation Group, Payne Institute for Public Policy, Colorado School of Mines. Source: https://viirs.skytruth.org/apps/heatmap/flaringmap.html.

The Significance of Methane & Black Carbon

The oil and gas industry is one of the main sources of anthropogenic methane emissions. Methane, a powerful greenhouses gas with a global warming potential about 84 times that of carbon dioxide when measured over a 20-year period, "is responsible for around 30% of the current rise in global temperatures," the International Energy Agency reports.[a] The good news is that the lifetime of methane is short compared to carbon dioxide—about 10 years compared to hundreds of years—which means reducing methane emissions now can help address climate change in the short-term.

Unlike methane, black carbon—a product of the incomplete combustion of fossil fuels, biofuels, and biomass—only persists in the atmosphere for a few days or weeks. Nonetheless, its impact is mighty. Black carbon's warming impact is 460 to 1,500 times more potent than that of carbon dioxide (per unit mass).[b] It is a significant contributor to the melting of polar ice caps, with research suggesting gas flaring emissions could account for around 40% of the annual black carbon deposits in the Arctic.[c] Moreover, exposure to black carbon poses many health risks, including respiratory and cardiovascular disease, cancer, reduced life expectancy, and birth defects.

Addressing the urgent need for emission reductions from natural gas flaring is crucial to limit near-term warming and improve air quality. Mitigating the environmental impact of this practice paves the way for a sustainable and healthier future, emphasizing the interconnected benefits of curbing such emissions for both climate and human well-being.

[a] https://www.iea.org/reports/global-methane-tracker-2022

[b] https://www.ghgsat.com/en/newsroom/natural-gas-flaring/

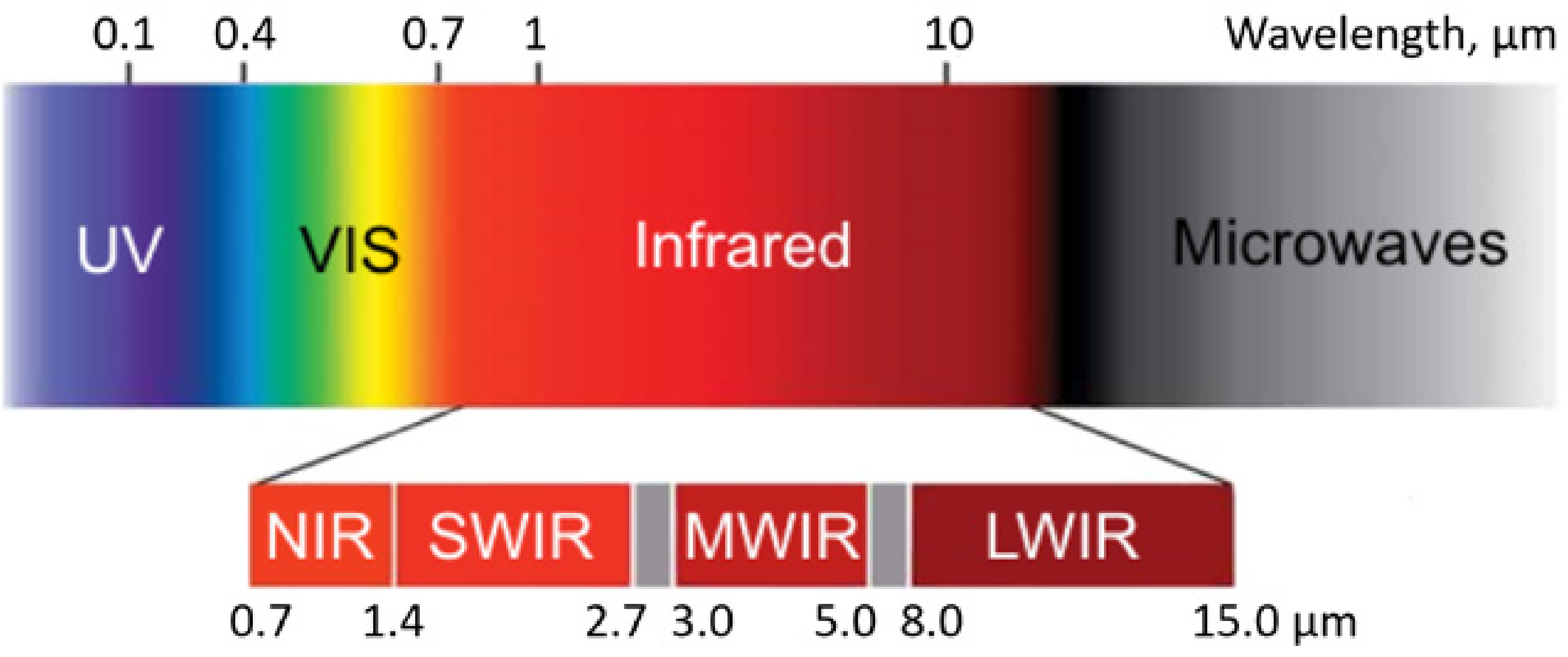
[c] https://doi.org/10.5194/acp-13-8833-2013

The international community has raised concerns about gas flaring, identifying it as a focal point for mitigating the environmental impact of the oil and gas sector. Various global initiatives, such as the Aiming for Zero Methane Emissions Initiative by the Oil and Gas Climate Initiative (OGCI), the World Bank's Global Zero Routine Flaring By 2030 (ZRF) Initiative, and the Global Methane Pledge Energy Pathway, involve commitments from oil and gas companies and governments to reduce emissions or eliminate routine flaring by 2030 through financial and technical support and policy actions.

Satellite data plays a pivotal role in advancing the scientific understanding of gas flaring that is needed to achieve the goals of these initiatives. Instruments like VIIRS enable scientists to analyze and quantify flare volumes with greater precision. This detailed information is crucial for implementing targeted actions to minimize unintentional methane leaks and foster more effective and environmentally sustainable practices.

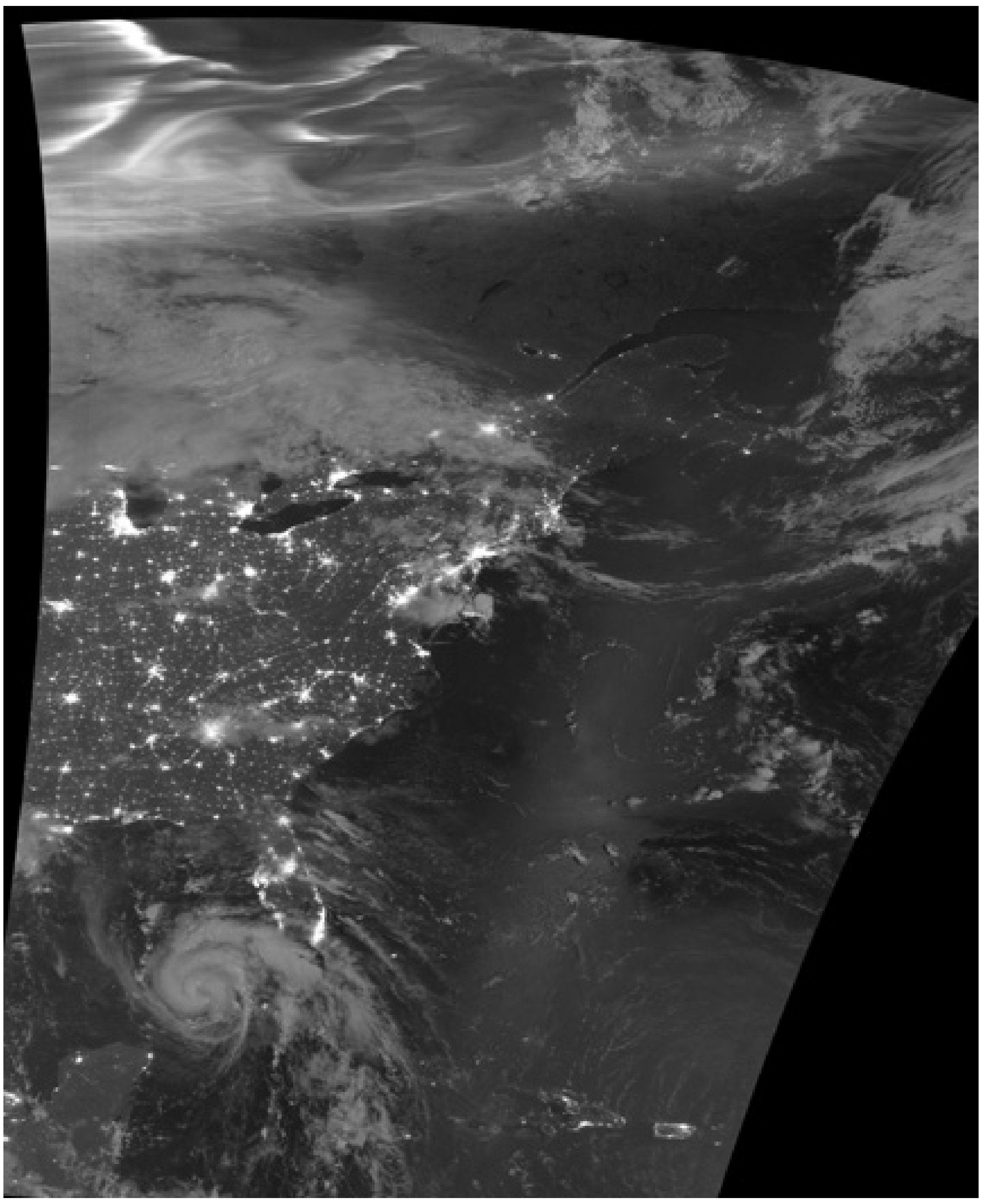
NIGHTTIME IS THE RIGHT TIME

The VIIRS instrument circles the globe in low Earth orbit onboard three satellites in the JPSS fleet: Suomi NPP, NOAA-20, and NOAA-21, launched in 2011, 2017, and 2022, respectively. Having all three on the same orbital plane enables overlap in observational coverage. At the Earth Observation Group, "we work with the data from all three VIIRS instruments," says Dr. Christopher Elvidge, "and we make nightly products, monthly products, annual products, and multi-year products."



Adapted from Photonics Media

Each day, VIIRS collects global imagery across several spectral bands that span visible and infrared wavelengths, a handful of which also collect data at night. Perhaps the most well-known provider of nighttime imagery is the VIIRS Day/Night Band, capable of capturing exceptionally low signals of emitted and reflected light in visible and near-infrared spectrums. The Day/Night Band excels at detecting the faintest sources of light on moonless nights, including fishing boats, wildfires, gas flares, rural and city lights, and even the aurora borealis. But it is four multispectral M-bands that collect data at night in the near-infrared (NIR) to shortwave infrared (SWIR) range that have proven to be the most valuable to Dr. Elvidge for analyzing gas flares.



VIIRS Day/Night Band image from August 28, 2021, showing the Aurora Borealis over Canada, lightning streaks in clouds over Wisconsin, city lights, and Hurricane Ida entering the Gulf of Mexico. Source: Cooperative Institute for Meteorological Satellite Studies (CIMSS).

VIIRS Bands That Collect Data at Night

VIIRS Band	Central Wavelength, µm	Spectral Region
M7	0.87	Near Infrared
M8	1.24	Near Infrared
M10	1.61	Shortwave IR
M11	2.25	Shortwave IR
M12	3.7	Mid-wave IR
M13	4.05	Mid-wave IR
M14	8.55	Longwave IR
M15	10.76	Longwave IR
M16	12.01	Longwave IR
DNB	0.7	Visible/Reflective

While many satellite instruments have NIR and SWIR bands, a lot of times these bands are turned off at night. "VIIRS is unique in that there are two near-infrared and two shortwave infrared channels that collect at night, and that is the real basis behind VIIRS Nightfire," explains Dr. Elvidge. These four VIIRS bands—M7, M8, M10, and M11—can detect the infrared emissions produced by the burning of natural gas in low light conditions—"[the instrument] is not using light intensification, it's recording data in a low light situation," he emphasizes. VIIRS mid-wave infrared (MWIR) and longwave infrared (LWIR) bands also collect nighttime data and can detect some combustion sources. Add to that the highly sensitive Day/Night Band (DNB), and VIIRS becomes an invaluable tool for detecting sources of light for a wide range of uses in addition to monitoring gas flares, like estimating a wildfire's fire radiative power, tracking illegal fishing vessels, assessing power restoration after a storm, estimating population, monitoring conflicts, and more. A list of VIIRS bands that collect data at night is included in the table above.

VIIRS NIGHTTIME DATA IN ACTION

The Earth Observation Group currently focuses on deriving products from VIIRS nighttime data. The image shown here highlights data from three of their products: VIIRS Nightfire (to analyze infrared emissions generated by natural gas flares and background sources of combustion), VIIRS Boat Detection (a multi-year accumulation of offshore vessel detections), and VIIRS Nighttime Lights (measurements of nocturnal light suitable for Earth system science applications).

In VIIRS Nightfire, a lot of filtering is done to separate gas flares from biomass burning. "When you look at VIIRS Nightfire detections around the world, the most common feature that gets detected is biomass burning, but we filter it out based on its temperature and its persistence," says Dr. Elvidge. Gas flares in the Permian Basin region can be seen above as concentrations of red dots in Texas and New Mexico.

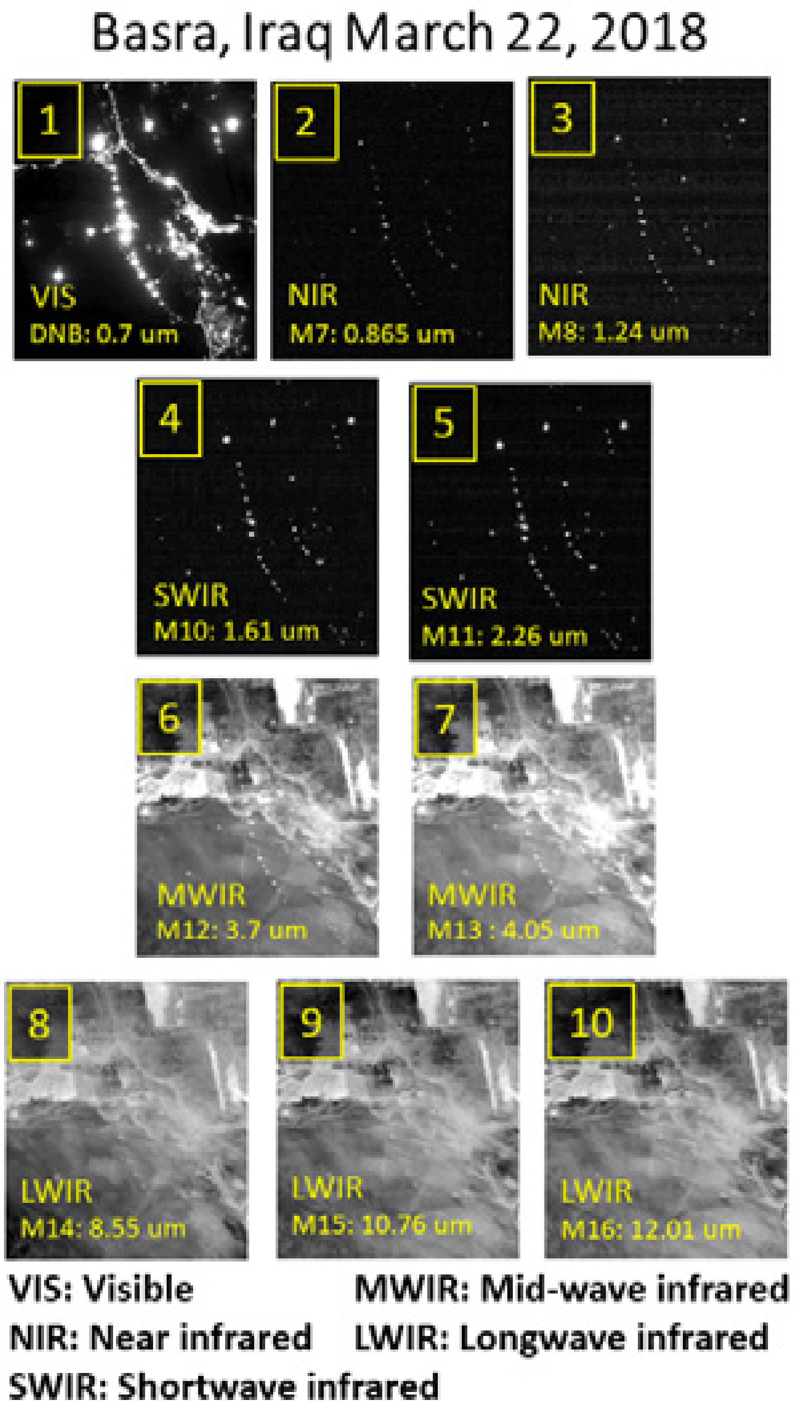
"In the boat detection algorithm, we're specifically trying to find lights out on the water and there are some really interesting things that show up," says Dr. Elvidge. Above, light from clusters of squid fishing vessels can be seen in the waters to the west of South America, and throughout Asia's eastern seas are boats that use lights to attract fish.

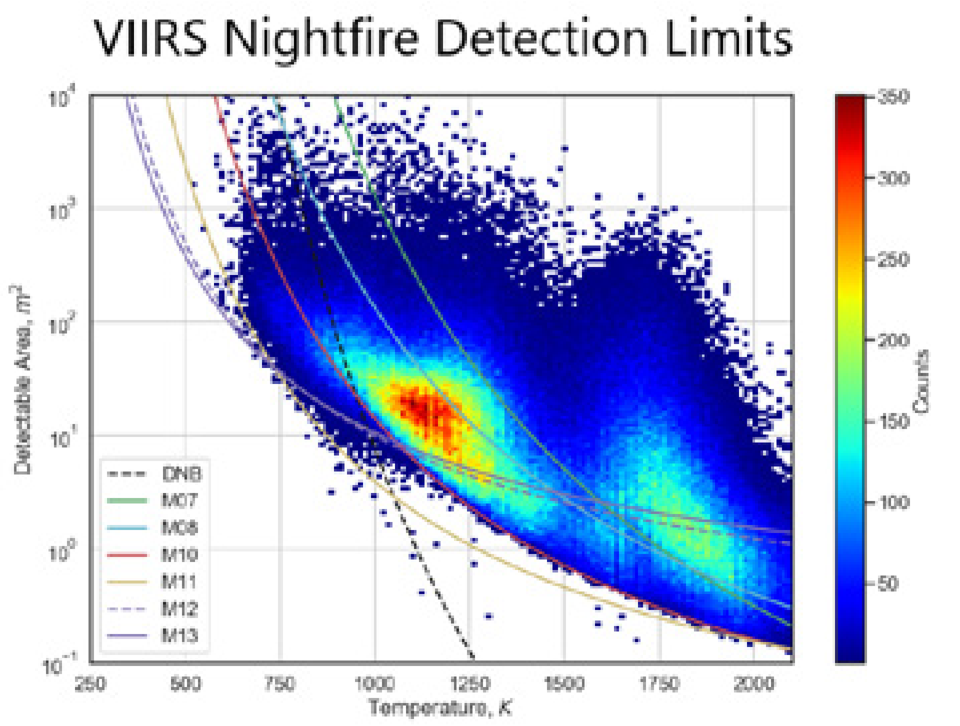
Another interesting feature is a series of faint parallel lines stretching across the North Atlantic Ocean from about Nova Scotia to Northern Europe. These lines correspond with specific flight paths that are assigned to transatlantic jets. Dr. Elvidge believes VIIRS is capturing moonlight being reflected off aircraft, noting, "you won't see this in a single night; it really takes years of accumulation [of data] to begin to see some of these features."

ANALYZING NATURAL GAS FLARING ACTIVITY WITH VIIRS NIGHTFIRE

Gas flares generate intense heat, with typical radiant emissions reaching between 1500 to 2000 Kelvin (2240-3140°F/1227-1727°C). Infrared signals from natural gas flares are strongest in short infrared wavelengths, corresponding well to the detection capabilities of VIIRS SWIR bands. This is demonstrated on the right in VIIRS nighttime imagery of a line of gas flares in Basra, Iraq on March 22, 2018. "You can see the flares very clearly in the near infrared and shortwave IR [#2-5], and you can still see them in the mid-wave IR [#6-7] but they're mixed in with all the other radiance that's coming from the Earth," says Dr. Elvidge. At the longest wavelengths (#8-10), the flares fade away—an expression of Planck's law, explained in the next section. Gas flares are also evident in VIIRS Day/Night Band imagery (#1); however, the Day/Night Band picks up radiant emissions from other combustion sources and artificial light, making it hard to distinguish individual flares.

VIIRS Nightfire uses a combination of complementary spectral ranges—relying mostly on NIR, SWIR, and MWIR bands—to detect and characterize natural gas flares. The graph on the previous page shows the product's radiance detection limits (temperature versus detectable area versus pixel counts), with individual band detection limits indicated by the curved lines. A key takeaway, emphasizes Dr. Elvidge, is that "detection limits from VIIRS are really small for hot objects but not that small for colder objects," making VIIRS suitable for providing detailed, site-specific information about gas flares to aid in monitoring.





Above top: Nighttime imagery from VIIRS bands collected in multiple wavelengths. A line of gas flares is evident in visible (VIS), NIR, SWIR, and MWIR spectral ranges, but is barely detectable in the LWIR range. Above bottom: VIIRS Nightfire detection limits for the VIIRS Day/Night Band and bands M7-13. Source: Elvidge et al, 2019.

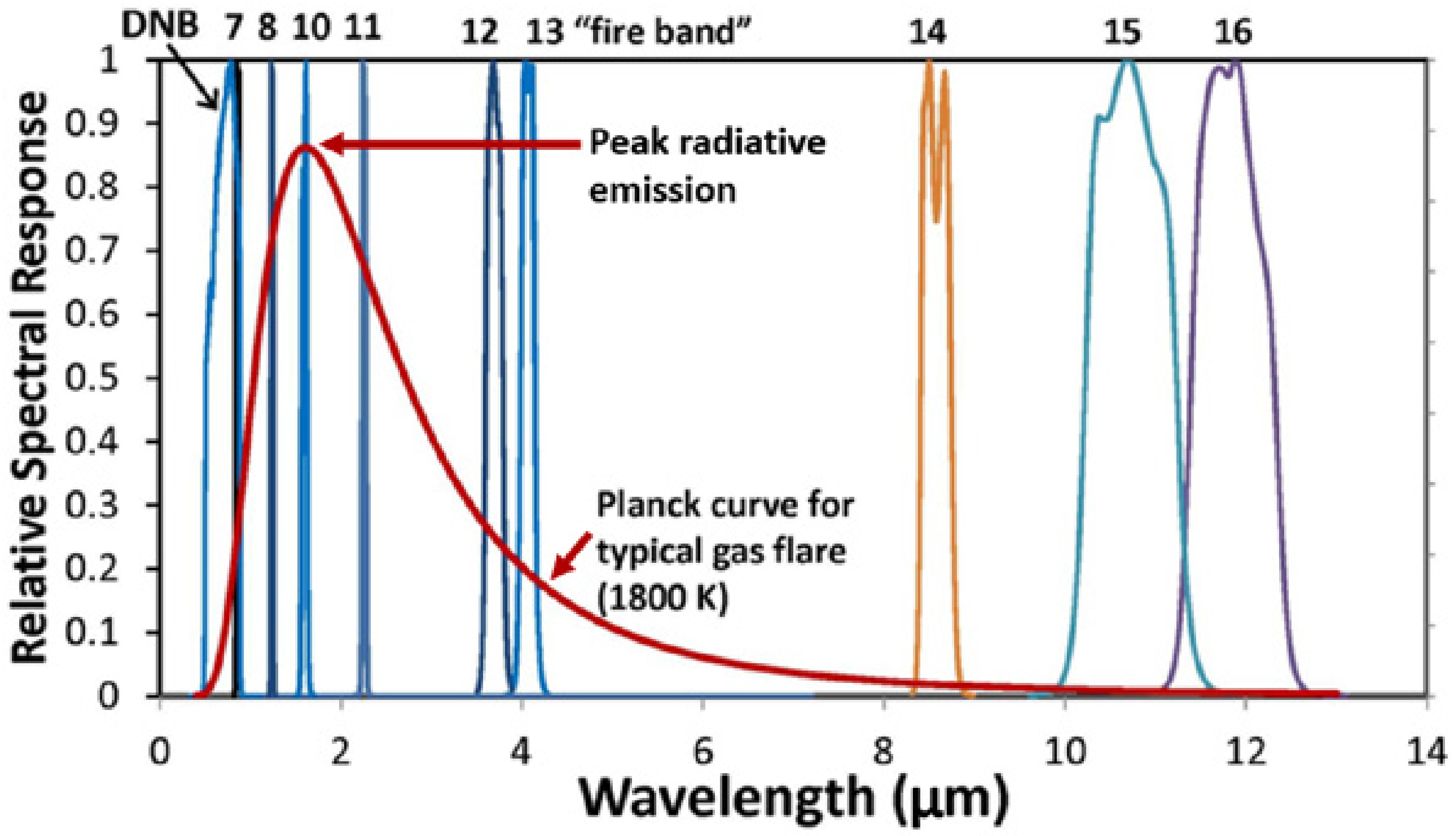
THE RELATIONSHIP BETWEEN TEMPERATURE AND EMITTED RADIATION

For more than a decade, the Earth Observation Group has used nightly data from VIIRS Nightfire to detect, characterize, and track global gas flaring activities. Through a series of complex calculations, VIIRS Nightfire estimates flare temperature, source size, radiant heat, and radiant heat intensity, making use of all VIIRS bands that collect data at night. The process involves fitting Planck curves using signals from VIIRS bands M7-16 to estimate the temperature of hot objects and the cooler background. Once the temperature is determined, other flare characteristics can be calculated.

Planck's Law

Planck's law describes how the intensity and distribution of radiation emitted by a black body (an idealized opaque, non-reflective object that absorbs all incident electromagnetic radiation) depend on its temperature. It states that as the temperature of the object increases, the intensity of emitted radiation increases, and the peak of the radiation shifts to shorter wavelengths.

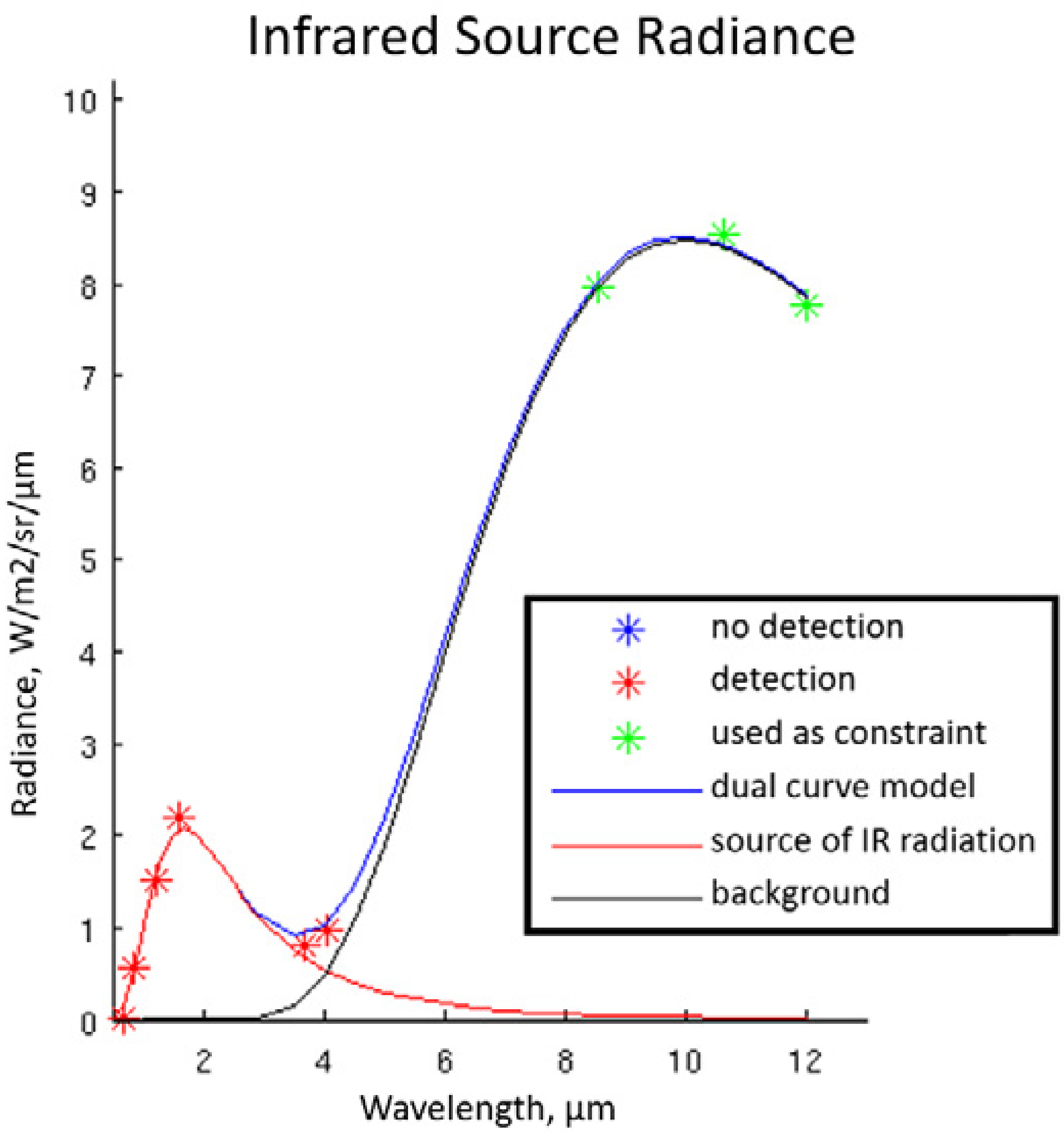
Planck curves illustrate how radiative emissions vary across the electromagnetic spectrum according to Planck's law, providing a mathematical framework to understand the relationship between temperature and emitted radiation. The spectral response of selected VIIRS bands relative to the Planck curve of a typical gas flare is shown on the next page. Peak radiative emission occurs around 1.6 µm (wavelength), which corresponds well to the spectral response of the VIIRS M10 band (SWIR), and to a lesser extent to M8 (NIR) and M11 (SWIR) bands, meaning that these bands are best for detecting natural gas flares at night as indicated in the Basra, Iraq example on the previous page.



Relative spectral response of VIIRS M-bands and the Planck curve of typical gas flares at 1800 Kelvin. DNB refers to the VIIRS Day/Night Band. Source: Elvidge et al, 2016.

Detecting radiance in multiple spectral bands enables the generation of Planck curves that are crucial for distinguishing gas flares from cooler sources of infrared radiation in the background, such as active volcanoes or steel mills. VIIRS measures the infrared radiation emitted by these sources, which each produce a signal with a distinct temperature and magnitude. Using an offshore flare as an example (below), simultaneous fitting of two Planck curves to the spectral response of various VIIRS bands (red and green stars) allows determination of the flare's radiance (red curve) and the background radiance (black curve). The blue line is the sum of the two curves. "One of the advantages of the near infrared and shortwave IR is that we can attribute all that radiance to the hot object [the flare]," explains Dr. Elvidge. "We can't do that in the mid-wave IR because we must allocate some part of [the radiance] to the background and some part of it to the hot object."

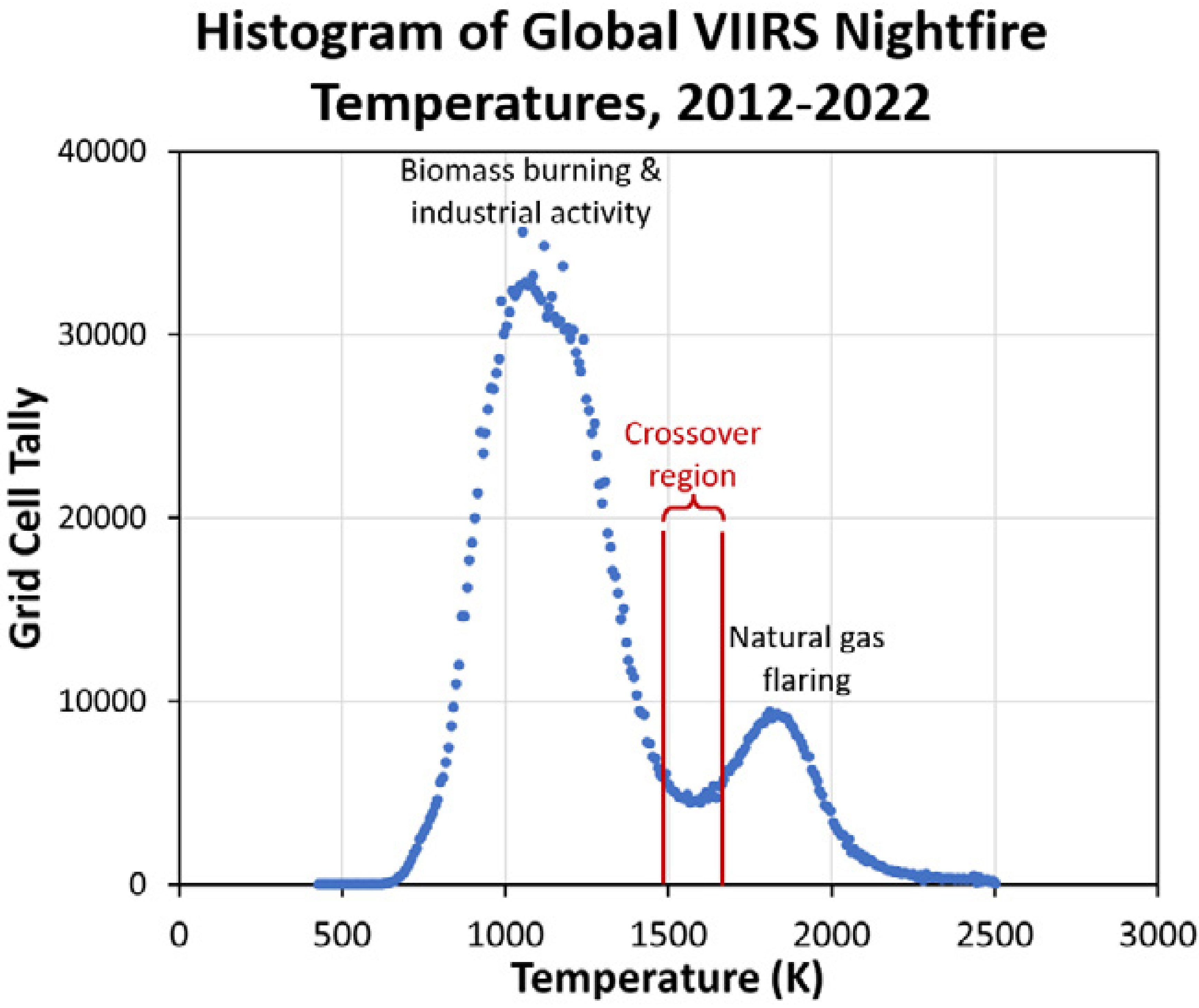
With Planck curve fitting and the application of physical laws, like Wein's displacement law and the Stefan-Boltzmann law, VIIRS Nightfire calculates the infrared emitter temperature, source area, and radiant heat. Gas flow volume is estimated using the amount of heat generated by the flare, which is almost proportional to the volume of gas being burned and calibrated with in situ data.



THE CROSSOVER REGION: DETECTING SMALLER, COOLER FLARES

VIIRS Nightfire retrieves temperatures over a wide spectral range, using mathematical computation to determine which are attributed to natural gas flaring. The exceptionally high temperatures and persistence typically associated with flare combustion make them distinguishable from most industrial infrared emitters and biomass burning, which tend to have relatively lower temperatures. But smaller gas flares can burn at temperatures around 1500-1600 Kelvin, making them hard to discriminate from other intense infrared emitters—extreme wildfires, for example—that are picked up by VIIRS Nightfire in the same range. The result is a bimodal temperature distribution to the detections where gas flares and other combustion sources co-exist in what Dr. Elvidge calls the "crossover region" between peaks.

The following histogram of global VIIRS Nightfire temperatures from 2012 to 2022 shows two peaks that correspond to detections. The small peak at 1800 Kelvin are natural gas flares. The higher peak, around 1000 Kelvin, is dominated by biomass burning, which burns at about half the temperature of methane, along with some industrial activity. Sources overlap in the dip between the peaks. "We have to tease the data apart in this crossover region because there are some areas of biomass burning, particularly savannahs, that burn [at a high temperature] where there is overlap with the temperatures from the gas flares," Dr. Elvidge remarks.

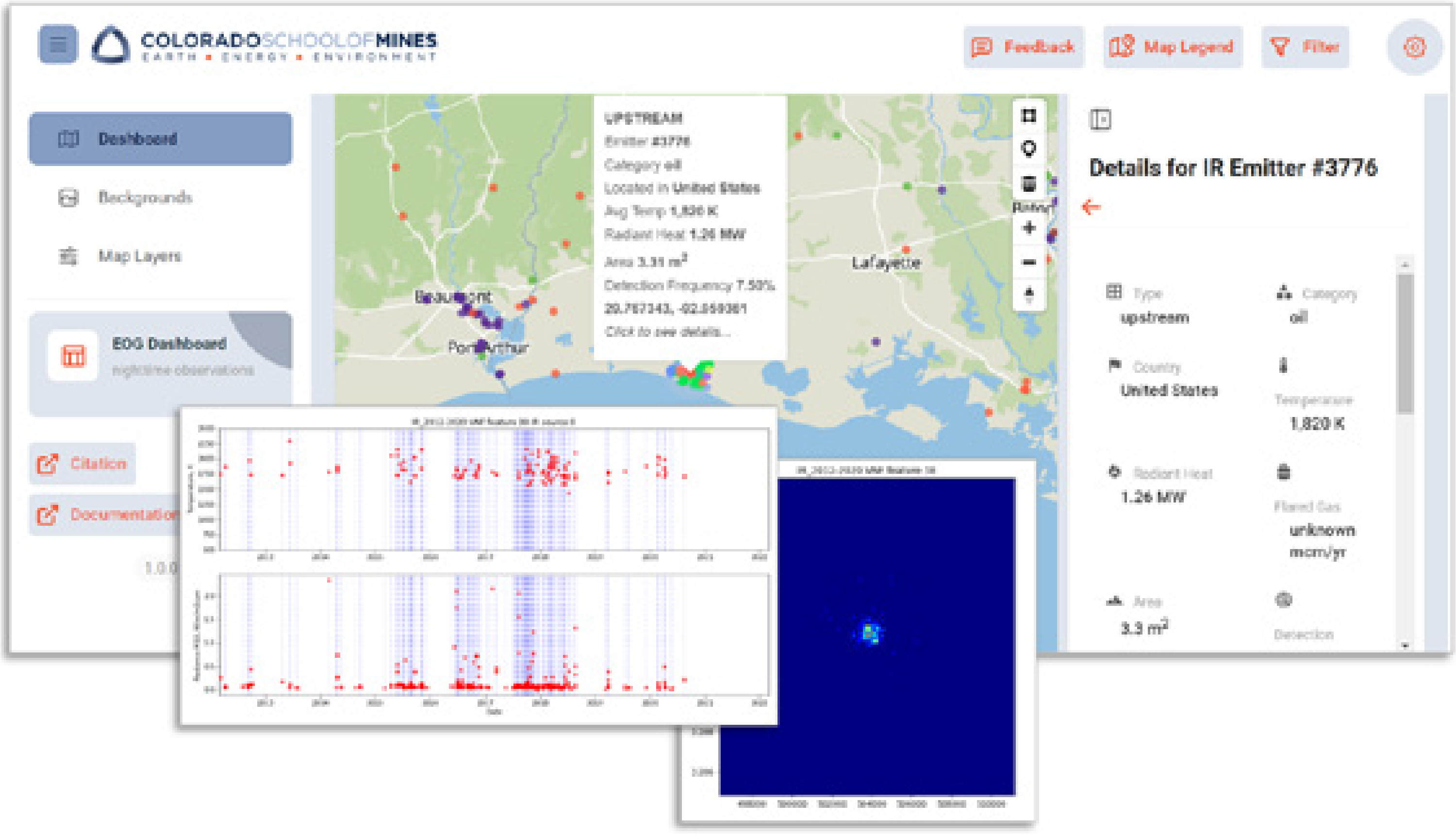


Histogram of global VIIRS Nightfire temperatures from 2012 to 2022 showing the bimodal nature of the detections of these sources.

Screenshot of the Earth Observation Group's Multiyear Infrared Emitter Site Catalog.

The group has developed methods for attributing detections to the proper source—information they have compiled into a multi-year catalog of industrial emitters of infrared radiation, including steel mills, cement factories, landfills, and natural gas flares. "We have about 20,000 sites [cataloged] and have built temporal profiles for each site, which are updated once per week," says Dr. Elvidge. There is the potential for broader use of the catalog beyond the oil and gas sector—Standard & Poor's, for example, uses the data to predict economic activity, while others use it in pollution modeling. Although the consumer base is still in its early stages of development, Dr. Elvidge expresses optimism about the use of his group's data across different sectors.

VIIRS Nightfire operates in near-real time, providing actionable information to users worldwide, with an archive that goes back to 2012. This archive enables scientists and policy makers to track sector trends and climate impacts over time. The archive and other products, including the site catalog mentioned above, an interactive global map of infrared emitters (Global Infrared Emitter Explorer, or GIREE), nightly temporal profiles, and other resources, are available through the Earth Observation Group's VIIRS Nightfire (VNF) Data Products and Services Portal.



Screenshots of the Global Infrared Emitter Explorer (GIREE), the Earth Observation Group's interactive web map service that incorporates data from VIIRS Nightfire.

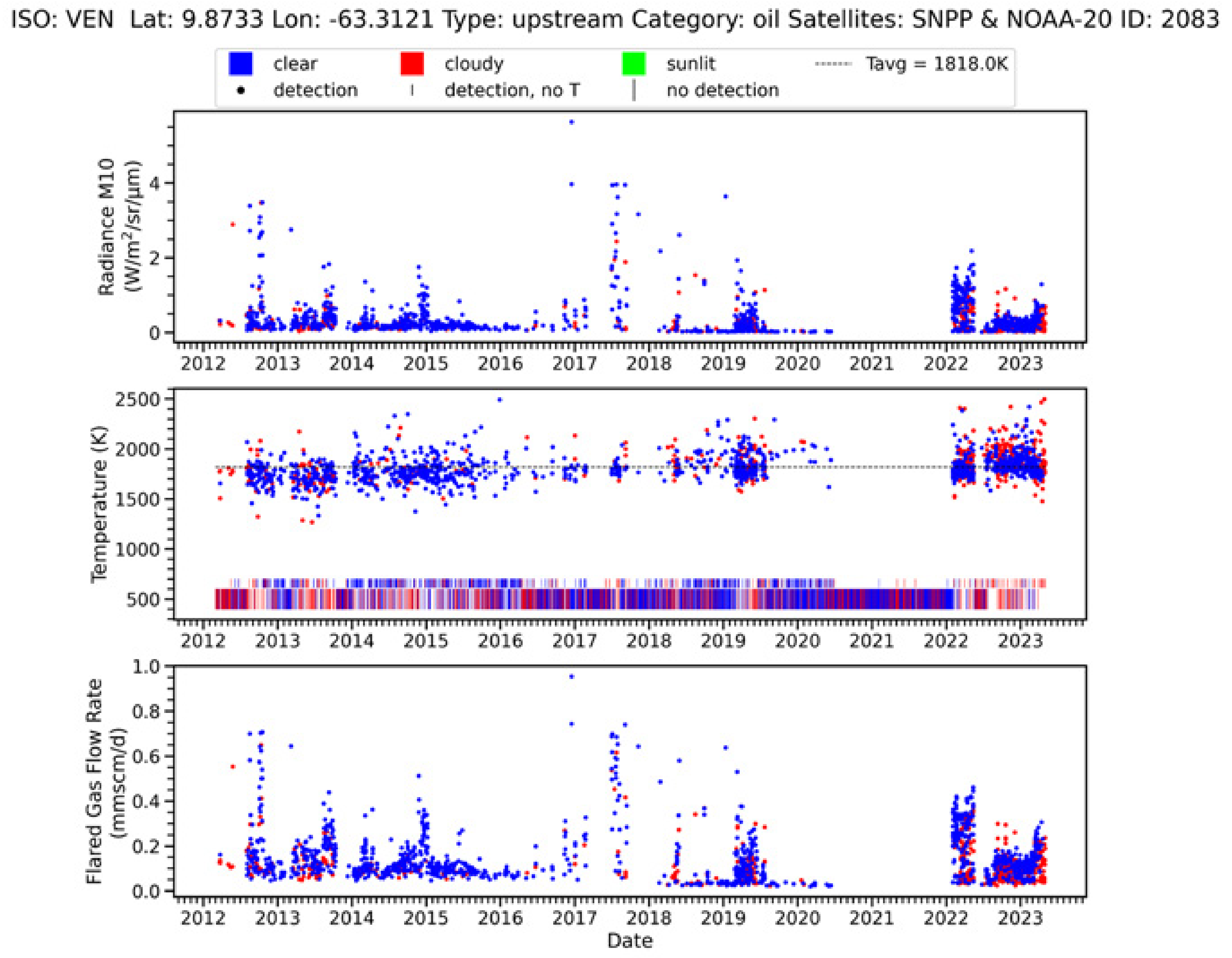
EXPLORING TEMPORAL PROFILES FROM VIIRS NIGHTFIRE

The Intermittent Flare

With data going back to 2012, VIIRS Nightfire temporal profiles help researchers and decision makers better understand changes in flare activity. The profiles are refreshed weekly, providing a long-term record of global flaring activity.

The profile below is for a natural gas flare at a Venezuelan oil refinery that has burned at varying rates—and at times intermittently—for the past decade. The top graph shows radiance at night in the VIIRS M10 band, the middle shows flare temperature, and the bottom graph is the flared gas flow rate. Clear gaps in flaring activity can be seen, most notably in 2021. Intermittent flaring may be the result of equipment malfunctions, maintenance activities, or persistent leaks.

Gaps in activity are significant for operators, says Dr. Elvidge, because when a flare is not burning, there is a possibility that methane is being released to the atmosphere without combustion. "One of the services that we're starting up," he notes, "is a service to alert interested parties regarding flares that we know were active recently, but have gone inactive, so that they might look at them with other instruments and determine whether there is venting [of methane] going on."

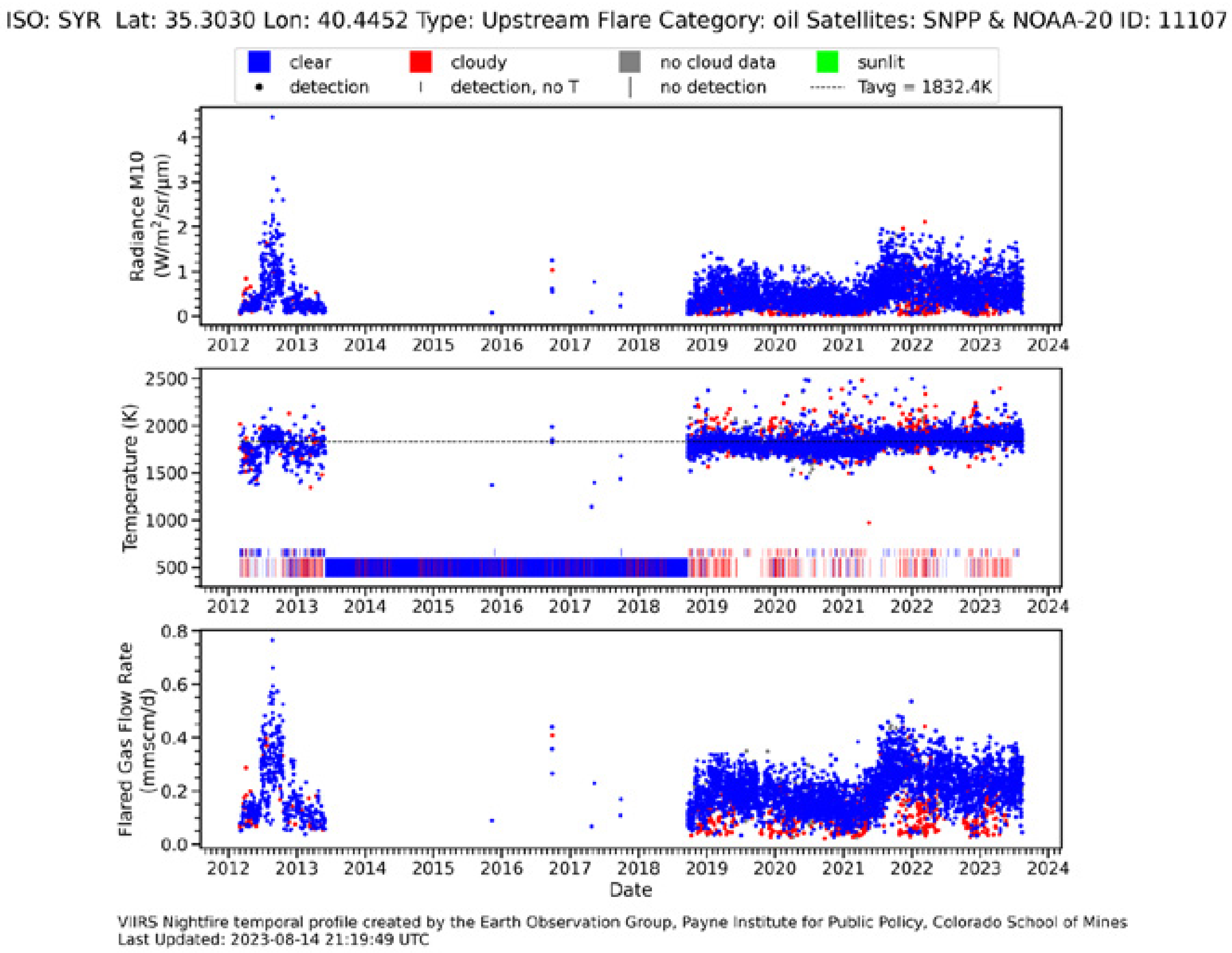


VIIRS Nightfire temporal profile created by the Earth Observation Group, Payne Institute for Public Policy, Colorado School of Mines
Last Updated: 2023-05-01 23:43:21 UTC

The Flare Outage

The lack of a signal from a known and catalogued flare may suggest various causes. Flares may extinguish due to wind, they might be intentionally turned off for regular maintenance or in response to an emergency, or well operations could have come to a halt. In regions with shifting geopolitical structures, like the Middle East, a flare outage could be conflict related.

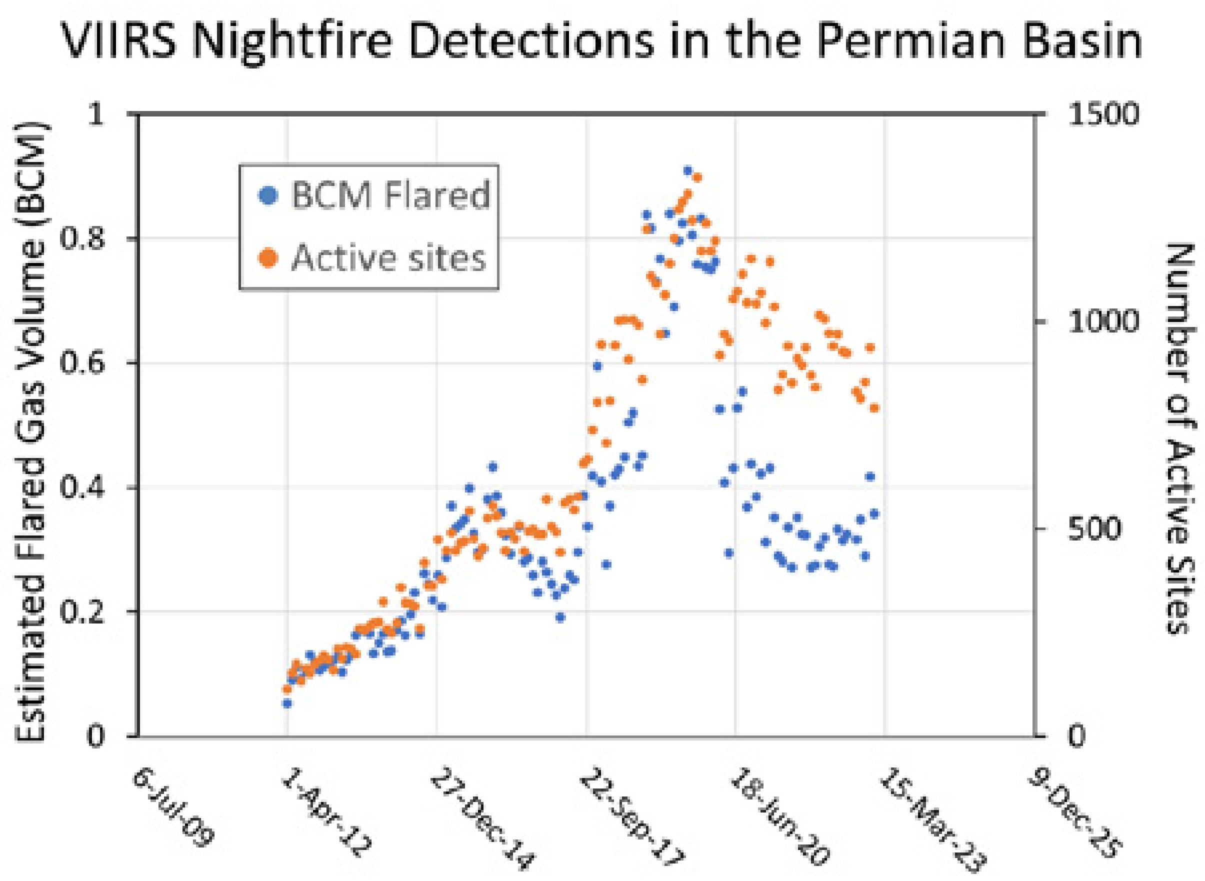
The temporal profile below shows nightly data from VIIRS Nightfire for a natural gas flare in Syria from 2012 to mid-2023. Like above, the top graph is radiance detected in the VIIRS M10 band, the middle is flare temperature, and the bottom graph is flared gas flow rate. Here, temperature consistently hovers around 1800 Kelvin, affirming that the radiance originates from a gas flare. But oil extraction and associated flaring activity stopped in 2013, which is evident in the graphs, around the time that the terrorist organization ISIS expanded its presence in this region of Syria during an ongoing civil war, and resumed in 2018 following the significant loss of Syrian territory by the organization the previous year. "This is a case where we can see a geopolitical impact or a conflict impact on gas flaring," Dr. Elvidge summarizes.



The Permian Basin

Covering a vast expanse of 86,000 square miles in West Texas and Southeast New Mexico, the Permian Basin is host to tens of thousands of producing oil wells. It is the largest oil producing basin in the U.S.

The plot below on the right of monthly flared gas volume from VIIRS Nightfire alongside the number of active sites in the Permian Basin reveals an interesting pattern. Between 2012 and 2019, flared gas volume (represented by blue dots) in billion cubic meters (BCM) and the number of active sites (depicted by orange dots) were generally in sync and following an upward trend, with a slight decrease in both in 2016. However, starting in 2020, a noticeable divergence emerged—while the number of active sites decreased, there was an even greater decline in volume of flared gas. Although the reason for the decline is uncertain, events in Texas around this time indicate a shift in industry practices toward capturing flared gas. In March 2020, the formation of the Texas Methane and Flaring Coalition pledged to eliminate routine flaring by 2030, complemented by more stringent regulations and ongoing investments in methane capture technology and infrastructure by Texas oil companies. "These are the sorts of things we can [infer] when we have a long temporal record," Dr. Elvidge reiterates.



Above (Left): The Permian Basin. Credit: United States Geological Survey. Above (Right): VIIRS Nightfire Detections in the Permian Basin From 2012 to 2019.

IN CONCLUSION

The Earth Observation Group processes about 450 gigabytes of VIIRS nighttime data each day from Suomi NPP, NOAA-20, and NOAA-21 satellites in near-real time with the VIIRS Nightfire algorithm—roughly equivalent to 4.5 million documents. These data are available on their website as a variety of products and services that provide site-specific information for tracking efforts to reduce natural gas flaring worldwide. Currently, the group is rolling out a new version of VIIRS Nightfire that will search for two discrete combustion phases, flaming and smoldering, which could improve emission modeling. "This is an advancement in what can be derived from nighttime multispectral data," says Dr. Elvidge.

Other enhancements are being considered, as well. Right now, the Earth Observation Group's product lines are separated—VIIRS Day/Night Band derived data are used for boat detection and nighttime lights products, while VIIRS Nightfire relies on data from VIIRS M-bands collected at night. But according to Dr. Elvidge, there are times when VIIRS Nightfire cannot detect a natural gas flare, but the Day/Night Band can. "There are fertile grounds for combining the Day/Night Band and VIIRS Nightfire," he says, "and we're really keen on this idea."

Monitoring natural gas flaring is crucial, as it releases significant amounts of methane and other greenhouse gases and pollutants, contributing to climate change and poor air quality. Accurate and real-time global data on flaring enables governments, industry, and environmental organizations to implement targeted strategies for minimizing the effects of flaring on humans and the environment. Moreover, consistent monitoring provides valuable insights into the efficiency of energy production processes. Observations from low Earth orbit instruments like VIIRS will continue to play a pivotal role in monitoring by providing real-time, global surveillance of natural gas flaring activity across vast and remote regions, as well as continuing the record for climate research and economic and technology trend analyses. ✦

STORY SOURCE

The information in this article is based, in part, on the August 21, 2023, LEO Science Seminar titled, "VIIRS Studies of Natural Gas Flaring," presented by Dr. Christopher D. Elvidge, Senior Research Associate and Director of the Earth Observation Group at the Colorado School of Mines, with contributions from Dr. Mikhail Zhizhin, Dr. Tamara Sparks, Dr. Tilottama Ghosh, and Stephen Pon of the Payne Institute of Public Policy/Earth Observation Group at the Colorado School of Mines.

FOOTNOTES

1 See Plant et al. (2022), Gvakharia, A. et al (2017), Schwietzke, S. et al (2014), and LaVoie, T.N. et al (2017).

2 Environmental Defense Fund. (2021). PermianMAP Final Report. https://www.permianmap.org/

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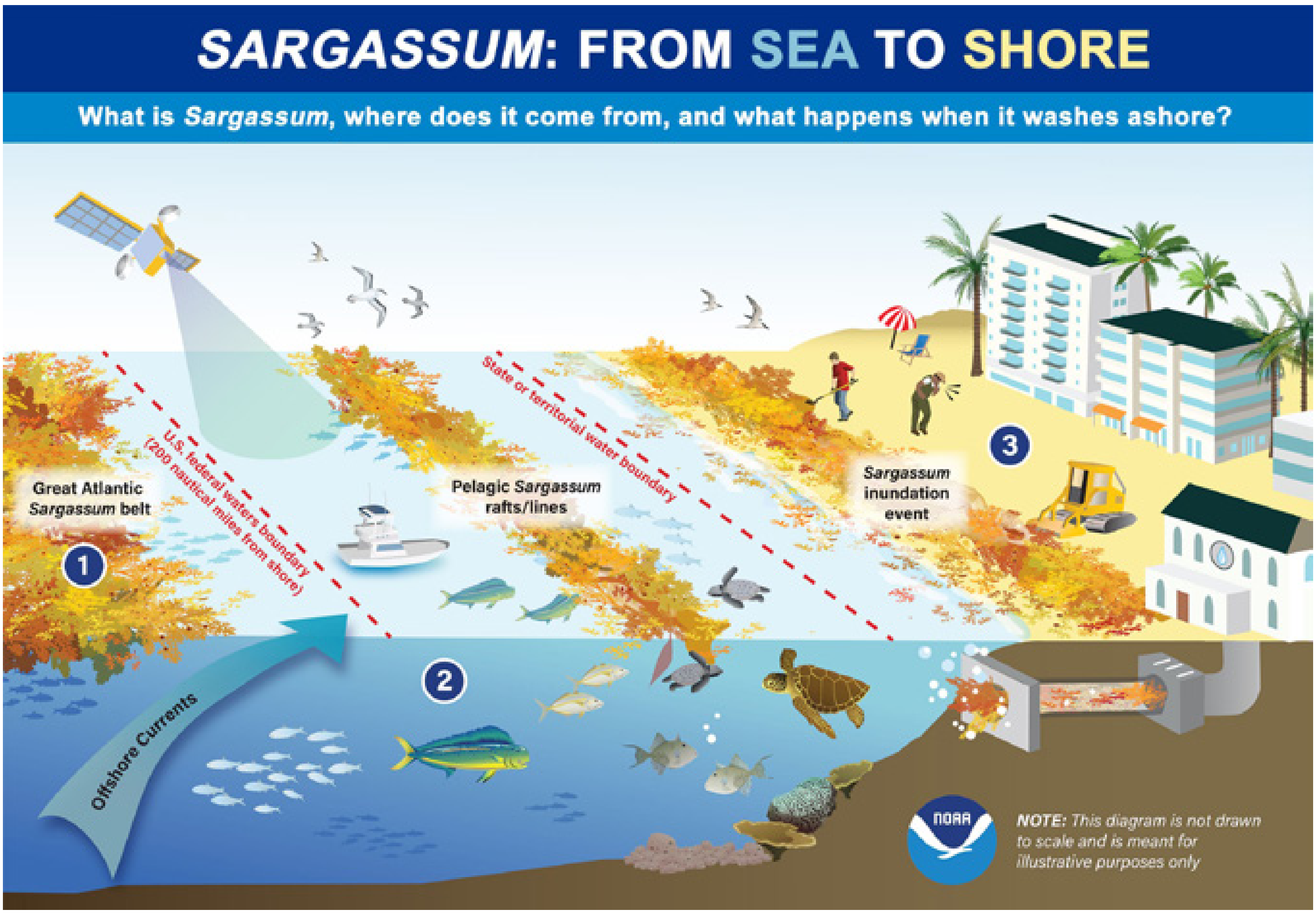
FEATURE 10

Enhancing Detection and Monitoring of *Sargassum* Seaweed Using Low Earth Orbit Observations

A beach on Saint Martin in the Caribbean (east of Puerto Rico) covered in Sargassum seaweed on November 19, 2011. Photo by Flickr user Mark Yokoyama. Used under a Creative Commons license. Source: NOAA AOML.



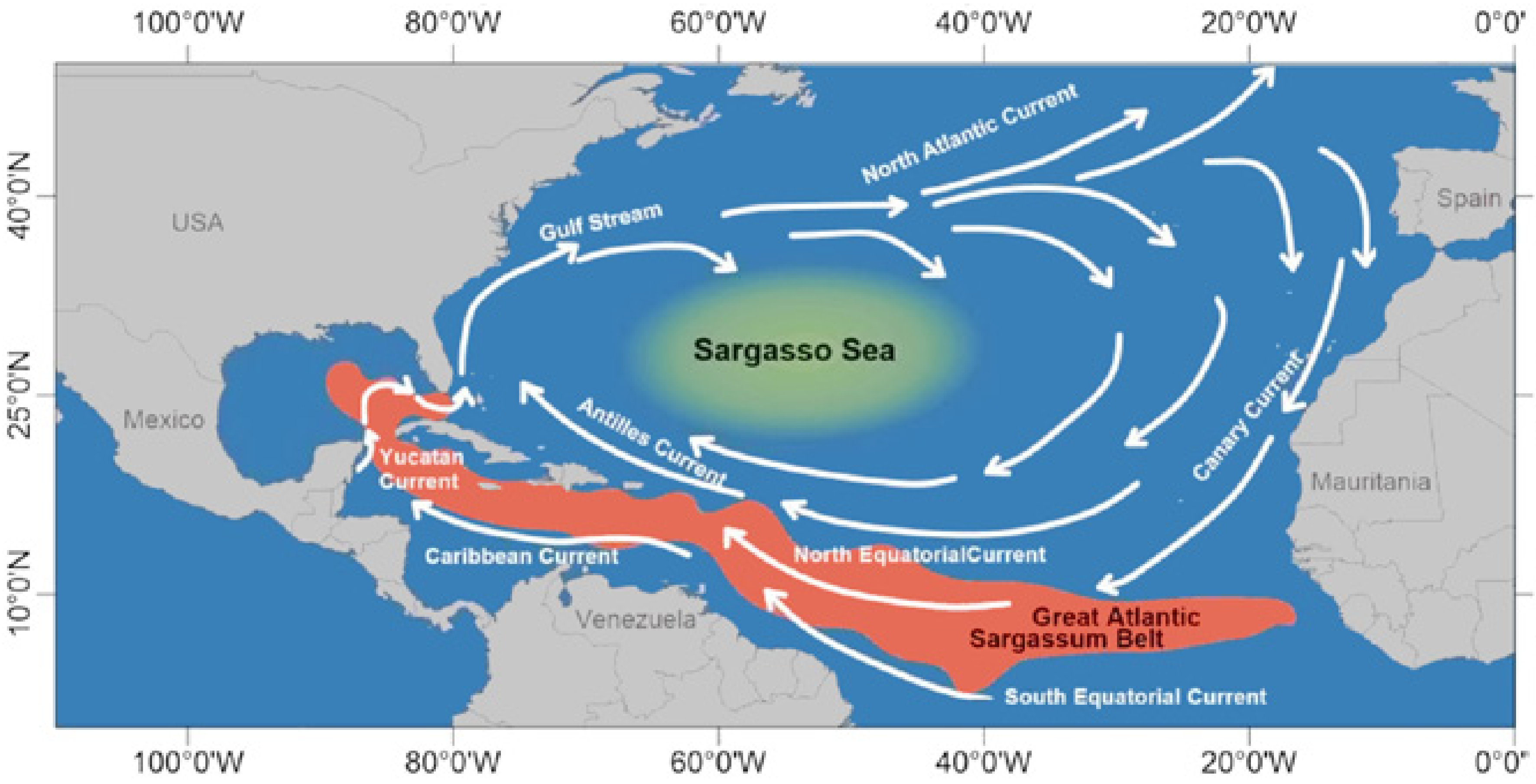
Out in the open ocean, rootless island-like mats of pelagic *Sargassum* seaweed, a type of buoyant brown macroalgae, serve as a refuge, breeding ground, and food source for important fish species, crabs, sea turtles, and seabirds. Occasionally, *Sargassum* makes its way to shore, where, in small quantities, it is beneficial, shielding beaches from erosion and adding nutrients to coastal ecosystems. But *Sargassum* inundation events—when large quantities of the seaweed accumulate in coastal areas or onshore within a short time—can have severe impacts on marine ecosystems and coastal communities.

As *Sargassum* decomposes along shorelines, it consumes oxygen in the water, leading to "dead zones" that can kill recreational and commercially important fish species and harm coastal ecosystems. Large floating mats along coastlines block sunlight below the surface, impacting the survival of seagrass and coral, which in turn affects the availability of food and habitats for other marine organisms. *Sargassum* mats along the shore can also reduce access to coastal waters and entangle fishing gear, leading to lower catch rates and reduced profits for fisheries.

Additionally, the accumulation of decomposing *Sargassum* on beaches—sometimes several feet high—negatively impacts tourism as it emits a foul smell and lessens the visual appeal of the shoreline. By one estimation[1], a bad *Sargassum* year could cause the Key West tourism industry to lose $20 million and 300 jobs in one season, not to mention the expense associated with cleanup (Miami-Dade County, Florida budgets $3.9 million per year for *Sargassum* removal).

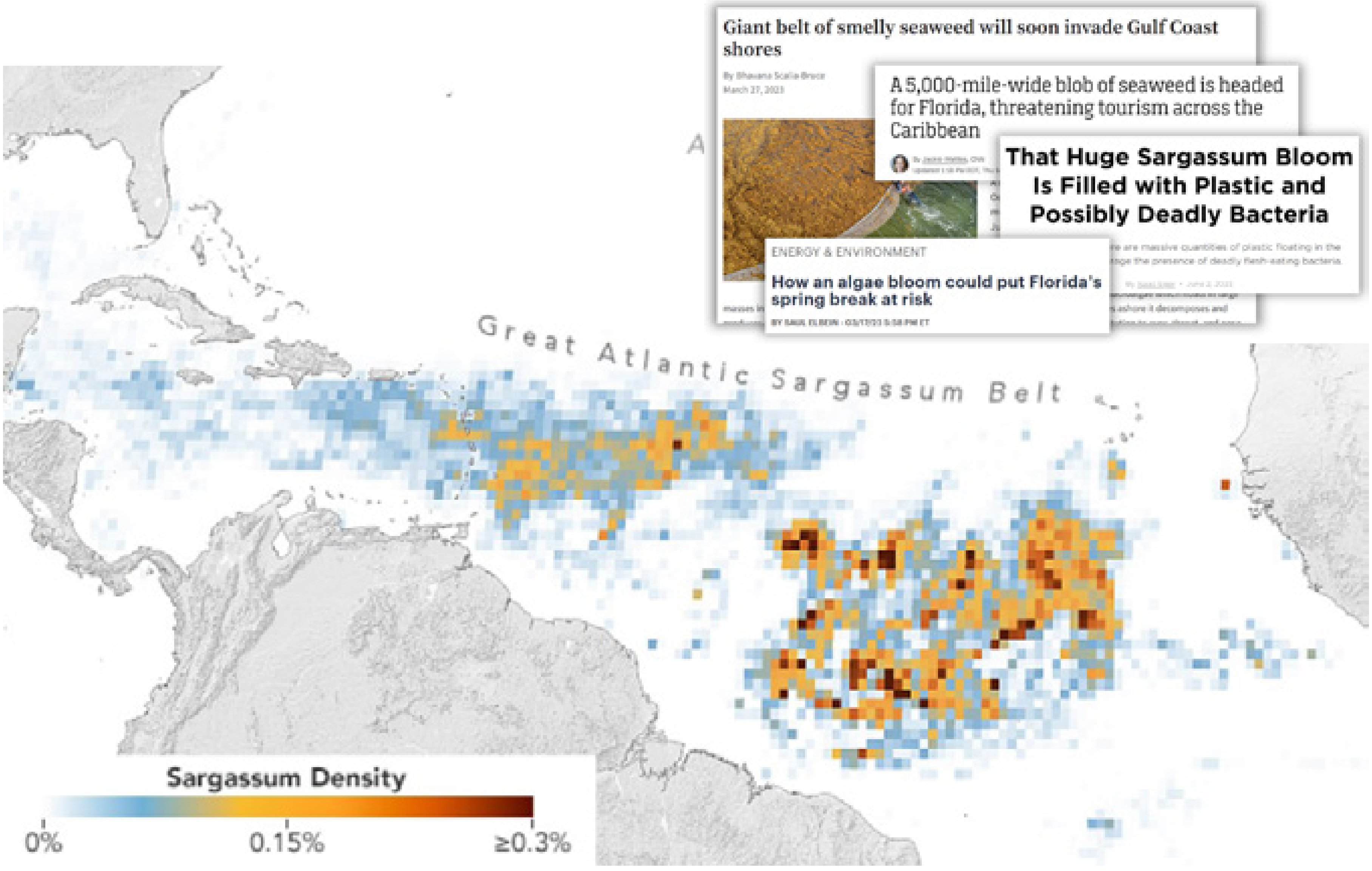
There are health effects, too. Decomposing *Sargassum* gives off hydrogen sulfide gas, which can cause respiratory irritation, heart palpitations, dizziness, and headaches when inhaled. The impact can be substantial: During an eight-month *Sargassum* inundation event in 2019, over 11,000 cases of "acute *Sargassum* toxicity" were reported on the Caribbean islands of Guadeloupe and Martinique.[2] Moreover, *Sargassum* mats have been found to contain *Vibrio* bacteria, the main cause of marine-related mortality in humans, as well as high levels of heavy metals and arsenic.

In 2011, an unprecedented amount of *Sargassum* washed up onto tropical Atlantic beaches, causing public health, economic, and environmental issues throughout the region. This event marked the beginning of a seasonally-recurring dense band of *Sargassum*, known as the Great Atlantic *Sargassum* Belt (GASB), that stretches thousands of miles between West Africa to the Gulf of Mexico and can contain upwards of 20 million tons of *Sargassum* biomass. The GASB, the world's largest macroalgae bloom, wreaks havoc and makes headlines nearly every year when *Sargassum* aggregations break off and overwhelm the coasts of Florida, Mexico, and the Caribbean islands in late spring.



The seasonal Great Atlantic Sargassum Belt stretches from West Africa to the Gulf of Mexico. Credit: López, M.J.L. et al (2021), CC BY 4.0 via Wikimedia Commons.

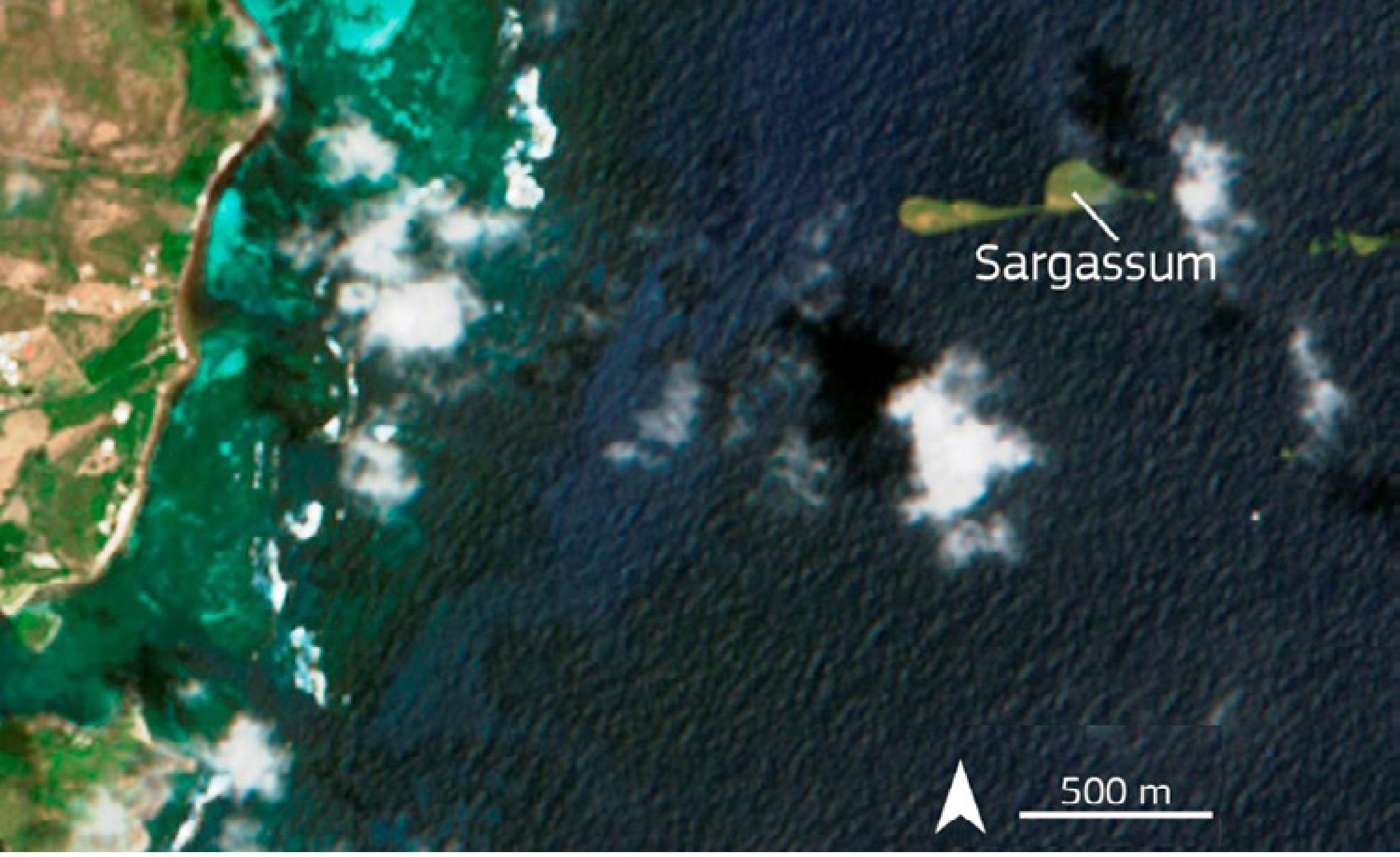
Monitoring *Sargassum* density in the open ocean and predicting its distribution and transport is crucial for helping communities prepare for possible inundation events and protecting vital marine and coastal ecosystems. This is challenging—the GASB is highly dynamic, influenced by physical and biogeochemical factors like wind patterns, ocean circulation, nutrient content, sea surface temperatures, and salinity. The complex interplay of drivers of *Sargassum* abundance, distribution, and transport makes it difficult to predict the seaweed's path, and satellite observations are playing a key role in understanding these factors and improving estimates of where beachings may occur.



The map above shows Sargassum density in the central Atlantic Ocean (including the Caribbean Sea and Gulf of Mexico) for March 2023. Red and orange areas show where Sargassum densities were the highest, in terms of the percent of the pixel covered with the seaweed. The mass spanned 8,000 kilometers and weighed 13.1 million tons (equivalent to 113,000 blue whales!), a record for this time of year. The data for the map were developed by scientists at the University of South Florida Optical Oceanography Laboratory using data from the Moderate Resolution Imaging Spectrometer (MODIS) onboard NASA Terra and Aqua satellites. Source: NASA Earth Observatory.

Researchers use satellites to help track the movement and distribution of *Sargassum* in the GASB, predict its density and coastal impact, and optimize response efforts to avoid wasting resources. While buoys, ships, and drones offer precise high-resolution surface measurements, they have limited range and spatial coverage and routine use for widespread monitoring is impractical. As a complement, satellites excel in observing *Sargassum* mats simultaneously across remote, vast regions of the seas, as they have the advantage of broad spatial and repeating temporal coverage. For example, the JPSS Visible Infrared Imaging Radiometer Suite (VIIRS) offers daily, global coverage, generating valuable data on *Sargassum* in the open ocean. For detection of smaller blooms closer to shore, Copernicus[3] Sentinel-2 satellites shine, providing detailed imagery at a spatial resolution as fine as 10 meters (m), although the revisit time is five days.

At the September LEO Science Seminar, Dr. Joaquin Trinanes, Operations Manager for the NOAA CoastWatch Caribbean and Gulf of Mexico Regional Node and Atlantic OceanWatch Node (an extension of CoastWatch) at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, gave an overview of how satellite sensors are used at NOAA to monitor and track *Sargassum* and challenges in predicting inundation events. Additionally, Víctor Manuel Jiménez Escudero, Associate Academic Technician C at the National Autonomous University of Mexico, discussed innovative efforts to develop satellite-based *Sargassum* detection and inundation prediction models at the National Laboratory for Earth Observation (LANOT) in Mexico.



This image from March 14, 2023, by one of the European Space Agency's Sentinel-2 satellites, captures Sargassum floating off the coast of the island of Martinique in the Caribbean. Credit: European Union, Copernicus Sentinel-2 imagery.

HARNESSING SATELLITE DATA FOR *SARGASSUM* TRACKING AT NOAA

"Satellite observation is instrumental if we want to understand the distribution and the movements of *Sargassum*," says Dr. Trinanes. "[Satellites] can give us very important information, key information about the extent dynamics of the Great Atlantic *Sargassum* Belt (GASB)." Satellite data, for instance, can be assimilated into models to create a time series of inundation risk, which are useful in developing effective *Sargassum* mitigation strategies. "Today we can take advantage of many technological advancements, data integration techniques, machine learning, big data analytics, in order to improve our monitoring capabilities," he explains.

At AOML and CoastWatch, Dr. Trinanes and his team develop and implement tools that apply satellite-based methodologies using data from a combination of satellite instruments, including low Earth orbit sensors like JPSS VIIRS and the MultiSpectral

NOAA CoastWatch

CoastWatch is a NOAA program that provides remotely sensed satellite and other environmental data to government decision makers and academic researchers. Areas of focus include the open ocean and coastal regions. The program is managed by the NOAA National Environmental Satellite Data and Information Service (NESDIS).

CoastWatch data are used for many applications, including *Sargassum* monitoring, biogeography studies, coastal ecosystem monitoring, fisheries support, hurricane operations and research, and to aid in atmospheric forecasting at both global and regional scales.

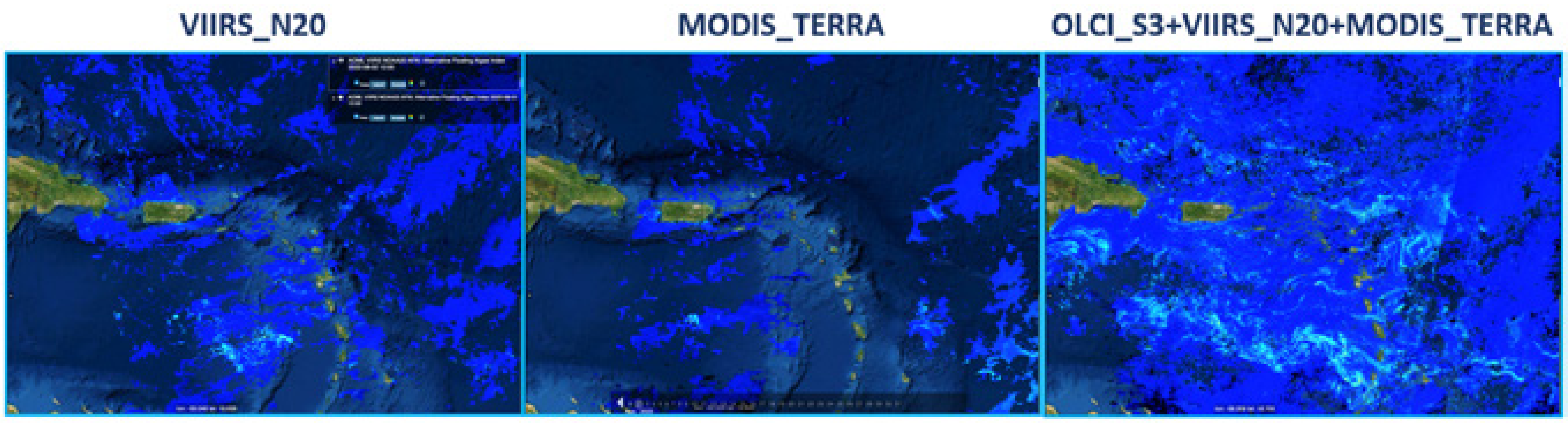
The Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami (FL) hosts both the CoastWatch Caribbean and Gulf of Mexico Regional Node and the Atlantic OceanWatch Node.

Learn more at:
https://cwcaribbean.aoml.noaa.gov/

Instrument (MSI) and Ocean and Land Color Instrument (OLCI) on Copernicus Sentinel-2 and Sentinel-3 missions, respectively. To avoid missing rapid changes, “we need to collect data from different sensors and those sensors should have the capability to provide *Sargassum* related information,” Dr. Trinanes says, noting that a precise combination of spectral bands is required to create parameters for extracting meaningful insights and generating useful indicators, such as the Maximum Chlorophyll Index. Temporal and spatial resolution of satellites are also important to ensure products have optimal coverage for monitoring the GASB. “We want to offer products that can be used in decision making by many types of users, each of them with their unique needs and interests,” emphasizes Dr. Trinanes.

Integrating data from different satellite sensors is necessary for achieving temporal and spatial coverage of *Sargassum* inundation events, but this integration poses technical challenges that need to be overcome. “Unfortunately,” explains Dr. Trinanes, “the clouds can block the signal and not capture useful data about the area of interest.” The advantage to his team’s approach to using multiple sensors is illustrated below in an example from AOML’s Ocean Viewer data visualization tool. Data from VIIRS (left), MODIS (middle), and from OLCI, VIIRS, and MODIS combined (right) delineate the presence of *Sargassum*, indicated by swirls of light turquoise. The overpass time for each sensor is different, so different data is captured by each as they and the clouds (medium blue) move, providing important clues about the trajectory of *Sargassum* mats. “The coverage increases a lot when we combine all the information available,” says Dr. Trinanes.

Leveraging satellite observations, Dr. Trinanes’ team has developed cutting-edge data products that offer unparalleled insights into *Sargassum*'s behavior and its effects on coastal communities and marine ecosystems. These technological advancements, a few of which are highlighted below, are a gateway to a new era in coastal management, enabling the implementation of data-driven approaches to more efficiently address the impacts of *Sargassum* inundation on both natural environments and local economies.



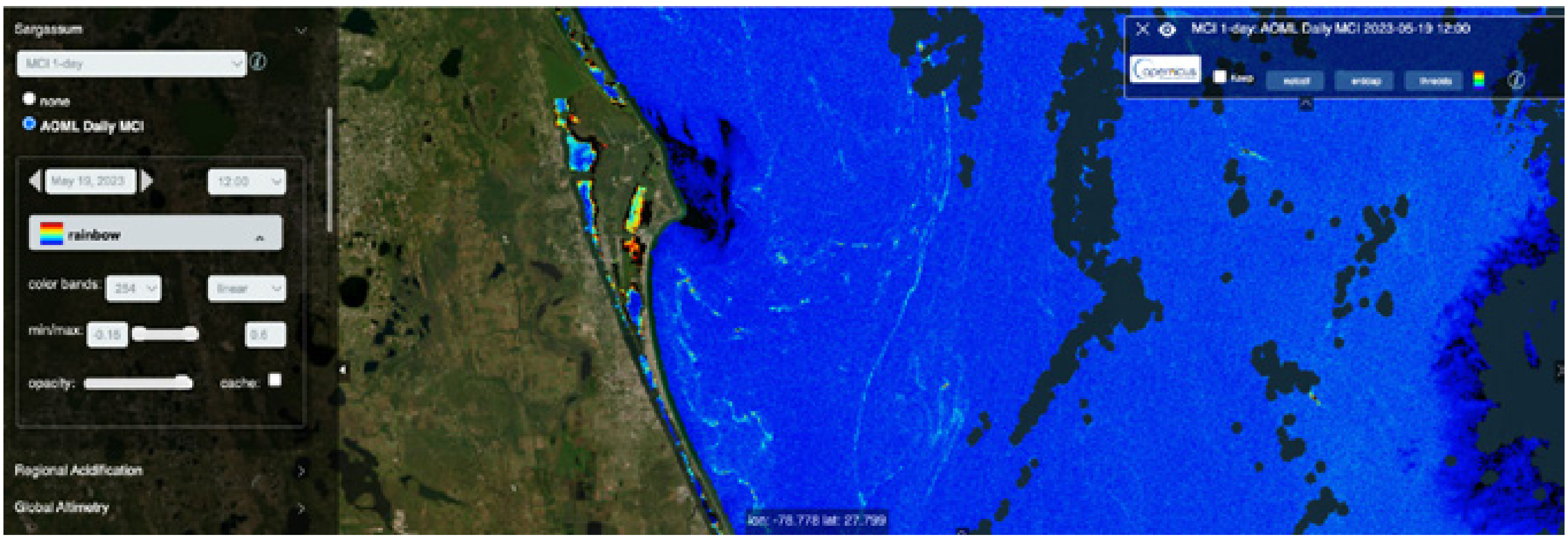
These examples of Sargassum detection from August 2, 2022, from various satellite sensors show that combining data from different sensors helps to fill gaps and improves resolution. Light turquoise denotes the presence of Sargassum, medium blue indicates clouds, and dark blue indicates water.

Tools To Enhance *Sargassum* Monitoring and Response

NOAA AOML and CoastWatch provide a platform for accessing, distributing, and visualizing satellite data for different data products. Their tools are developed and implemented to deliver interoperable products through a service-oriented architecture that facilitates automatic communication between different systems, using internationally recognized standards for data and metadata. Following best practices of interoperability makes the products more useful to the consumer.

A wide selection of regional and global ocean and coastal datasets and products are available through Ocean Viewer (screenshot below) and the CoastWatch Data Portal, each providing an interface for visualizing and combining data from different satellite sensors. These tools can be used to explore the relationship between *Sargassum* and other variables. For example, users can view and download retrospective and current information on the distribution and movement of *Sargassum* in the GASB, daily insights into risks associated with *Vibrio* (an infectious bacteria found in marine environments and with the potential to harbor in *Sargassum*), sea surface temperatures, ocean currents, and many other factors influencing the state of coastal and marine ecosystems.

Dr. Trinanes and his team are also at the forefront of creating value-added data products. One example—they are leveraging machine learning approaches to delineate *Sargassum* mats and using that information for models and to generate *Sargassum* indicators. Several examples of these innovative products are featured below.

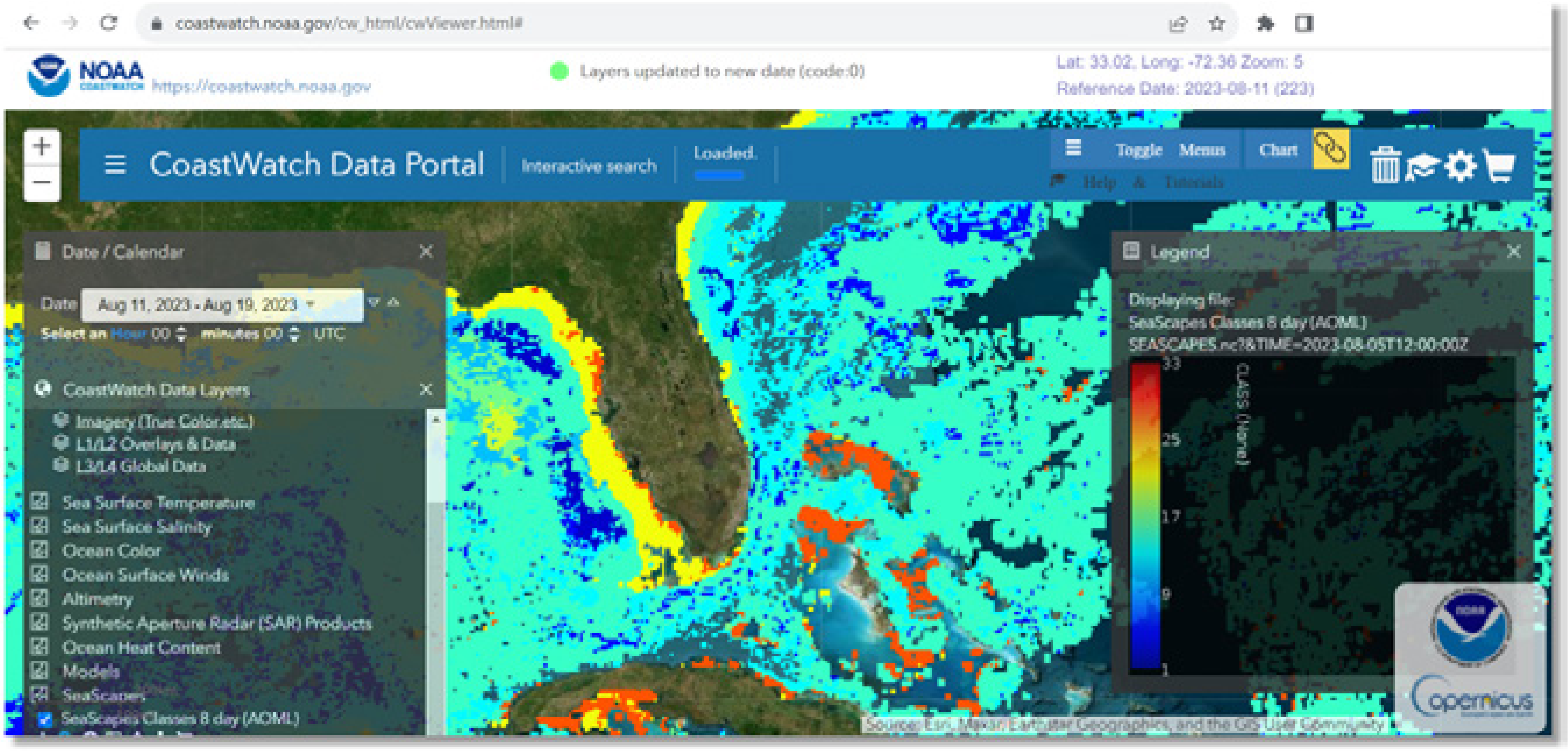


Screenshot of Ocean Viewer showing the presence of Sargassum along Central Florida on May 19, 2023. The Maximum Chlorophyll Index (MCI) identifies those areas with high concentrations of chlorophyll. We can see the characteristic lines of high MCI along the coast, indicating the presence of Sargassum. There are also high values of MCI in the lagoons near Cape Canaveral that do not represent Sargassum, but rather, coastal eutrophic areas. Source: Ocean Viewer

A Biogeographical Dimension: Changing Seascapes

"There is a biogeographical dimension in *Sargassum* studies," explains Dr. Trinanes, and much like how land has landscapes, seas have seascapes—regions distinguished by unique characteristics that influence community structure and function. Seascape maps provide a biogeographical framework to help scientists track ecosystem changes and assess relationships between dynamic habitats and species movement. Additionally, seascape observations inform species distribution models and can help determine the vulnerability of pelagic organisms to environmental stressors.

In collaboration with the Marine Biodiversity Observation Network (MBON), the U.S. Integrated Ocean Observation System (IOOS), and NOAA NESDIS Center for Satellite Applications and Research (STAR), Dr. Trinanes' team uses data from models and satellite sensors, including VIIRS, to generate monthly and weekly global seascape maps. The MBON Seascapes product, available in the CoastWatch Data Portal (screenshot below), is used as a biogeographical framework for classifying and describing ever-changing ocean habitats. The data, says Dr. Trinanes, "allows us to monitor the different habitats in the ocean and gives us a kind of predictive capability in order to identify the presence and distribution of marine organisms" like *Sargassum*. This information is instrumental in forecasting potential shifts in species abundance in these seascapes. Current MBON Seascapes products include monthly and 8-day time steps at 5 kilometer resolution.



Screenshot of the CoastWatch Data Portal showing 8-day SeaScapes classification in Florida and the Caribbean from August 11-19, 2023. Colors coordinate with different seascape characteristics, such as sea surface temperature and salinity. Source: CoastWatch Data Portal.

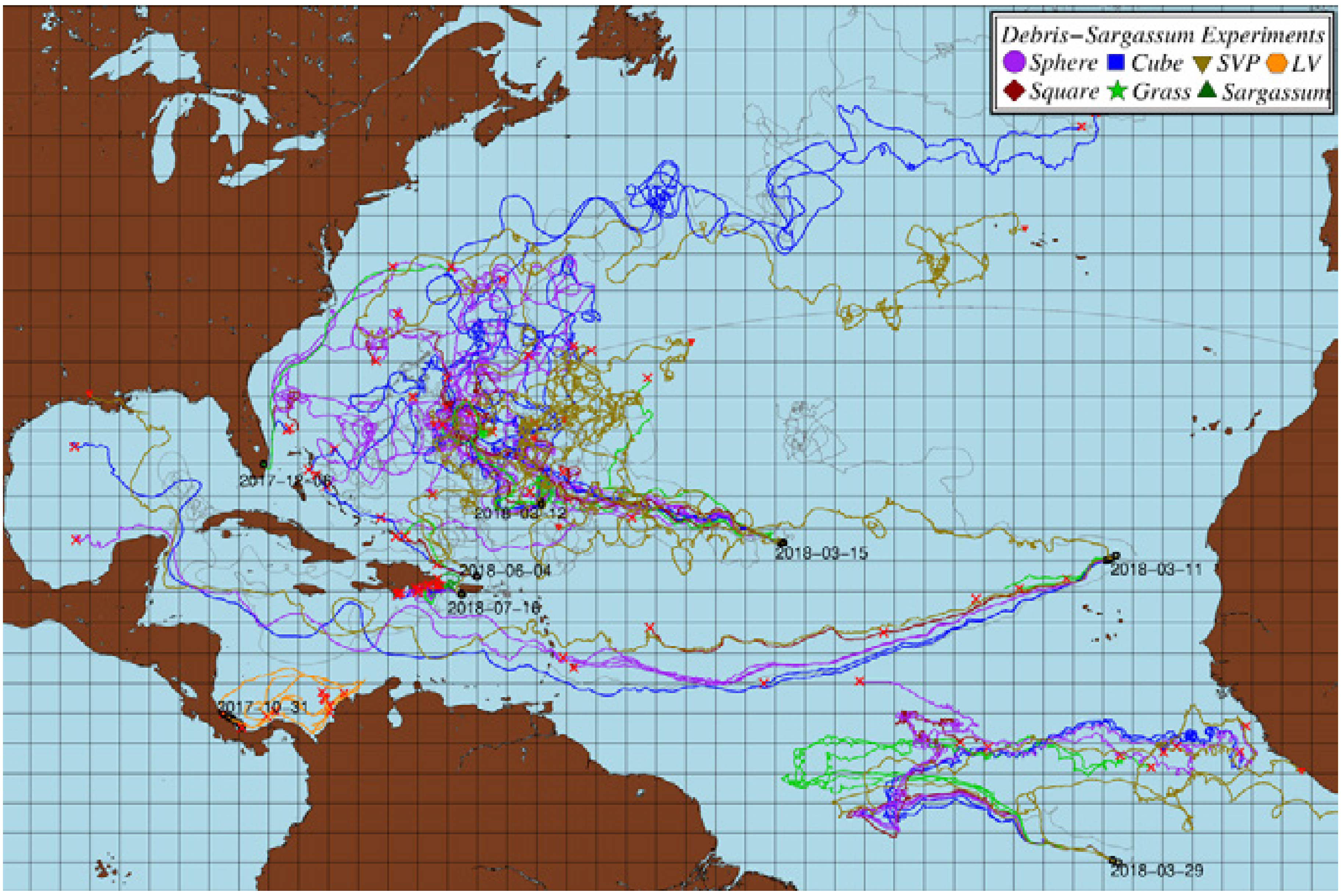
Forecasting *Sargassum* Trajectories

Forecasting the movement, arrival time, and biomass content of pelagic *Sargassum* mats in the GASB is crucial for coastal community preparedness, gaining insights into coastal and local dynamics, and identifying key drivers of blooms and beachings. "Understanding the trajectories of *Sargassum* is essential for assessing the impact of inundation events," Dr. Trinanes emphasizes. The AOML Physical Oceanography Division has been conducting experiments with GPS-equipped drifters (unanchored buoys of varying shapes) in the tropical Atlantic Ocean and Caribbean Sea, some attached to floating debris, some attached to pelagic *Sargassum* mats, and others affixed to "pseudo-*Sargassum*"—synthetically made *Sargassum* mats designed to mimic the seaweed in the open ocean. The goal? To understand and assess the impact of ocean dynamics and winds on *Sargassum* and marine debris in the open ocean. "We want to infer how different conditions of currents and winds make the trajectories different," says Dr. Trinanes. His team is developing a product that incorporates this data and provides an interface where users will be able choose a specific time and apply various wind and ocean current datasets to generate *Sargassum* trajectories and probabilities for *Sargassum* inundation events.

Left: A drifter with a GPS tracker is deployed near a Sargassum mat. Right: Artificial Sargassum with a GPS-equipped drifter attached. Source: NOAA AOML.

Sargassum Inundation Reports: Estimating the When and the Where

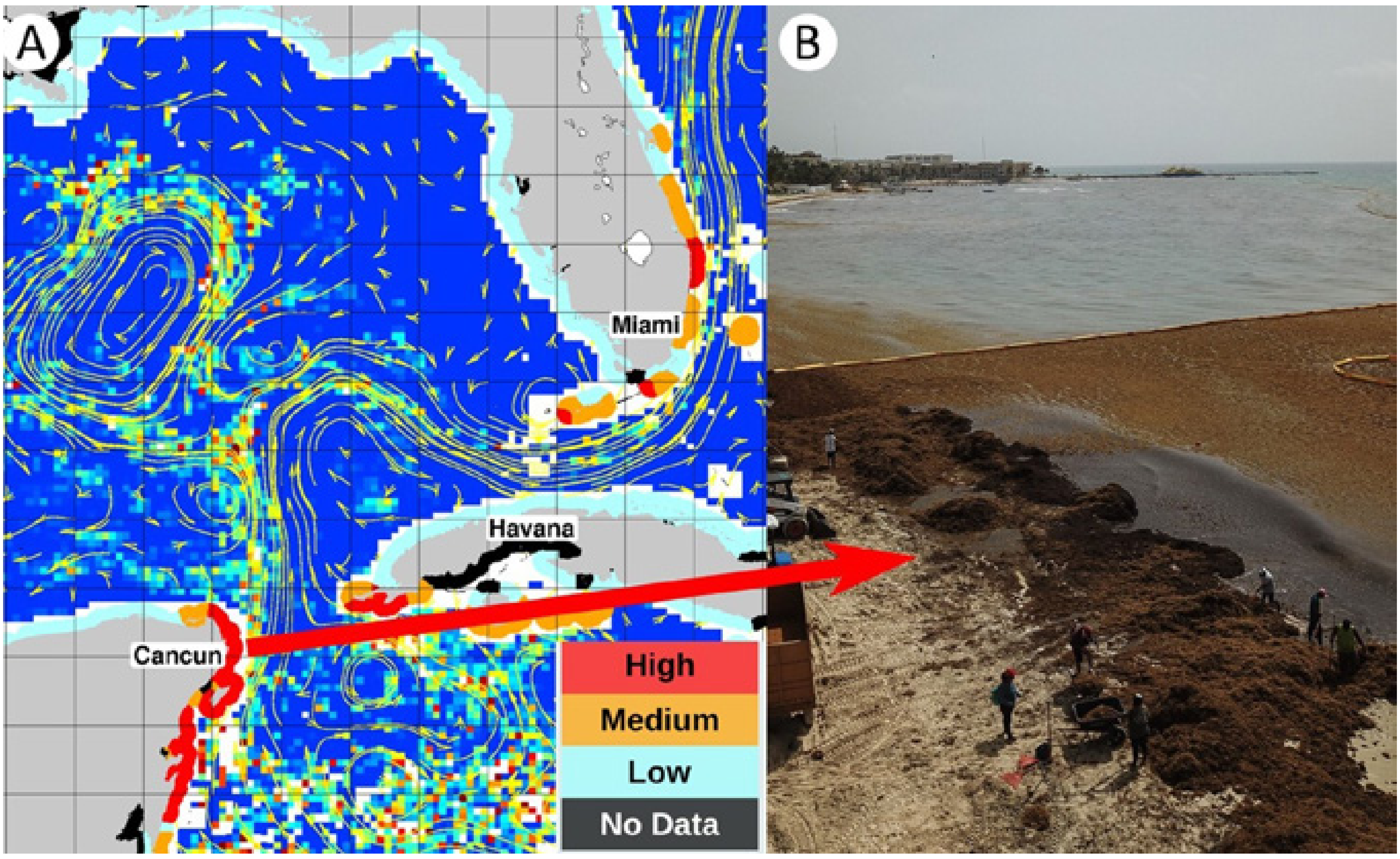
Since 2019, the experimental *Sargassum* Inundation Report (SIR) has provided an overview of the risk of *Sargassum* coastal inundation in the Caribbean, tropical Atlantic, and Gulf of Mexico regions. Such information can help enhance the monitoring and response to inundation events, thereby reducing impact on coastal communities and regional economies. Updated weekly, the SIR represents significant collaboration between AOML, CoastWatch/OceanWatch, and the University of South Florida.



Trajectories of drifters deployed in the debris-Sargassum experiments conducted by the AOML Physical Oceanography Division.

The SIR is a statistically-based report that leverages satellite detections of pelagic *Sargassum* to gauge the likelihood of *Sargassum* inundation events within a 50 kilometer radius of the coast. Its underlying data is derived from VIIRS and MODIS. Using these observations as inputs, the SIR algorithm estimates the abundance of pelagic *Sargassum* and its potential to reach land, a process quantified by a 7-day Floating Algae density index. Estimates are categorized into three levels of inundation risk—low, medium, and high—and delivered as color coded maps (see below). However, the likelihood of inundation depends heavily on local ocean dynamics to include currents, tides, and wind and wave conditions.

Comparative analysis of SIR estimates and in situ observations indicates reasonable agreement in coastal conditions, an example of which is shown on the right. This alignment is crucial for decision-making—when to close beaches, for instance—and it highlights the value of satellite observations and the SIR for evaluating the distribution, temporal variation, and inundation risk of pelagic *Sargassum*.



(A) Sargassum Inundation Report (SIR) for July 2-8, 2019, that indicates high (red) Sargassum inundation potential for Cancun, and (B) a photo showing severe coastal inundation of Sargassum in Cancun for the same area. Source: Trinanes et al. (2022).

Dr. Trinanes and his team are working on transitioning the experimental SIR to operational status under NOAA NESDIS, with a goal to produce the report daily. They continue to explore the integration of satellite data with machine learning algorithms to automate *Sargassum* detection, and collect and incorporate data from citizen science projects—on-the-ground observations to supplement space-based monitoring. "We consider this [collecting citizen science data] very important because we need to fill the observational gaps that we currently have in the Caribbean and the Gulf of Mexico and West Africa," Dr. Trinanes emphasizes. All these efforts are a critical part of AOML's and CoastWatch's broader effort to provide value-added data products for better understanding the dynamics of the GASB and the impact of beaching events.

ADVANCING *SARGASSUM* DETECTION AT MEXICO'S NATIONAL EARTH OBSERVATION LABORATORY (LANOT)

For the past four years, researchers at Mexico's National Earth Observation Laboratory (LANOT) have been working on innovative approaches to *Sargassum* detection along Caribbean coasts using satellite observations. Like NOAA AOML and CoastWatch, their objective, says Víctor Manuel Jiménez Escudero, "is detecting and monitoring *Sargassum* beds to prevent their arrival at reefs and beaches." Recently, they developed an innovative *Sargassum* detection algorithm using data from MultiSpectral Instrument (MSI) sensors onboard the Sentinel-2 low Earth orbit mission comprised of two satellites: Sentinel-2A and -2B. MSI has the high spatial resolution (down to 10m) needed to detect smaller *Sargassum* mats along coastlines that break off from the GASB, which may be undetectable by sensors with coarser spatial resolution like VIIRS (375m) or MODIS (250m).

National Earth Observation Laboratory (LANOT)

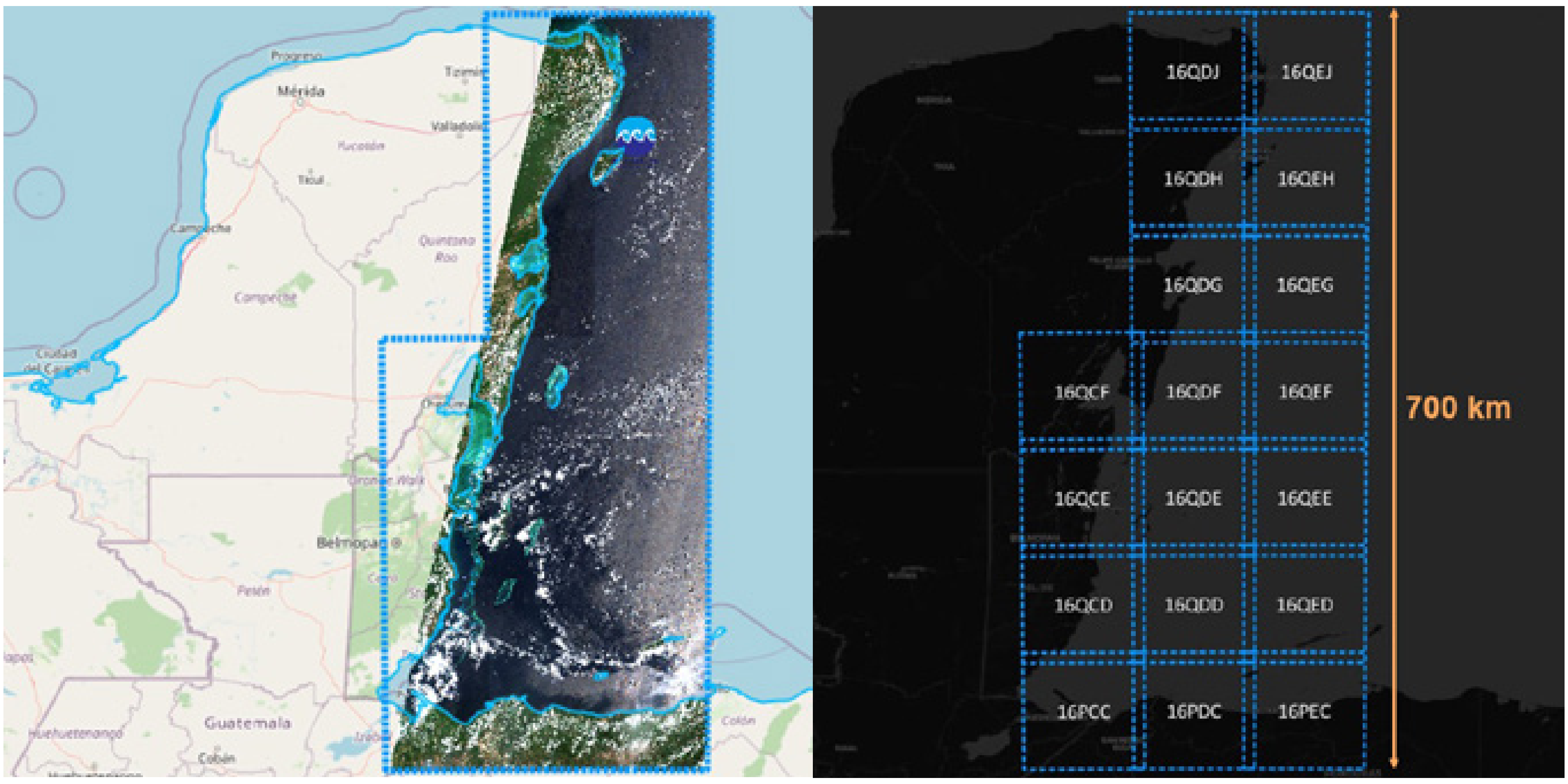
Founded in 2017, the National Earth Observation Laboratory (Laboratorio Nacional de Observación de la Tierra (LANOT)), headquartered in the Institute of Geography of the National Autonomous University of Mexico, has been of capital importance for risk prevention for the population of Mexico.

The primary objectives of LANOT are to receive, store, process, and carry out the interactive distribution of satellite data and imagery, enabling research on oceanic and atmospheric monitoring, land use change and vegetation cover, and their interrelationships and impacts on society.

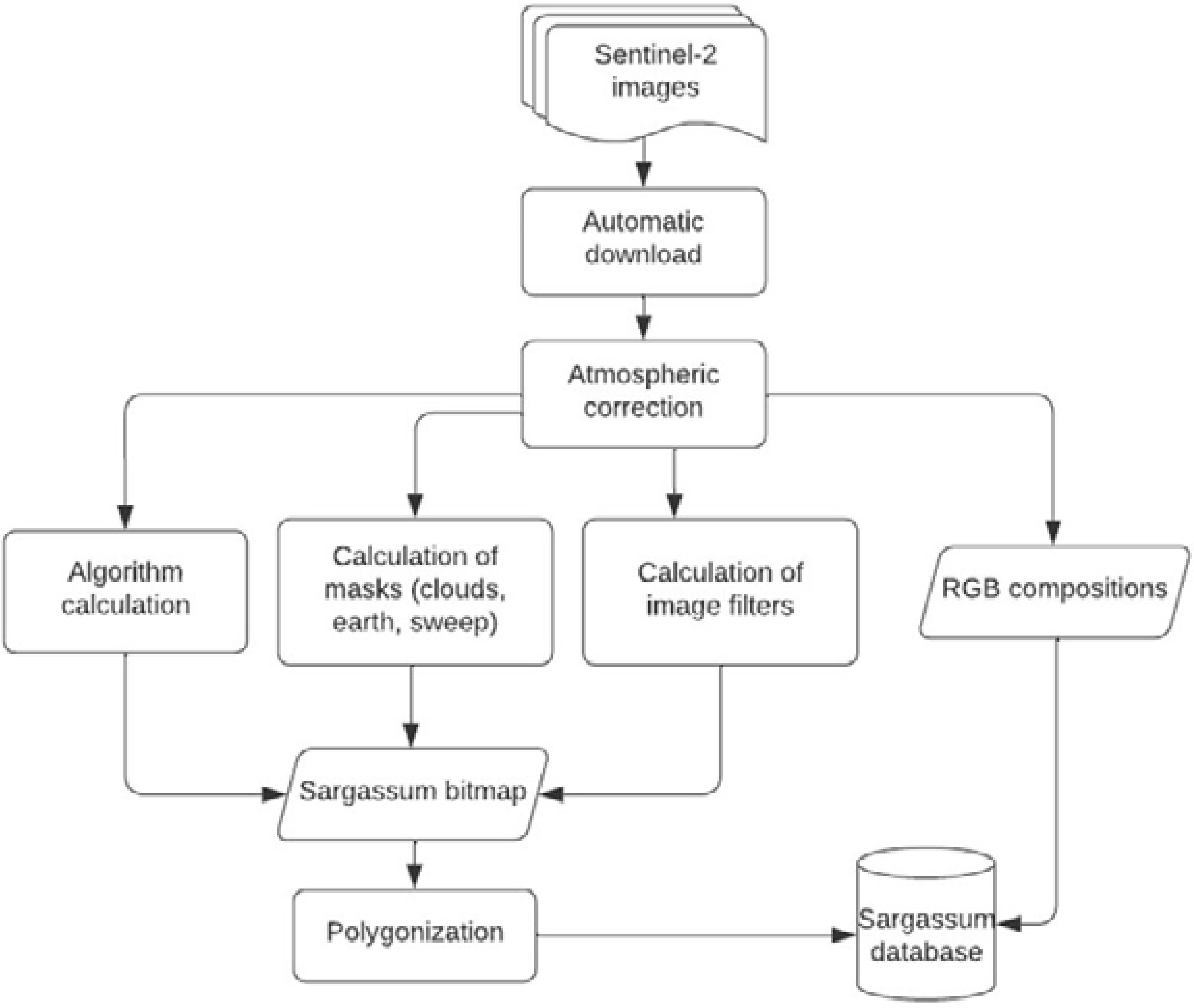
LANOT's main research lines include meteorology, remote sensing, spatial data infrastructures, high performance computing, and digital image processing.

Learn more at https://www.lanot.unam.mx/.

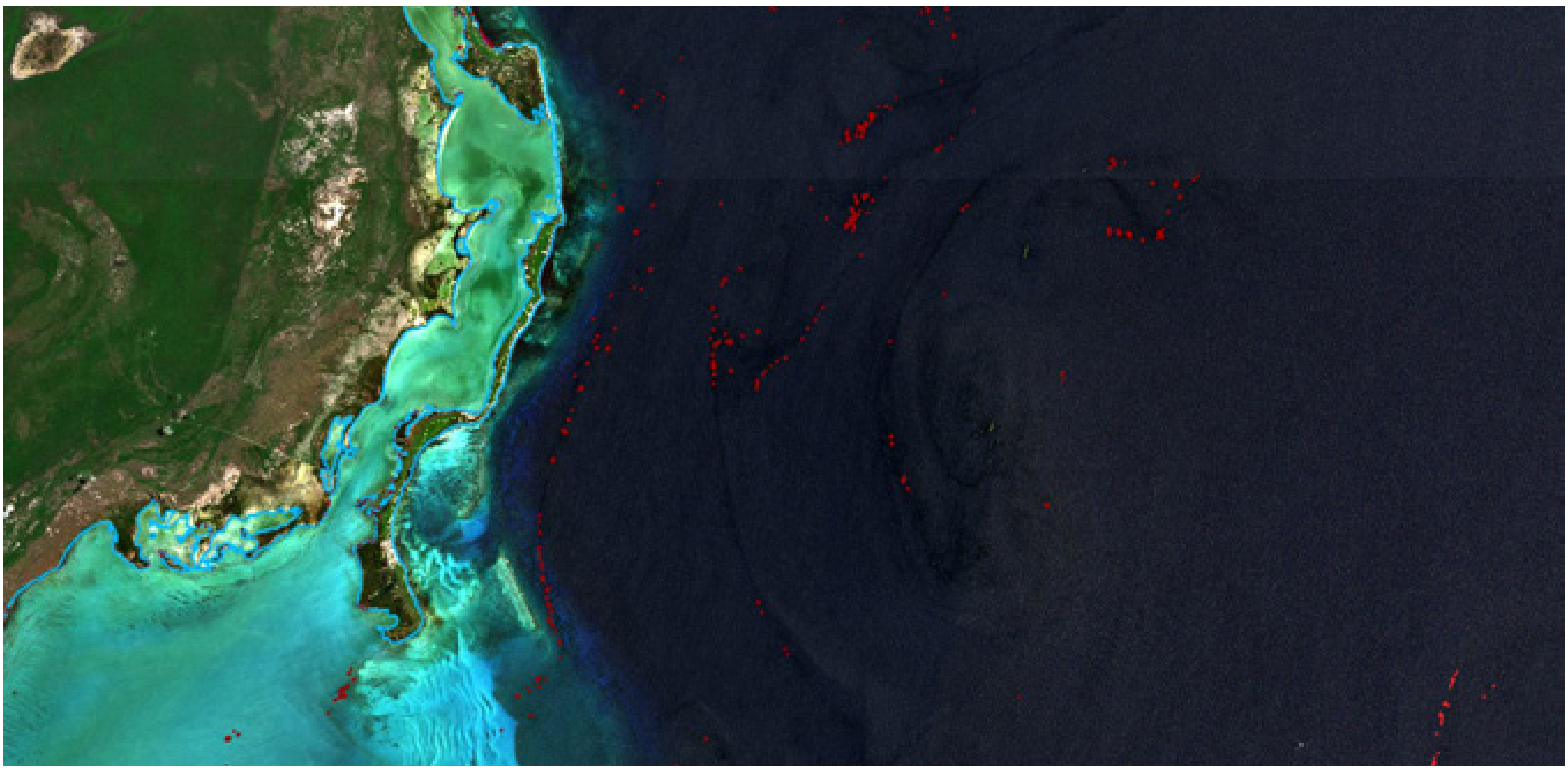
For now, LANOT's *Sargassum* detection algorithm is focused on the Mexican Caribbean—the entire coast of Quintana Roo and extending to 230 kilometers offshore, extending into Belize, Guatemala, and a portion of Honduras. "To detect *Sargassum*, the region is divided in 18 tiles. Each tile is monitored using Sentinel-2 imagery, with a repeat cycle of 5 days," explains Jiménez Escudero. These images are retrieved from three high-resolution MSI bands, ranging in spatial resolution from 10 to 20 meters, that are chosen for their spectral responsiveness to *Sargassum* across various wavelengths. These include the visible spectrum (Band 4), near-infrared (Band 8A), and shortwave infrared (Band 11) wavelengths. The LANOT algorithm processes these images to create a mosaic covering about 150,000 square kilometers, applying atmospheric correction and cloud, land, and beach masking. This ultimately results in a map of probable *Sargassum* locations.



Left: The study area for LANOT's Sargassum detection algorithm. Right: Eighteen Sentinel-2 tiles (images) cover the area.

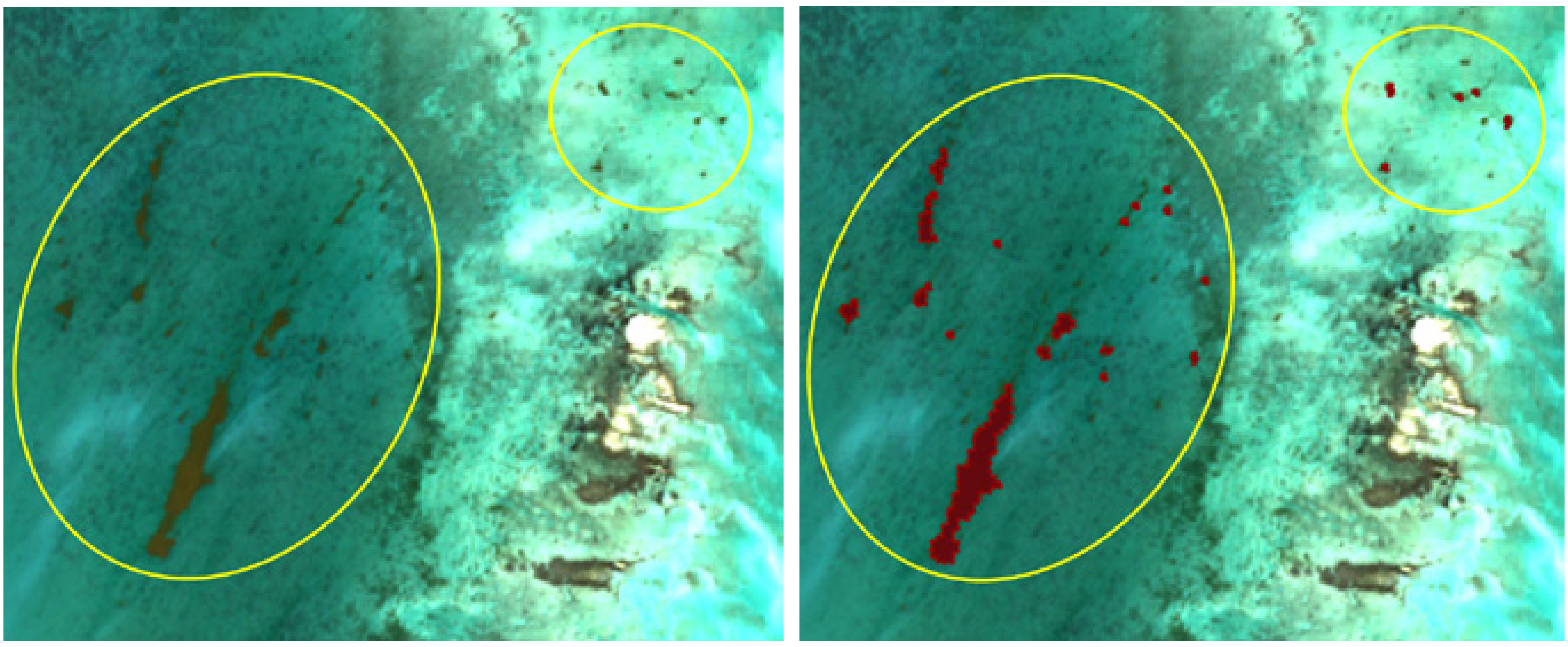


Above is a flowchart illustrating the process. After atmospheric correction, the algorithm is applied to the Sentinel-2 MSI images, generating a binary classification map indicating the presence or absence of *Sargassum* in each image pixel, where each pixel corresponds to the spatial resolution of its respective band. For instance, the MSI B4 band captures imagery at a resolution of 10m, meaning that each pixel in a B4 image represents a 10-meter by 10-meter area on the ground—fine enough resolution to detect smaller patches of *Sargassum*. To generate a digitized representation, the binary map is vectorized, converting it into polygons. True color imagery (RGB) compositions are made separately to identify areas where *Sargassum* is visible. Time series of these data are collectively stored in a spatial database, which allows for the representation of polygons and other simple geometric objects.



Example detection results from the LANOT Sargassum detection algorithm shows Sargassum (indicated by red dots) in the sea off the coast of the Quintana Roo region in Mexico, near Punta Allen.

The system's capabilities are impressive. Comparing detection results from the LANOT algorithm (red dots in the right image, below) with *Sargassum* mats in a visible image (indicated by brown in the left image), Jiménez Escudero points out, "you can see it [the algorithm] detects blooms of *Sargassum* very well." The LANOT team validates results using airborne measurements from drones and its own aircraft laboratory. "With our algorithm we can estimate the area of *Sargassum*, and field work confirms the depth of the *Sargassum*," explains Jiménez Escudero. "Using these data, we can calculate density of the bloom area." This information is critical for estimating the impact of looming *Sargassum* inundation events and implementing preventive measures that can potentially save communities millions in clean-up costs and safeguard the health of numerous individuals. But the revisit time of Sentinel-2 satellites presents challenges in nearshore environments that can change quickly.

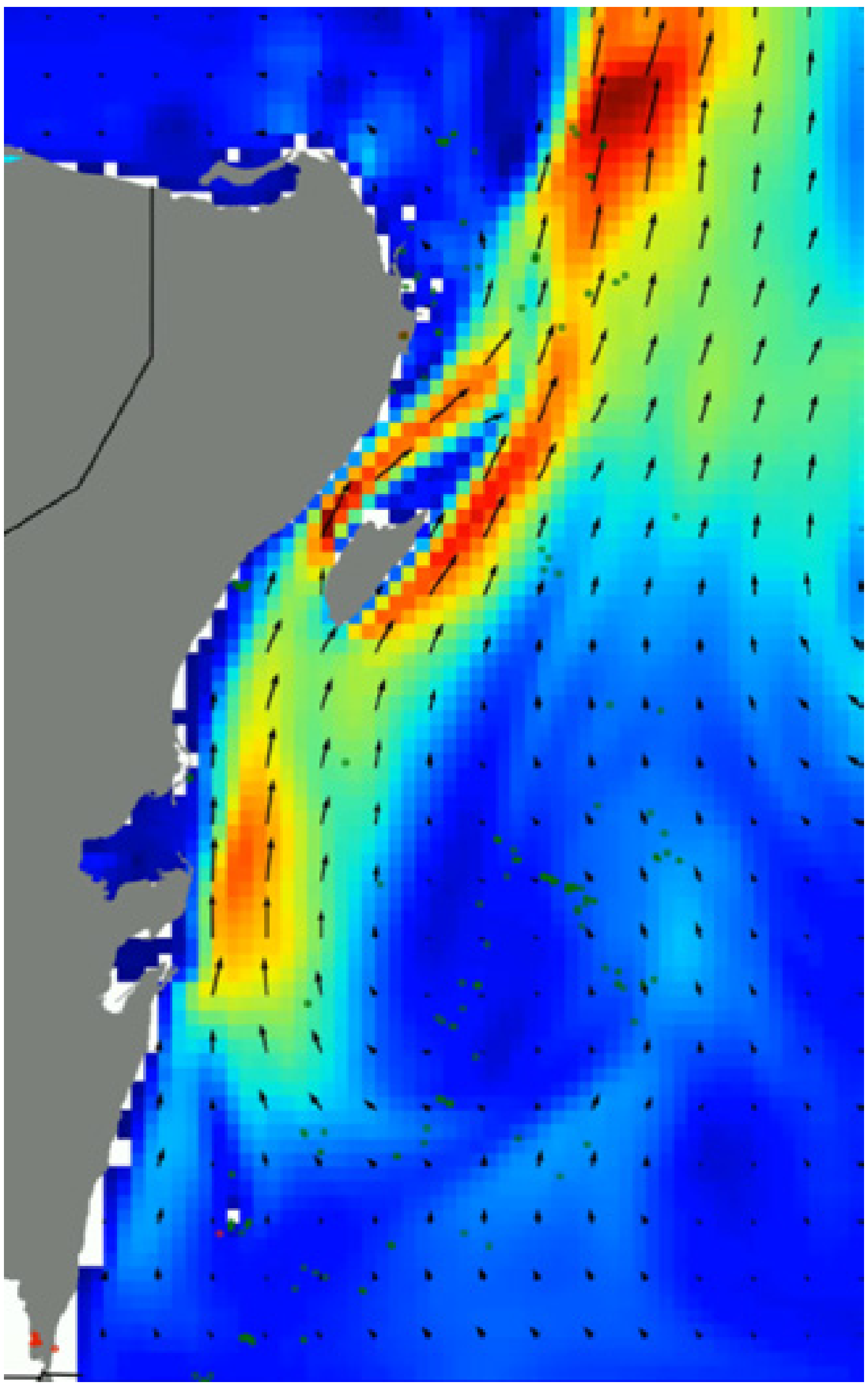


Left: Visible imagery showing Sargassum blooms in the sea off the coast of Quintana Roo, Mexico. Right: The same Sargassum blooms detected by the LANOT algorithm. Detected blooms are indicated by red dots.

Balancing Act: High Spatial Resolution at the Cost of Low Temporal Frequency

High spatial resolution Earth observation missions like Sentinel-2 are essential for effective coastal monitoring and management of local *Sargassum* blooms and smaller mats that have separated from the GASB. But the revisit period of Sentinel-2 is five days at the equator if both mission satellites are used (10 days if only one satellite is used), and data latency—the time between when data are retrieved by a sensor and when these data are made available to the public—can extend this period. "Sometimes it takes another several days for the data to appear on the Copernicus portal," Jiménez Escudero laments. This is a problem for mapping and tracking locally dynamic *Sargassum* situations. In the future, a new reception and processing node in Canada may reduce waiting time, but Jiménez Escudero says the ideal situation would be to receive and process the data at LANOT.

For now, LANOT bridges the five-plus day gap between available Sentinel-2 images with ocean current data from the Hybrid Coordinate Ocean Model (HYCOM). Using *Sargassum* detections from LANOT's algorithm as input (depicted below in shades of green, yellow, orange, and red where orange and red indicate higher density), this predictive model allows for the dynamic forecasting of *Sargassum* flow (illustrated with arrows, on the previous page) along the coast during periods when Sentinel-2 data are unavailable. An estimated quantity of beached *Sargassum* mats is also calculated (not shown). The accuracy of these forecasts is validated through real-world data gathered from drift buoys attached to *Sargassum* mats, which collect speed and location data.



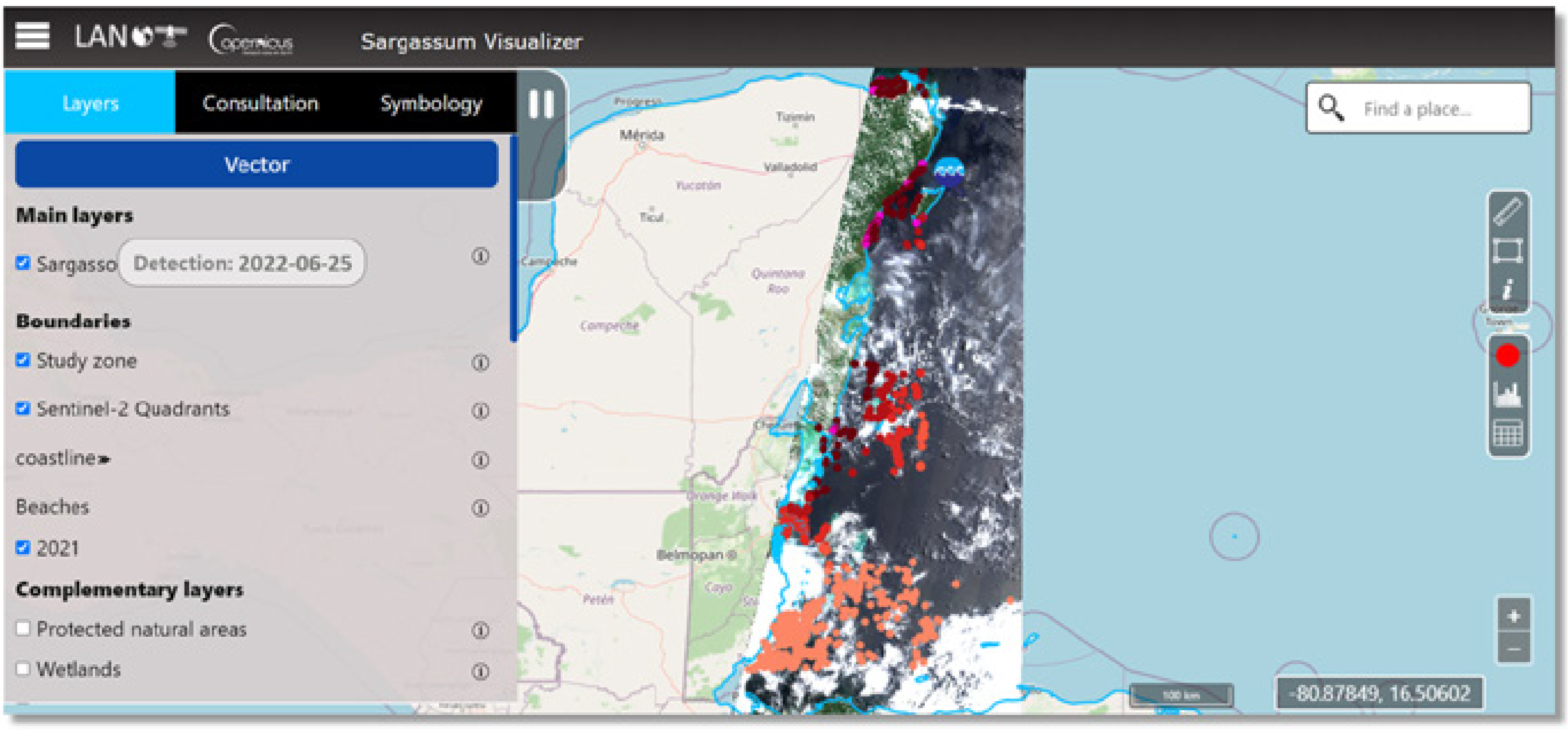
Sargassum detections from the LANOT algorithm are depicted by shades of green, yellow, orange, and red where orange and red indicate higher density. Predicted Sargassum flow from HYCOM is shown by arrows.

Even with these challenges, Sentinel-2 MSI remains vital in managing *Sargassum* along coastlines. Its high spatial resolution offers detailed views of coastal areas, allowing scientists and decision makers to reliably identify and track the extent and movement of *Sargassum* mats and localized blooms, and respond efficiently. This capability makes Sentinel-2 satellites a cost-effective and valuable resource for formulating strategies for coastal management.

LANOT *Sargassum* Visualizer

LANOT's *Sargassum* Visualizer is a web-based viewer that displays data obtained from their detection algorithm and predictive model. The tool integrates various data layers and allows the user to quantify the area and density of *Sargassum* mats using a point and click selection tool to define an area of interest. The *Sargassum* Visualizer also enables time series analysis of Sentinel-2 images going back to late 2015. Further development underway includes algorithms based on other satellite sensors like VIIRS, MODIS, and the GOES Advanced Baseline Imager (ABI), which will cover larger geographic areas in the *Sargassum* Visualizer and help to address the time gaps between Sentinel-2 satellite passes.

LANOT continues to enhance their capabilities for monitoring and managing *Sargassum*, including using VIIRS and other sensors to train their deep learning



Screenshot of LANOT's Sargassum Visualizer. Sargassum detections are depicted by red and orange dots.

technologies. They are also compiling a historical analysis of *Sargassum* detections spanning from 1985 to 2022 from VIIRS and Landsat to expand their scientific understanding of the origin and dynamics of *Sargassum* blooms in the Mexican Caribbean.

Moreover, Jiménez Escudero says LANOT is collaborating with international institutions to extend the coverage of their algorithm to the wider Caribbean area, offering essential resources to countries lacking their own monitoring platforms.

LOOKING AHEAD

Since it was first observed in 2011, the Great Atlantic *Sargassum* Belt has been growing, causing more disruption each summer in the tropical Atlantic, Caribbean, and Gulf of Mexico regions. Consequently, using satellites to track *Sargassum*'s distribution and density is crucial for providing accessible and timely data to predict and prepare for its impact, and for uncovering patterns that do not emerge at the scale of in situ measurements. Given the massive disruption *Sargassum* can cause in coastal communities, along with its potential harm to public health and the economy, enhancing observational and modeling capabilities is essential. Doing so is necessary to gain a clearer understanding of the factors influencing the GASB, which will enable more effective preparation and management strategies.

"We need more data," Dr. Trinanes urges, "especially in coastal areas." Increasing the number of satellite sensors used enhances nearshore coverage, but challenges persist—notably due to retrieval interference from clouds and aerosols and sun-glint conditions—and there is often a trade-off between spatial resolution and revisit frequency. Focusing on the future, Dr. Trinanes asserts, "we need to increase the range of products, increase the quality, and we need to continue working with machine learning procedures and developing citizen science projects to improve [estimates of] *Sargassum* inundation risk, because the *Sargassum* inundation risk can provide the basis for an early warning system."

NOAA AOML, CoastWatch, and LANOT are at the forefront of these efforts, developing sophisticated algorithms and machine learning models to improve *Sargassum* detection, even under challenging conditions like cloud cover or varying light. At NOAA, Dr. Trinanes notes that his team is integrating NOAA Science Council's six science and technology focus areas—artificial intelligence, unmanned systems, cloud computing, omics, data innovation, and citizen science—into their projects. "We are integrating these strategies to advance in the development of data driven applications, using different data streams, filling the gaps, for example, in understanding the growth and decay of *Sargassum*," he says.

The coming years will see a boost in ocean observations as more satellites launch, like JPSS-3 and -4 and the upcoming NASA PACE (Plankton, Aerosol, Cloud, Ocean ecosystem) mission. Observations such as these will lead to an increase in available ocean data to bolster the advancements being made. New data and cutting-edge data products will support more effective and proactive monitoring of *Sargassum*, enabling faster and targeted response to its impacts. Such improved surveillance is crucial for protecting marine ecosystems and the well-being of communities that depend on coastal resources. ✦

STORY SOURCE

The information in this article is based, in part, on the September 18, 2023, LEO Science Seminars titled "Satellite Monitoring of Pelagic Sargassum and Assessment of Coastal Inundation Risk" presented by Dr. Joaquin A. Trinanes, Operations Manager for the NOAA CoastWatch Caribbean and Gulf of Mexico Regional Node and Atlantic OceanWatch Node at the Atlantic Oceanographic and Meteorological Laboratory (AOML), and "National Earth Observation Laboratory (LANOT) Sargassum Detection" presented by Víctor Manuel Jiménez Escudero, Associate Academic Technician C at the National Autonomous University of Mexico (UNAM). The full list of contributors follows.

"Satellite Monitoring of Pelagic Sargassum and Assessment of Coastal Inundation Risk" contributors include:

- Gustavo Goni, NOAA (Node Manager, Gulf of Mexico/Caribbean and Atlantic OceanWatch)
- Rick Lumpkin, NOAA (Director, AOML Physical Oceanography Division)
- Veronica Lance, NOAA (Program Manager, CoastWatch/OceanWatch/PolarWatch)
- Emily Smail, NOAA-UMD Cooperative Institute for Satellite Earth System Studies (CISESS)
- Chuanmin Hu, University of South Florida
- Josefina Olascoaga, University of Miami
- Javier Beron-Vera, University of Miami
- Philippe Miron, University of Miami
- Nathan Putman, LGL Ecological Research Associates
- Lowell Andrew Iporac, Florida International University
- Julio Morell, Caribbean Coastal Ocean Observing System (CARICOOS)

"National Earth Observation Laboratory (LANOT) Sargassum Detection" contributors include:

- Jorge Prado Molina, Instituto de Geografía, National Autonomous University of Mexico
- Raúl Aguirre Gómez, Instituto de Geografía, National Autonomous University of Mexico
- José Antonio Quintero Pérez, Instituto de Geografía, National Autonomous University of Mexico
- Uriel Mendoza Castillo, Instituto de Geografía, National Autonomous University of Mexico
- Alejandro Aguilar Sierra, Instituto de Ciencias de la Atmósfera y cambio climático, National Autonomous University of Mexico
- Luis Octavio Ramírez Fernández, Instituto de Geografía, National Autonomous University of Mexico
- Jesús Hernández Torres, Instituto de Geografía, National Autonomous University of Mexico
- Guadalupe Tapia Varela, Instituto de Geografía, National Autonomous University of Mexico
- Itzel Millan Ortega, Instituto de Geografía, National Autonomous University of Mexico
- Víctor Manuel Jiménez Escudero, Instituto de Geografía, National Autonomous University of Mexico
- Ilma Huy Hernández, Instituto de Geografía, National Autonomous University of Mexico
- Gabriela Gómez Rodríguez, Instituto de Geografía, National Autonomous University of Mexico
- Hugo Enrique Lazcano Hernández, El Colegio de la Frontera Sur (ECOSUR)
- Javier Arllano Verdejo, El Colegio de la Frontera Sur (ECOSUR)
- Steven Czitrom, Instituto de Ciencias del Mar, National Autonomous University of Mexico
- Ivan Penié, Centro Ecológico Akumal

FOOTNOTES

1 https://www.monroecounty-fl.gov/DocumentCenter/View/29184/Sargassum-in-the-FL-Keys--Visitor-and-Economic-Impact-Evaluation-Executive-Summary-060421?bidId=

2 https://www.reuters.com/article/us-health-travel-toxic-seaweed/toxic-seaweed-a-menace-to-caribbean-tourists-idUSKCN1UL1ZG/

3 Copernicus is the Earth observation component of the European Union Space Programme, managed by the European Commission and implemented in partnership with the EU Member States, the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF), the Joint Research Centre (JRC), the European Environment Agency (EEA), the European Maritime Safety Agency (EMSA), Frontex, SatCen and Mercator Océan.

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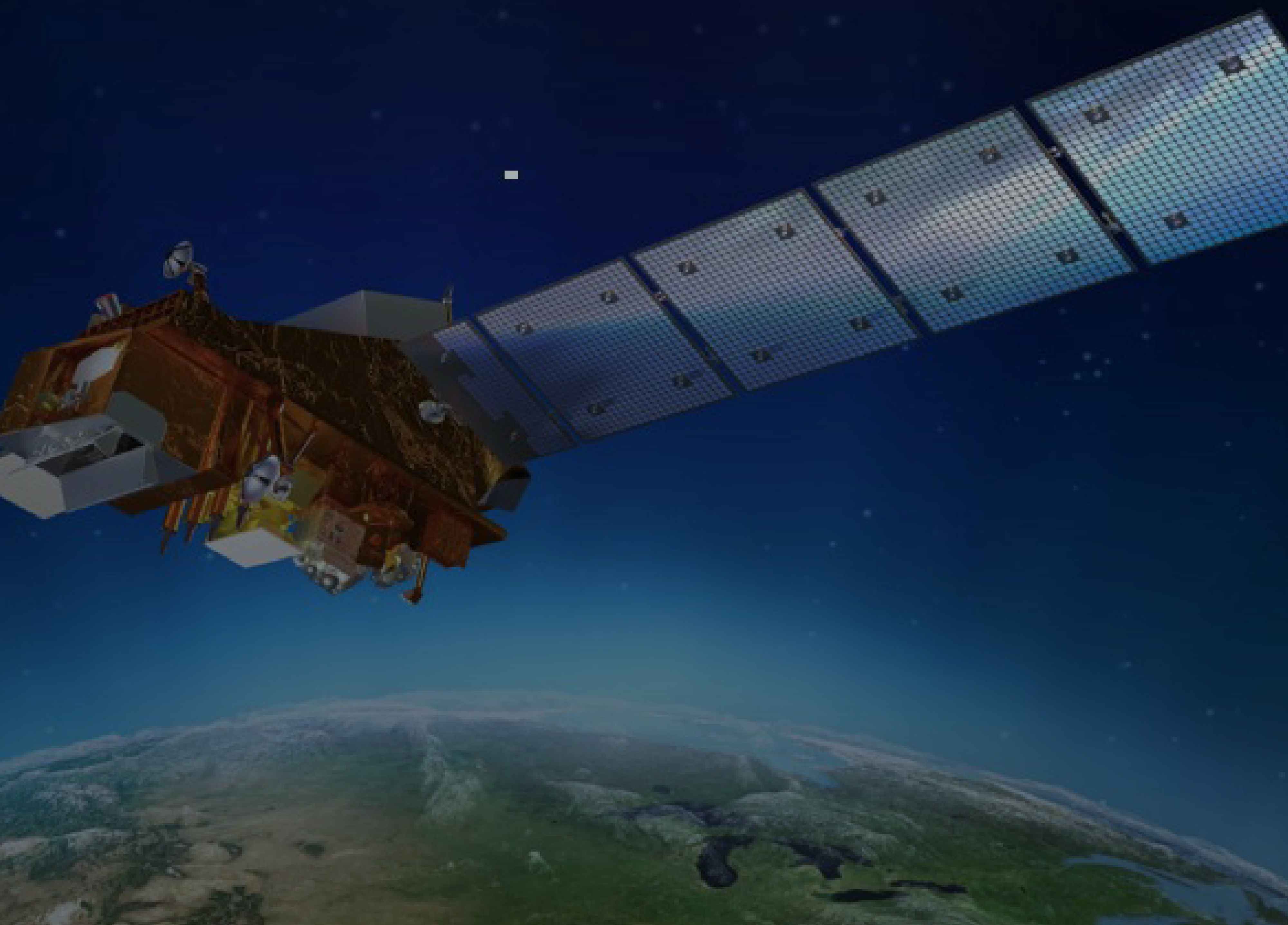
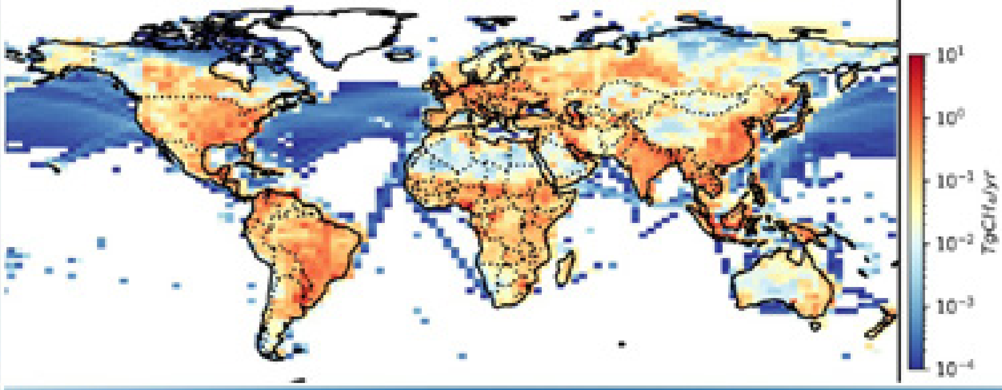
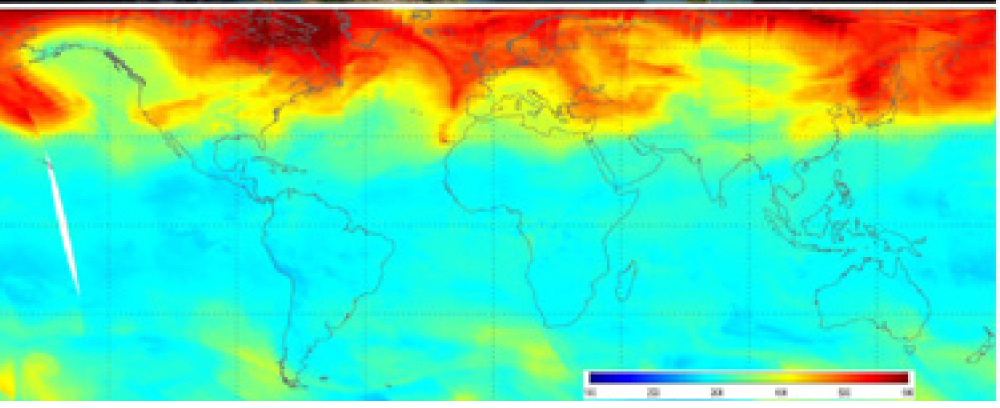
FEATURE 11

NOAA NESDIS-OAR Collaboration: Synergies between OAR Observing Capabilities and NESDIS Satellite Missions for Trusted Data and Product Development







Clockwise from top left: Artist rendering of NOAA-21 launched on November 10, 2022, operated by the NOAA NESDIS Office of Low Earth Orbit Observations (LEO) (source: NOAA NESDIS); total mean global methane emissions in TgCH4/year for 1997-2021 at 3°x2° degree spatial resolution (source: NOAA GML CarbonTracker-CH4); NOAA OAR Global Monitoring Laboratory Barrow Atmospheric Baseline Observatory in the Arctic, which collects and analyzes ground-based measurements of atmospheric trace gases, aerosols, surface and total column ozone, and solar radiation (source: NOAA GML); total ozone in Dobson Units from the Ozone Mapping and Profiler Suite (OMPS) onboard Suomi NPP on March 30, 2016 (source: NOAA NESDIS STAR).

NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) manages the United States' operational environmental satellites, essential for weather forecasting, climate monitoring, and understanding environmental changes. NESDIS plays a key role in collecting and disseminating satellite data and products to stakeholders (scientists and policymakers), crucial for understanding Earth's weather and climate systems, and responding to natural disasters. Concurrently, the NOAA Office of Oceanic and Atmospheric Research (OAR) is at the forefront of environmental research, focusing on improving our understanding of the Earth's oceans, atmosphere, and climate by addressing key areas like weather patterns, climate change, air quality, and ocean processes. Within OAR, the Global Monitoring Laboratory (GML) plays a critical role, specializing in monitoring and assessing changes in the Earth's atmosphere and its chemical composition, including tracking greenhouse gases, studying the ozone layer, and examining atmospheric conditions that impact climate and weather. GML's research using global in situ data is important for providing up-to-date information about atmospheric trends and their implications. Together, NESDIS and OAR, with GML's support, play pivotal roles in advancing scientific knowledge and contributing to NOAA's mission of science, service, and stewardship of the Earth's atmospheric and oceanic resources.

In 2020, a three-year collaboration between NESDIS and OAR was initiated as an outcome of the OAR/NESDIS Leadership Collaboration Summit held on January 30, 2020, which was dedicated to promoting collaborative efforts and synchronizing the use of transformative technologies in shared areas of interest. The partnership has played a crucial role in supporting NOAA's mission to understand our changing climate and its effects on long-term shifts in the atmospheric composition of both the stratosphere and troposphere.

Since the inception of this collaboration, eight joint workshops have been conducted by NESDIS and OAR/GML. These workshops centered on various opportunity areas identified during the Summit, such as establishing observational contributions to research and operations (for example, calibration/validation activities), developing merged products and applications for societal benefit, aligning NESDIS's observation requirements with future OAR models, and creating effective platforms for interaction to promote data-driven science.

This cross-office collaboration has yielded significant benefits for both NESDIS and OAR, and by extension, to NOAA's National Weather Service, a key user of NESDIS data as critical input for numerical forecast models and the basis for mid- and long-range forecasts. These forecasts enable operational forecasters to make informed decisions for public safety, such as issuing early severe weather warnings and coordinating evacuations. The partnership has also led to enhanced synergies between NESDIS satellite missions and OAR's observing capabilities, furthering their shared goals. The following are highlights of the collaborative efforts and achievements of the NESDIS and OAR teams over the past three years that are relevant to the NESDIS Office of Low Earth Orbit Observations (LEO) Joint Polar Satellite System (JPSS) program.

A MODEL OF SUCCESS: HIGHLIGHTS FROM THE COLLABORATIVE EFFORTS OF NESDIS AND OAR

The goal of the three-year collaboration between NESDIS and OAR was to harness GML's high-quality ground-based and aircraft measurements to enhance the accuracy of NESDIS's satellite-based observations. This partnership aimed to augment ground-based observations for more effective global monitoring and assessments. The collaborative efforts were in line with three key GML research themes: 1) tracking greenhouse gases and understanding carbon cycle feedbacks, 2) guiding the recovery of stratospheric ozone and comprehending changes in water vapor, and 3) monitoring and deciphering alterations in surface radiation, clouds, and aerosol distributions. The following sections include highlights from the activities and outcomes of these three themes as they relate to JPSS.

Theme #1: Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks

Project Leads
Nicholas Nalli, Bianca Baier, Andrew R. Jacobson

Project Co-leads & Participants
Juying Warner, Lihang Zhou, Lori Bruhwiler, Youmi Oh, Xin Lan, Colm Sweeney

High-quality, independent datasets (in situ, remotely sensed, and numerical models) are essential as reference data for the development and validation of carbon trace gas profile environmental data records (EDRs) retrieved from operational hyperspectral thermal infrared (TIR) sounders, such as the JPSS Cross-track Infrared Sounder (CrIS), and the NOAA-Unique Combined Atmospheric Processing System (NUCAPS). NOAA OAR/GML, a leader in acquiring and providing high-quality atmospheric trace gas measurements and trace gas mole fraction fields from inverse models, and NOAA NESDIS, a leader in operational satellite sounder products and validation, partnered together in this endeavor. The following highlights selected outcomes from the three years of collaboration between NESDIS and GML in improving NUCAPS satellite products and their development, satellite calibration/validation (cal/val) applications, and supplementing GML's Global Greenhouse Gas Reference Network and model products with trusted satellite products.

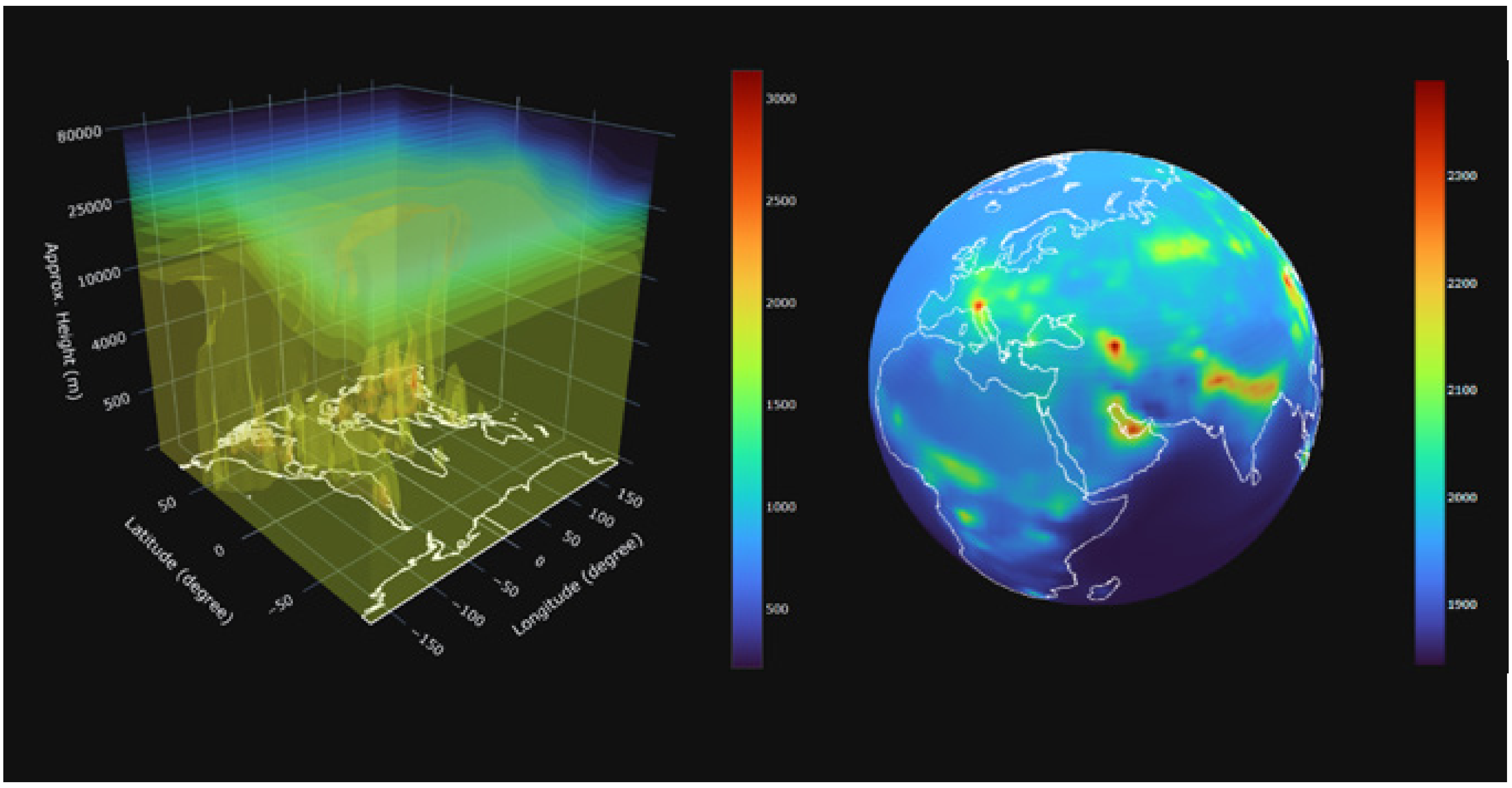
NUCAPS is an advanced data processing system used by NOAA to process satellite soundings—temperature, moisture, and trace gases—in the vertical. The NUCAPS algorithm is the NOAA operational algorithm for satellite soundings from hyperspectral infrared sounders, including CrIS onboard JPSS satellites and the Infrared Atmospheric Sounding Interferometer (IASI) carried on European Space Agency MetOp missions. As part of the NESDIS and GML collaboration, the NUCAPS system was enhanced to include Averaging Kernels, with the upgraded version (v3.1) set for release in January 2024 within the NESDIS Common Cloud Framework (NCCF). This upgrade, initiated through a formal user request from the GML team, will improve the operational NetCDF product files, the format for storing multidimensional scientific data. The addition of Averaging Kernels into the

Averaging Kernels
An Averaging Kernel (AK) is a mathematical tool used to understand and interpret remote sensing measurements of the atmosphere. Specifically, it helps in determining how satellite derived atmospheric parameters (like gas concentrations) relate to the true atmospheric state. AK is related to the amount of information determined from radiances (retrieved from satellite sensors) versus from first guess or a priori (that is, based on theoretical deduction rather than empirical observation).

NUCAPS product files along with the a priori trace gas profiles facilitate identifying the relative contributions of the retrieval versus the a priori and assessing the vertical sensitivity of the retrieved profiles.

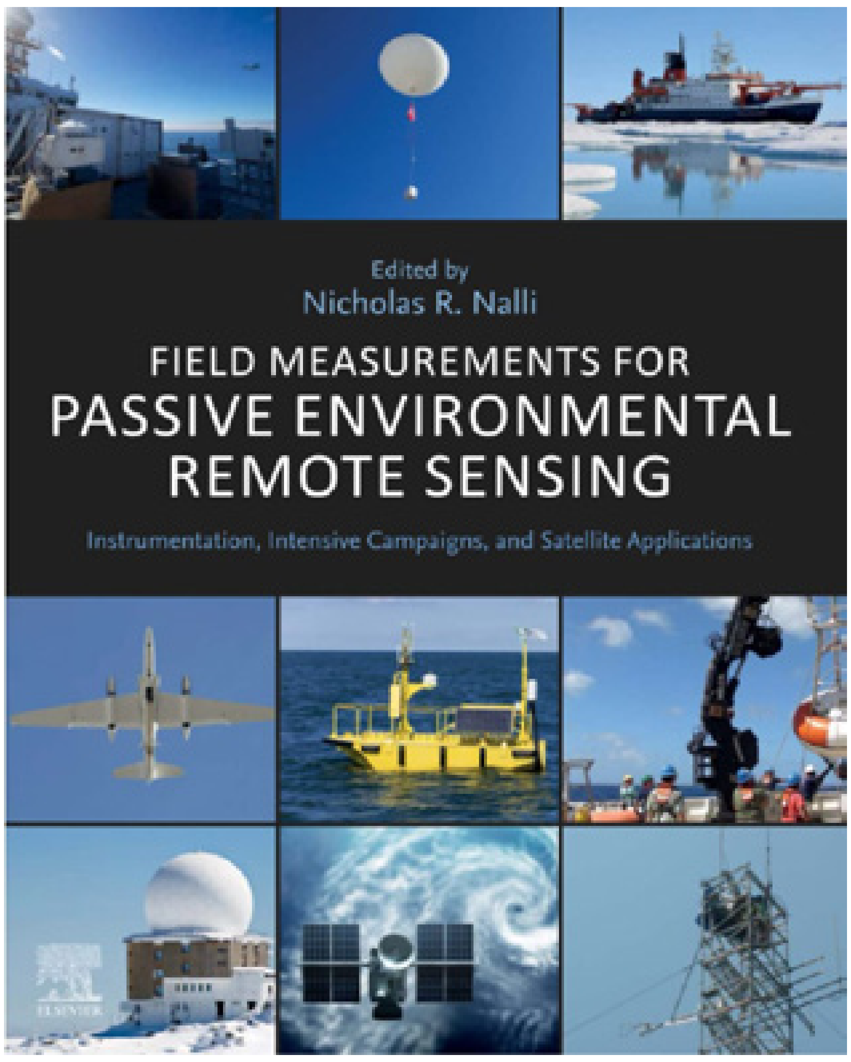
The NESDIS and GML collaboration also benefited from the second release of the CarbonTracker-CH_4 data assimilation product. CarbonTracker-CH_4 is a prototype system designed for Monitoring, Measurement, Reporting, and Verification (MMRV) of methane emissions. It integrates long-term monitoring of atmospheric methane (CH_4) and its stable carbon isotope, $\delta^{13}C$-CH_4, to understand how methane emissions are influenced by climate changes and human activities like fossil fuel use and agriculture. As an open access tool, CarbonTracker-CH_4 aims to enhance emission monitoring, align emission estimates with inventories, and validate emission reduction strategies by offering quantitative global estimates of methane emissions from various sources. It provides valuable insights for detecting interactions between methane and climate change and helps refine climate projection models. In the future, the team plans to compare NESDIS CrIS products and Japan Aerospace Exploration Agency (JAXA) GOSAT products with CarbonTracker-CH_4 to improve both satellite and CarbonTracker-CH_4 model algorithms.

All measurement data and model results are publicly available on the CarbonTracker-CH_4 website, including 3D methane mole fraction fields, optimized methane fluxes, comprehensive documentation, and 3D visualization tools for scientists, policymakers, and the public. Specifically, two web-based data visualization tools were created. The Volumetric Visualization tool provides monthly global volumetric plots of atmospheric methane simulated by CarbonTracker-CH_4. The Spherical Visualization tool provides monthly global spherical plots of atmospheric methane at different pressure levels simulated by CarbonTracker-CH_4. See Feature 4 for an in-depth look at CarbonTracker-CH_4 and its valuable data.



Left: An example of the CarbonTracker-CH_4 Volumetric Visualization tool. Right: An example of the CarbonTracker-CH_4 Spherical Visualization tool. Units are in parts per billion (ppb).

Several notable publications also resulted from this collaboration, including a comprehensive reference book titled "Field Measurements for Passive Environmental Remote Sensing" published in September 2022. This book synthesizes in situ measurement techniques and their application in environmental remote sensing, featuring contributions from subject matter experts including those from NOAA NESDIS, GML, and the Atlantic Oceanographic & Meteorological Laboratory (AOML). In addition, a paper titled "Validation and Utility of Satellite Retrievals of Atmospheric Profiles in Detecting and Monitoring Significant Weather Events" was published in the *Bulletin of the American Meteorological Society* (*BAMS*), which focuses on NUCAPS, including its application in carbon gas retrievals. In MDPI's *Remote Sensing* Special Issue in 2023, "Spatiotemporal Variability of Global Atmospheric Methane Observed from Two Decades of Satellite Hyperspectral Infrared Sounders" highlights over 20 years of global TIR methane observations from CrIS and AIRS, the Atmospheric Infrared Sounder on NASA's Aqua satellite. The authors describe how global trends align with GML's ground-based measurements and discuss a seasonal "phase shift" in satellite and in situ data, attributable to differences in vertical sensitivity and large-scale transport. Also, a paper detailing the prototype CarbonTracker-CH_4 inversion model was published in *Atmospheric Chemistry and Physics*. The paper, "Estimating emissions of methane consistent with atmospheric measurements of methane and δ13C of methane" showcases the depth and impact of this collaborative effort.



These selected activities reflect the collaborative efforts in enhancing environmental monitoring and understanding through improved technology and research. The Theme #1 partnership between NESDIS and OAR/GML involved collaborations with a range of stakeholders and users, including NASA (specifically with the Orbiting Carbon Observatory-2, OCO-2, team and OCO-2/3 validation team), the JAXA GOSAT project, the National Center for Atmospheric Research (NCAR) Measurement of Pollution In the Troposphere (MOPITT) validation team, NASA's Atmospheric Tomography Mission (ATom) science team, and the remote sensing communities of the Total Carbon Column Observing Network (TCCON) and COllaborative Carbon Column Observing Network (COCCON).

Future plans for this collaboration include developing a long-term routine trace gas monitoring system using trace gas products retrieved from the current and future hyperspectral sounder radiances, time and space collocations of in situ, model, satellite observations to scale and map different temporal and spatial resolutions for fit-to-purpose applications, statistical metrics, trends, and analyses. As a result, data products derivable from the monitoring system could lead to mission agnostic blended product development through synergistic use to monitor atmospheric composition, trace gas concentrations, climate change, and Earth system processes.

Theme #2: Guiding Recovery of Stratospheric Ozone

Project Leads
Irina Petropavlovskikh, Lawrence Flynn, Murty Divakarla

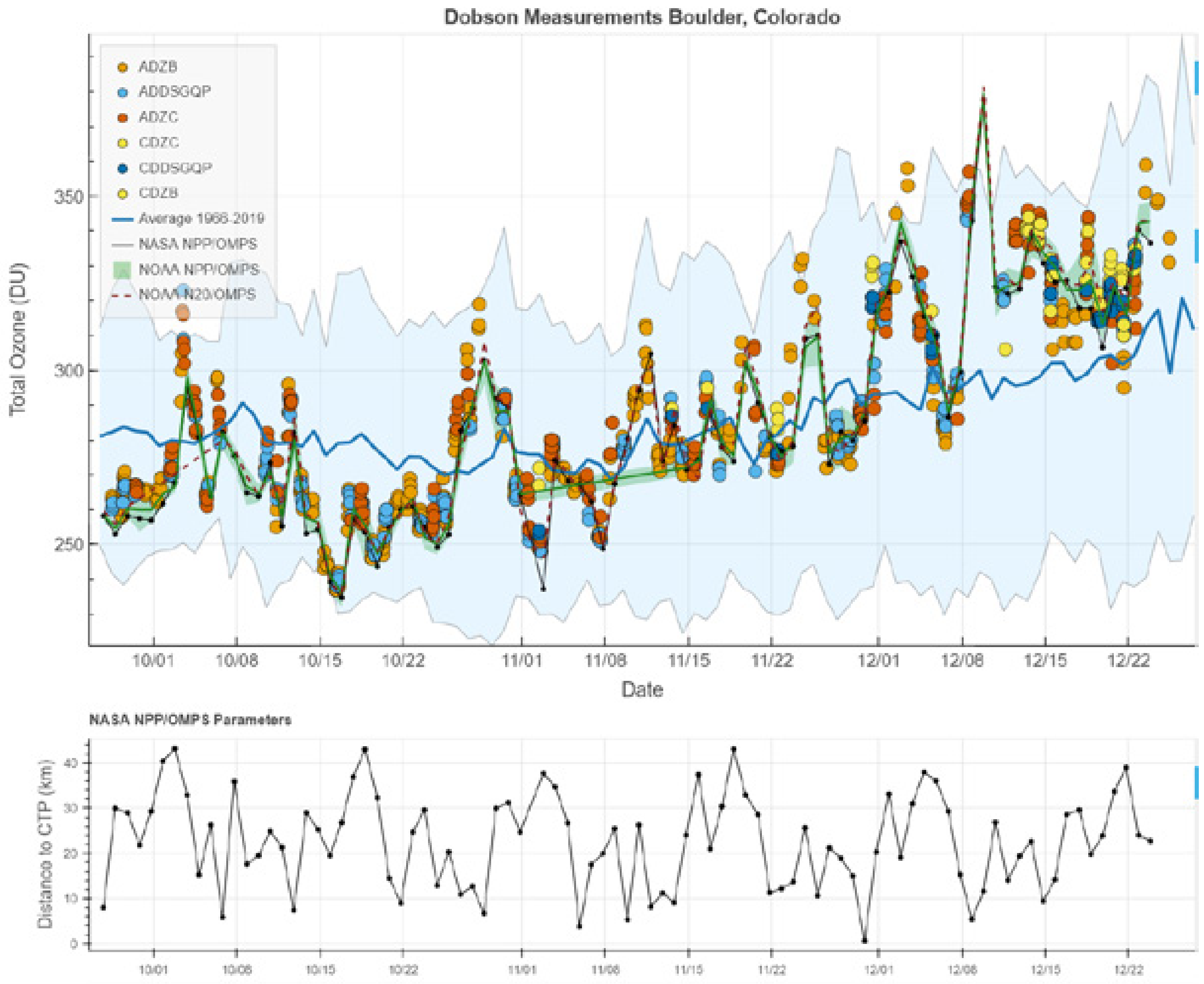
Project Co-leads & Participants
Bryan Johnson, Glen McConville, Koji Miyagawa, Eric Beach, Jeannette Wild, Nicholas Nalli, Tong Zhu, Ken Prior, Jianguo Niu, Dale Hurst, Gary Morris, Changyi Tan, Chunhui Pan, Zhihua Zhang, Robert Lindsay

Ozone and water vapor in the upper troposphere and lower stratosphere (UTLS) are key radiative absorbers, significantly influencing the radiative budget, surface temperatures, and precipitation patterns. Global recovery of stratospheric ozone has been documented, but this recovery rate is affected by climate change and potentially other factors like albedo modification interferences (intentional efforts to increase the amount of sunlight that is scattered or reflected back to space). Plus, the factors driving long-term changes in UTLS composition are not fully understood. The increase in the tropospheric ozone burden and its health impacts, as studied by the International Global Atmospheric Chemistry (IGAC) Tropospheric Ozone Assessment Report Phase II, point to the need for a more extensive network of ground-based and aircraft observations. Satellite sensors, including the JPSS Ozone Mapping and Profiler Suite (OMPS) and CrIS, provide a global perspective on ozone across the stratosphere, UTLS, and troposphere, crucial for monitoring pollution, confirming stratospheric ozone recovery, and assessing climate change impacts through tracking changes in upper atmospheric water vapor. Addressing the long-term stability, representativeness, and uncertainty of satellite products is vital for both users and distributors. The initiatives under this theme are specifically designed to tackle these challenges. Selected outcomes relevant to the JPSS program from Theme #2 are summarized below. Other activities, such as balloon launches to deploy ozonesondes and frost point hygrometers in strategic areas to capture expansion of the tropics and shifts in global atmospheric circulation, were also performed.

- **Sustainability and Expansion of Ground-based Measurements:** Over the past 40 years, NOAA OAR/GML has been consistently gathering, calibrating, and verifying ozone and water vapor observations. In 2021 and 2022, GML continued to collect carefully calibrated records including daily total column ozone measurements, daily ozone profiles, weekly detailed ozone profiles, and monthly water vapor profiles. These datasets serve as benchmarks for daily ozone and water vapor observations from instruments on the Suomi NPP and NOAA-20 satellites, namely OMPS and CrIS.

The primary goal of this effort was to extend the reference records for ozone and water vapor by an additional year. Additionally, the long-term ground-based observations were used to confirm the consistency of ozone records from satellites. This is crucial for developing a cohesive, long-term global satellite record of ozone (termed "COHesive (COH) dataset"), which is vital for climate research and predicting future Earth conditions. The NOAA COH dataset combines OMPS and Solar Backscatter Ultraviolet Instrument (SBUV) data creating an over 40-year record of ozone data for use in trends and ozone monitoring.

- **Upgrading Near Real-Time (NRT) Systems For Data Collection:** The ground-based data collected by GML are essential for evaluating the long-term stability and accuracy of spatial and temporal variations in operational satellite retrievals of ozone and water vapor. From 2020 to 2022, NOAA enhanced its ground-based and in situ observation systems to enable near real-time (NRT) data collection. This upgrade facilitates efficient data gathering, quality assurance, and processing.



Above top: Total ozone for October 1-December 22, 2023, from Dobson Stations at GML in Boulder, Colorado. Above bottom: Total ozone for the same period from Suomi NPP OMPS. The goal is tracking stability of OMPS satellite observations with respect to GML ground-based observations in near real-time. Source: https://gml.noaa.gov/ozwv/dobson/plots/

Significant updates were made to the GML operational Dobson data system at locations including Boulder, Mauna Loa Observatory, the South Pole, and Lauder. These updates involve 3-month plots that compared ground-based and satellite station overpass observations, available on the GML website. These plots are crucial for monitoring the consistency of records and for comparing the Suomi NPP OMPS operational ozone products with the calibrated ground-based reference, specifically the Dobson ground-based total column ozone measurements.

Dobson Data

The Dobson Ozone Spectrophotometer, developed in the 1920s, has been a crucial tool for studying total ozone, the total amount of ozone in the atmospheric column from the Earth's surface to the edge of the atmosphere. This instrument plays a significant role in global efforts to understand the impact of stratospheric ozone on atmospheric chemistry, the biological and ecological effects of solar UV radiation, and its influence on climate and weather. The GML operates 15 stations worldwide that utilize the Dobson Ozone Spectrophotometer for measuring total ozone.

- **Restoration of Dobson Observations In the Southern Hemisphere:** The Southern Hemisphere has limited Dobson observational capabilities, and notably, the Dobson instrument in Perth, Australia, has been non-operational since 2016. The Perth location is crucial for understanding the differences in global circulation between the Southern and Northern Hemispheres, which plays a significant role in detecting, attributing, and forecasting the recovery of global ozone levels. Additionally, Southern Hemisphere observations are vital for understanding the differences between the Suomi NPP and NOAA-20 OMPS operational ozone profile products.

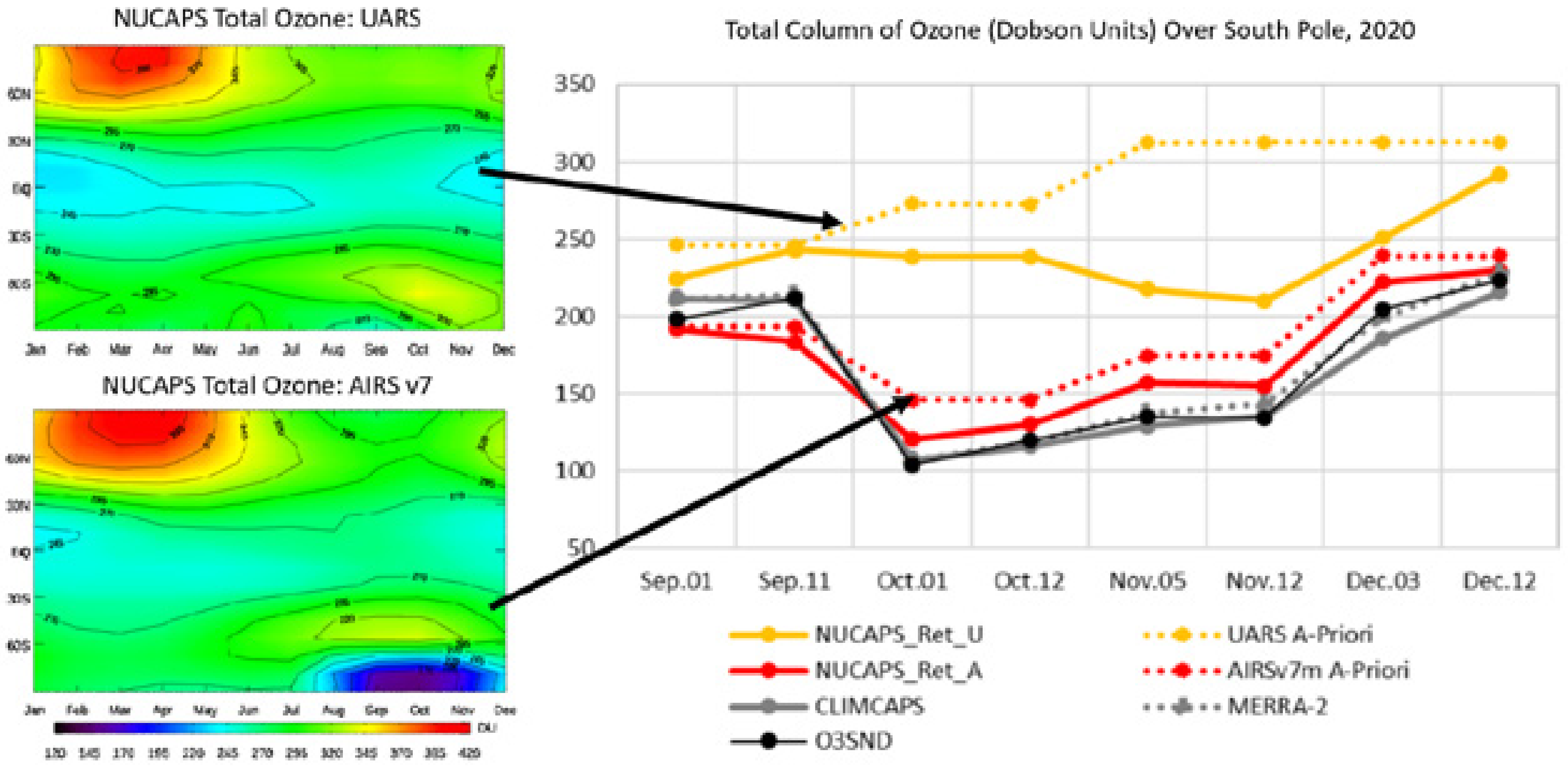
  In response to this need, GML transported the Perth Dobson instrument to Boulder, Colorado, in the winter of 2022. During its time in Boulder, the instrument was fitted with the new WinDobson operational system—a unique software package for operation, data analysis, and quality assurance of Dobson spectrophotometer observations—and underwent calibration. It was returned to Perth in late 2022. In addition, a comprehensive inter-comparison of satellite ozone products, including both total column and profile measurements, against the Dobson instrument was performed.

- **Data Product Development and Analyses:** GML initiated the development of a system for near real-time delivery of ground-based data via the NOAA GML FTP platform. This system is designed to format the data (specifically in NetCDF format) to facilitate rapid evaluation of NESDIS satellite retrievals. A key aspect of this initiative is the creation of ozonesonde collocations that align with satellite-retrieved ozone products. This alignment enables direct comparisons between satellite data and in situ measurements from ground and airborne sources. To enhance the accuracy of these comparisons, GML employs NUCAPS and Umkehr 9-layer Averaging Kernels to refine ozonesonde profiles (Umkehr ozone profiles are retrieved from Dobson spectrophotometers). The application of Averaging Kernels smooths the in situ profiles, thereby reducing biases, and enabling a more effective evaluation of the information content in the compared products. This approach is essential for ensuring the reliability and precision of satellite data evaluations.

A Dobson spectrophotometer. Source: https://gml.noaa.gov/ozwv/dobson/

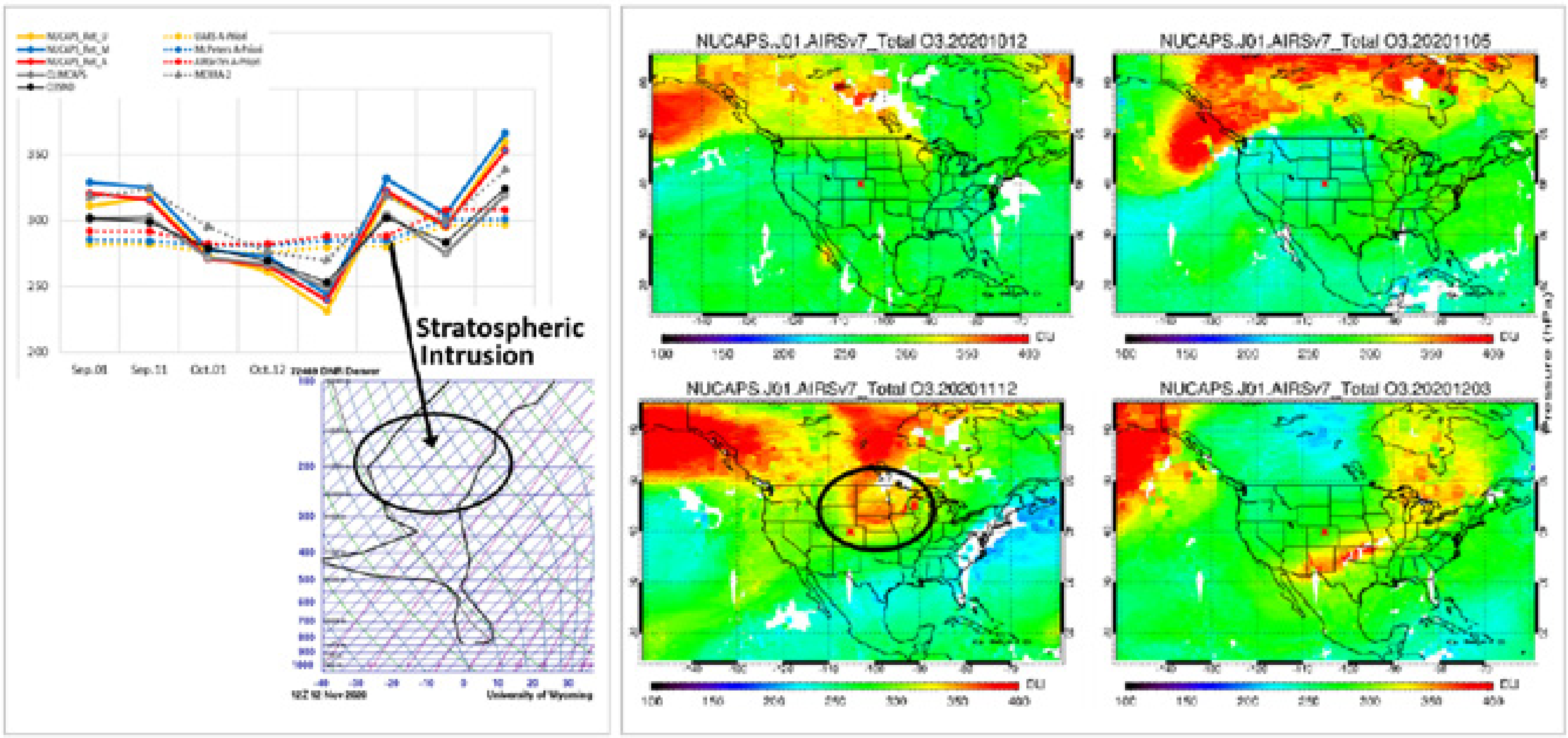
Several NUCAPS and CLIMCAPS ozone profile data packages were generated using the ground-based station overpass criteria, focusing on specific dates in 2020 (CLIMCAPS stands for the Community Long-term Infrared Microwave Combined Atmospheric Processing System, which generates and maintains a long-term record of satellite-based atmospheric soundings across multiple instruments and platforms, specifically from the hyperspectral CrIS and AIRS sensors). These data were compared against records at the South Pole and Boulder, Colorado, and with Suomi NPP OMPS ozone overpass profiles, revealing biases particularly over the Antarctic region due to different a priori profiles. The a priori for NUCAPS ozone profiles was updated following comparisons with operational profiles from various ozonesonde stations, and further improvements are planned in the upcoming NUCAPS version for Suomi NPP and NOAA-20 satellites.

These updates aim to facilitate analysis of long-term trends using reprocessed datasets. Additionally, data from 2017-2022, including from Suomi NPP OMPS, Umkehr ozone profiles from Dobson measurements, and ozonesonde data, were assessed against SAGE III/ISS (the Stratospheric Aerosol and Gas Experiment III onboard the International Space Station) and NASA Aura Microwave Limb Sounder (MLS) records, identifying potential anomalies in Suomi NPP OMPS in 2021-2022, which are currently under investigation.



Right: Evaluation of NUCAPS ozone retrievals over Antarctica during the spring to summer transition (September to December 2020. Data is from NUCAPS, CLIMCAPS, ozonesondes, and MERRA-2. Top left: NUCAPS ozone retrievals from UARS (ozone a priori validated maturity version, top). Bottom left: NUCAPS ozone retrievals from AIRS (ozone new a priori, bottom).

A variety of NUCAPS sounding products are currently ingested into the Advanced Weather Interactive Processing System (AWIPS, the processing and display system that is the cornerstone of National Weather Service operations) for their utility by many Weather Forecasting Offices (WFOs) nationwide for analyzing atmospheric instabilities, potential outbreaks of severe weather, and now-casting applications. One such investigation of the NUCAPS ozone product analyses indicated the potential for stratospheric intrusion during the second week of November 2020 (below left). The development of a deep mid-to-upper level low-pressure trough over the Western U.S. reflected an increase of ozone as measured by NUCAPS, as well as ground-based measurements over Boulder, Colorado on about November 12, 2020. NUCAPS-derived total ozone maps (below right) show a cyclonic orientation associated with the cyclogenesis and frontogenesis over the following week that eventually resulted in a severe weather outbreak over the Eastern U.S.



The availability of NUCAPS infrared (IR) ozone retrievals from both afternoon orbit (NOAA-20) and late morning orbit (MetOp-C) allows for the study of diurnal ozone variations. Further, the availability of NUCAPS IR retrievals over the polar night scenes adds an additional advantage of continuous coverage of retrieval products to study ozone variations over the poles. In addition to the OMPS Nadir Mapper, OMPS Nadir Profiler, and OMPS Limb Profiler products, NESDIS operationally produces the Total Ozone from Analysis of Stratospheric and Tropospheric components (TOAST) product combining the NUCAPS IR ozone product with the OMPS products leading to improved product accuracy.

Theme #2 involved various key players and projects, prominently featuring the WMO-UNEP Ozone Assessment 2022, which utilized GML and NESDIS ozone records for trend analysis. LOTUS (Long-term Ozone Trends and Uncertainties in the Stratosphere), a research activity supported by SPARC, used the COH dataset (NOAA's COHesive ozone record) and ground-based data for data homogenization and comparing ozone anomalies. Other significant outputs include extension of the COH product's long-term record by a year for enhanced trend analysis and the impending integration of the NUCAPS ozone product into AWIPS, further expanding its application scope.

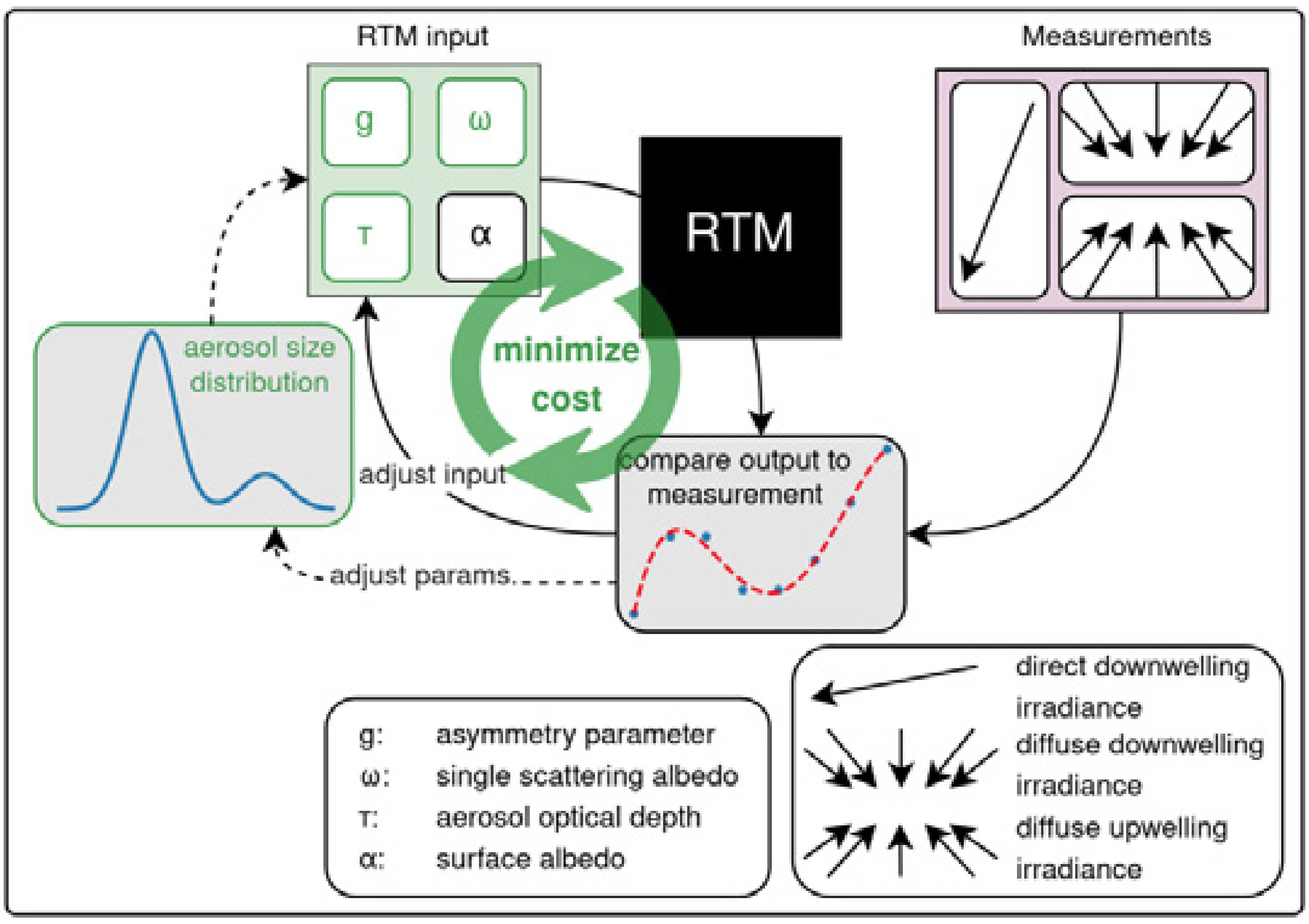
Theme #3: Monitoring and Understanding Changes in Surface Radiation, Clouds, and Aerosol Distributions (NGsT3)

Project Leads
Hagen Telg, Kathy Lantz, John Augustine, Istvan Laszlo, Shobha Kondragunta, Yunyue Yu, Andrew Heidinger, Norm Wood

The Theme #3 project, NGsT3, aimed to achieve five primary goals: 1) establishing strong communication, 2) maximizing data sharing, 3) developing tailored data products, 4) enhancing cal/val activities, and 5) conducting field studies. The communication goal focused on regular meetings to share research, measurement principles, and ideas for joint projects. Data sharing emphasized the importance of accessible, comprehensive data for successful cal/val and scientific activities. Product development aimed to create data products that meet the specific needs of both NESDIS and OAR/GML, aligning development efforts for mutual benefit. Cal/val activities, traditionally led by NESDIS, now involve GML in developing independent validation procedures and collaborative validation during specific atmospheric conditions. Lastly, field studies involved planning and executing measurements that support this collaboration, including integrating new measurements at network sites and participating in field campaigns. Selected major outcomes from these activities that are relevant to the JPSS program are highlighted below. Additionally, many other activities were performed by the NGsT3 team to improve and evaluate geostationary satellites and ground-based observations.

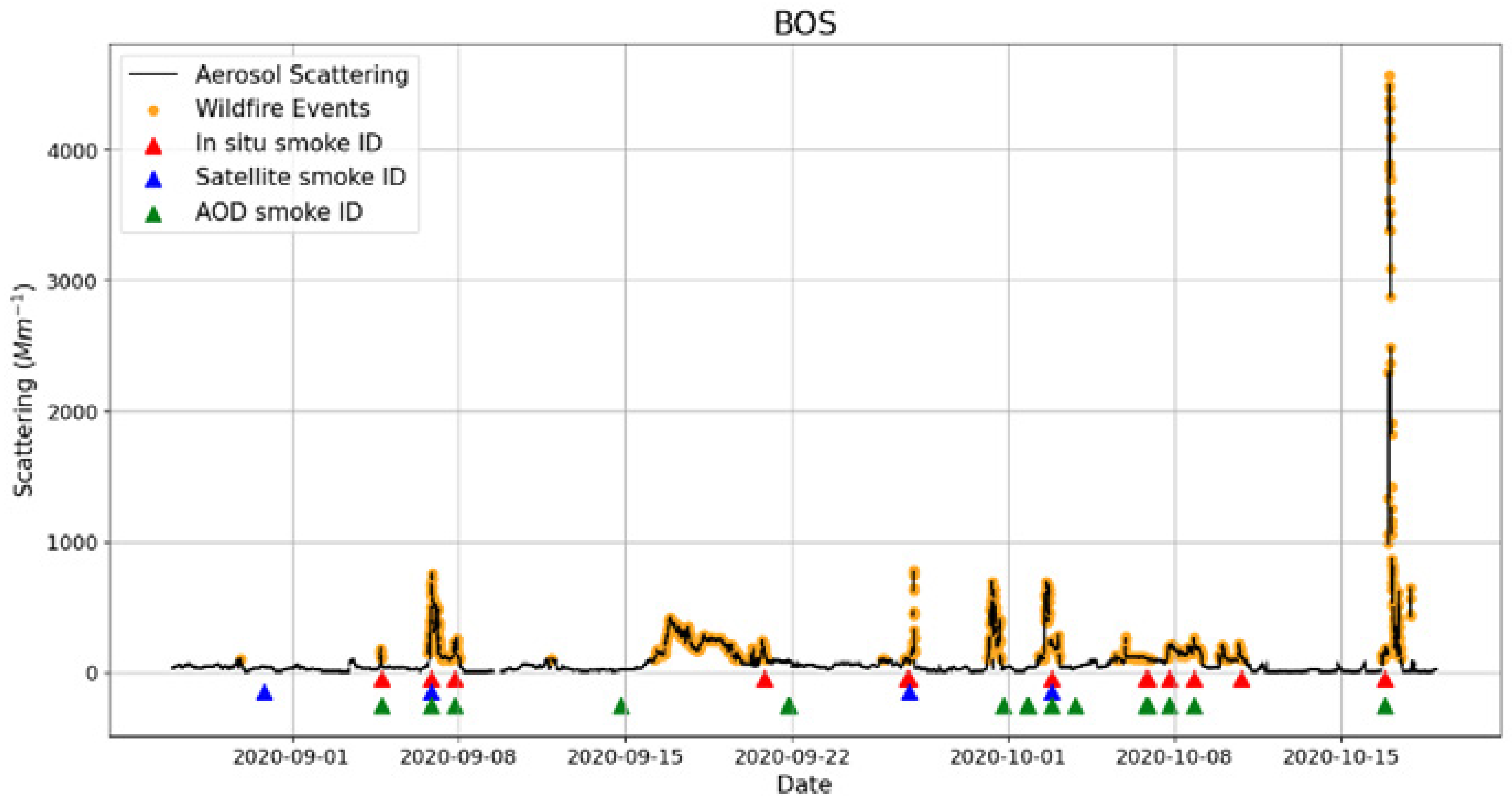
Progress by the GML Global Radiation, Aerosols and Clouds (GRAD) program in the development of the spectral surface albedo provided a key component in an inversion strategy of aerosol properties (particle single scatter albedo (ω), aerosol asymmetry factor (g), size). This strategy, which is depicted in the chart below, comprises a fit routine that optimizes the input parameters for aerosols of a radiative transfer model, such that the model's output of spectrally resolved direct and diffuse upwelling and downwelling irradiances matches their observatory counterparts. Resulting aerosol properties, which are all relevant to satellite observations, include the asymmetry parameter, single-scattering albedo, and aerosol optical depth. It is further possible to estimate the aerosol size distribution as it can be used to derive the aforementioned aerosol parameters.

A cal/val activity performed by the team involved wildfire analysis at the Table Mountain observation site north of Boulder, Colorado. In this activity, three methods of smoke detection were evaluated: 1) detection by in-situ surface aerosol measurements, 2) detection by the NOAA-20 polar-orbiting satellite, and 3) detection by SURFRAD (Surface Radiation Budget) Network aerosol optical depth (AOD) measurements. The analysis is preliminary, as the team is currently only comparing these methods at the Table Mountain location.



Strategy for an inversion of aerosol optical and microphysical properties from short wave radiation measurements.

Smoke is detected using the in-situ surface aerosol measurements by setting a threshold for aerosol scattering coefficient (which indicates aerosol amount) of 100 Mm-1, and then confirming this detection with an aerosol typing matrix using absorption Ångström exponent (which indicates aerosol composition) and scattering Ångström exponent (which indicates aerosol size). Smoke is detected by satellites through use of thresholds on the aerosol absorbing index (AAI) and dust smoke discrimination index (DSDI). Smoke is detected using the SURFRAD AOD



Comparison between different smoke detection methods.

measurements by analyzing 15-minute moving windows of the computed column Ångström exponent for stability, where stable periods indicate smoke. Initial results show that in general, all three smoke detection methods do well at identifying thick smoke at Table Mountain (see plot above). Thin smoke events are harder for the satellites to detect. To dig deeper into hypotheses as to why satellites are not detecting thin smoke events, the team will be extending the analysis to more satellites, additional stations, and longer time periods.

For another cal/val activity, NESDIS STAR used GML's smoke classification in evaluating the JPSS Visible Infrared Imaging Radiometer Suite (VIIRS) smoke mask product. Preliminary analysis of two months of data is complete and the study was extended to more locations, adding dust in addition to smoke, and covering two years' worth of Suomi NPP and NOAA-20 VIIRS data. The analysis of two months of data for the Table Mountain observation site showed that VIIRS misses detecting thin smoke plumes but does well detecting thick smoke plumes. Other similar work involved evaluating data from geostationary satellites.

The Theme #3 collaboration between NESDIS, GML, and their predecessor departments and laboratories played a crucial role in the calibration, validation, and development of foundational satellite retrievals, forming the basis of many higher-level products. This collaboration significantly impacted the quality and reliability of satellite data used by various stakeholders. An essential aspect of this collaboration was the quantification of uncertainties in satellite products, which is vital for accurate scientific interpretation and future research. This process also aids product developers in improving retrieval performance. The intercomparisons of cloud property products between NESDIS and GML were key to validating these uncertainties. Furthermore, the collaboration extended beyond the satellite community, reaching users and stakeholders beyond the satellite community.

The SURFRAD Network, initially established to support satellite cal/val, has been instrumental in numerous studies, including validating NOAA's High-Resolution Rapid Refresh (HRRR) model and supporting solar and wind energy research. The consolidation of these efforts under Theme #3 is expected to amplify their impact further.

FORGING AHEAD: THE PROMISING FUTURE OF NESDIS AND OAR COLLABORATIONS

The activities and outcomes detailed herein represent only a small number of the successes stemming from the three-year collaborative efforts between the NOAA OAR Global Monitoring Laboratory (GML) and NESDIS JPSS and Geostationary Operational Environmental Satellites (GOES-R) programs. This partnership has produced significant advancements in environmental monitoring and data analysis, and has set a precedent for future cooperative ventures in the field of atmospheric and Earth sciences. Moving forward, NESDIS and OAR are committed to deepening their collaboration, particularly in the development of innovative products and services in the areas of trace gases, aerosols, clouds, and radiation. These ongoing efforts are expected to enhance the scientific understanding of Earth's systems, contributing to more accurate and comprehensive weather forecasting, global monitoring, and decision-making tools to protect life and property.

Acknowledgement is extended to the late Dr. James Butler, former Director of NOAA's Global Monitoring Laboratory, for his significant contributions and dedication in initiating the collaboration between NESDIS and OAR/GML. His visionary leadership in atmospheric science has greatly advanced global environmental understanding. Dr. Butler's role in fostering this partnership enhanced the capabilities of both organizations, and established a model for future collaborations in atmospheric monitoring and research. ✦

STORY SOURCE

The information in this article is unclassified and based, in part, on NOAA internal reports cited in the references below. It was written in collaboration with Dr. Lihang Zhou, Data Product Management and Services (DPMS) Deputy and JPSS Product Portfolio Manager, JPSS Ground Segment DPMS, NOAA NESDIS Office of Low Earth Orbit Observations (LEO). Portions of the text were compiled from internal reports; content herein is designated unclassified.

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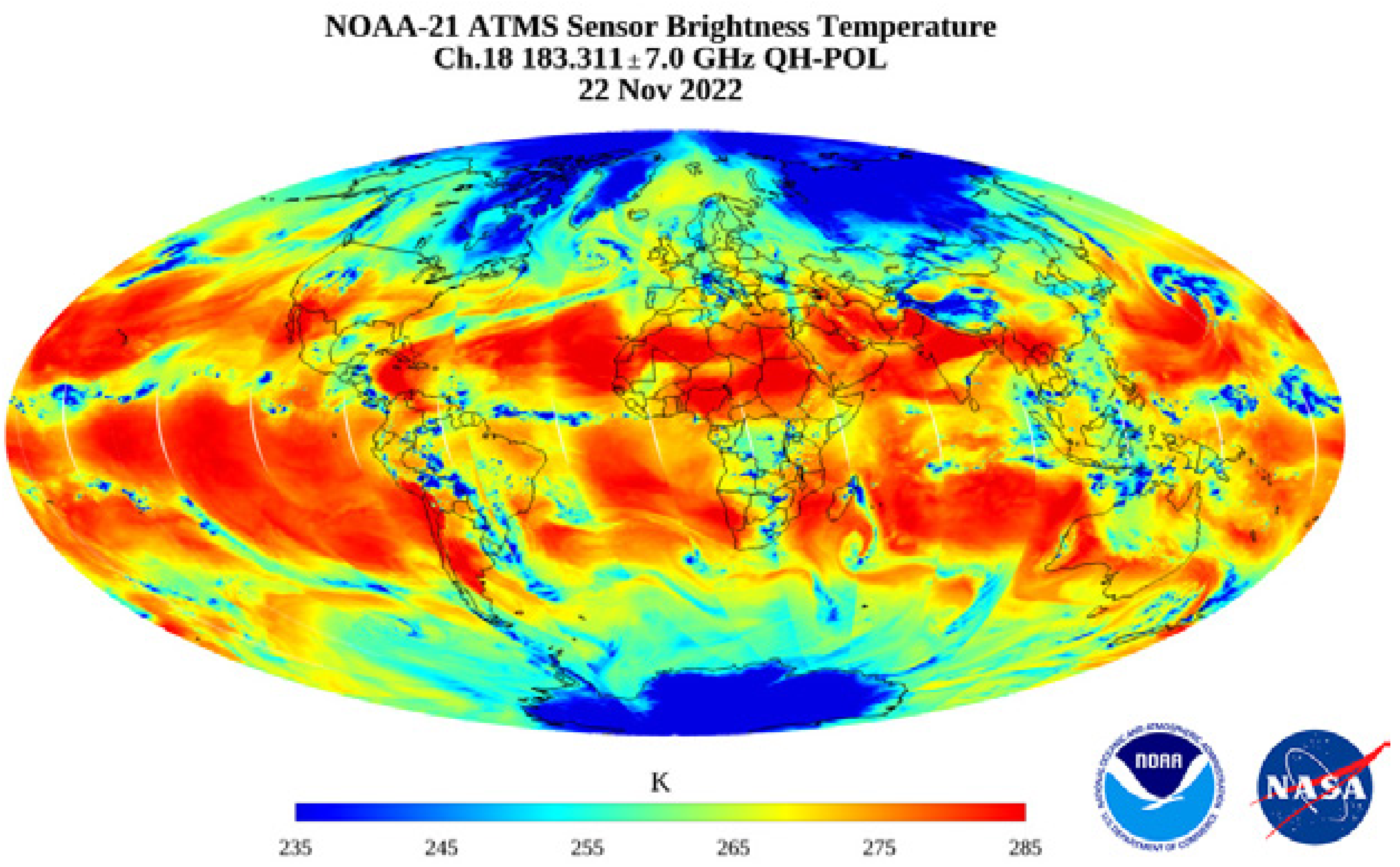
NOVEMBER 23, 2022

FIRST LIGHT IMAGE FROM NOAA-21'S ATMS SENSOR

Jenny Marder
Lead Editor, Earth Science News Team
NASA Goddard Space Flight Center



This image by the NOAA-21 satellite shows global water vapor. Image processing by NOAA/Center for Satellite Applications and Research. Contributors: Mark Liu, Ninghai Sun, NOAA/NESDIS/STAR; Vince Leslie, MIT-LL, JPSS ATMS SDR Team.

The Advanced Technology Microwave Sounder (ATMS) instrument onboard the NOAA-21 satellite captured its first global image on Tuesday, November 22, 2022, 12 days after successfully launching from the Vandenberg Space Force Base, California. Originally known as JPSS-2, the satellite was officially renamed NOAA-21 earlier this week, following NOAA's naming conventions for polar orbiting satellites.

This marks the first in a series of first-light images from NOAA-21's four instruments that will be released by NOAA before the satellite goes into full operational mode. ATMS is a key sensor used for numerical weather prediction models.

The ATMS instrument gives weather forecasters a global 3D picture of our atmosphere's temperature and moisture—the most fundamental information needed by weather models that forecast daily weather and warn us of hurricanes, floods, droughts, heat waves, snowstorms, and other weather events. Because ATMS observes Earth in the microwave portion of the electromagnetic spectrum, it sees through clouds like an X-ray, allowing us to view the structure of the atmosphere underneath those clouds, and see inside of storms.

ATMS works closely with the satellite's Cross-track Infrared Sounder (CrIS) instrument to take detailed measurements of the atmospheric conditions, such as temperature and water vapor soundings, needed to generate extreme weather forecasts days in advance. Data from ATMS also contribute to a global record of atmospheric measurements that dates back 40 years. These data are used in climate models to help us understand how our atmosphere has been changing over time.

“This information is used to determine initial conditions for numerical weather prediction models to provide accurate forecasts for the future,” said Joint Polar Satellite System Program Scientist Satya Kalluri. “ATMS data are also used for measuring precipitation, hurricane intensity and surface temperature.”

The image above from November 22 uses NOAA-21 data to show the state of atmospheric water vapor. Red indicates little water vapor. Light blue shows more abundant water vapor, while dark blue in the polar region indicates surface snow and ice.

Together, NOAA and NASA oversee the development, launch, testing, and operation of all the satellites in the Joint Polar Satellite System 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/first-light-image-noaa-21s-atms-sensor

FEBRUARY 15, 2023

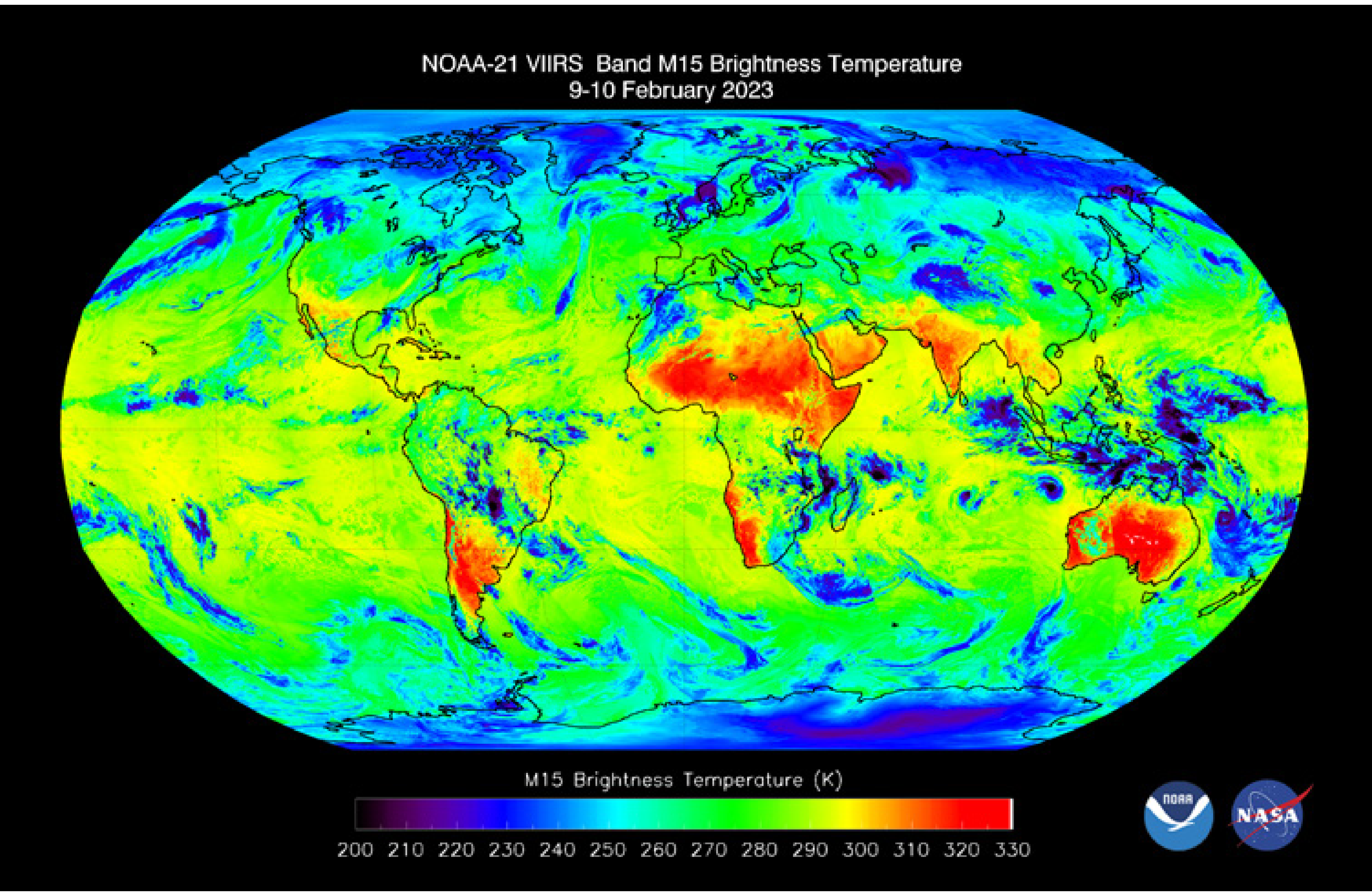
VIIRS SENSOR ON NOAA-21 NOW COLLECTING NEW IMAGERY

Sara Leeds
Science Writer and Social Media Specialist
NOAA NESDIS

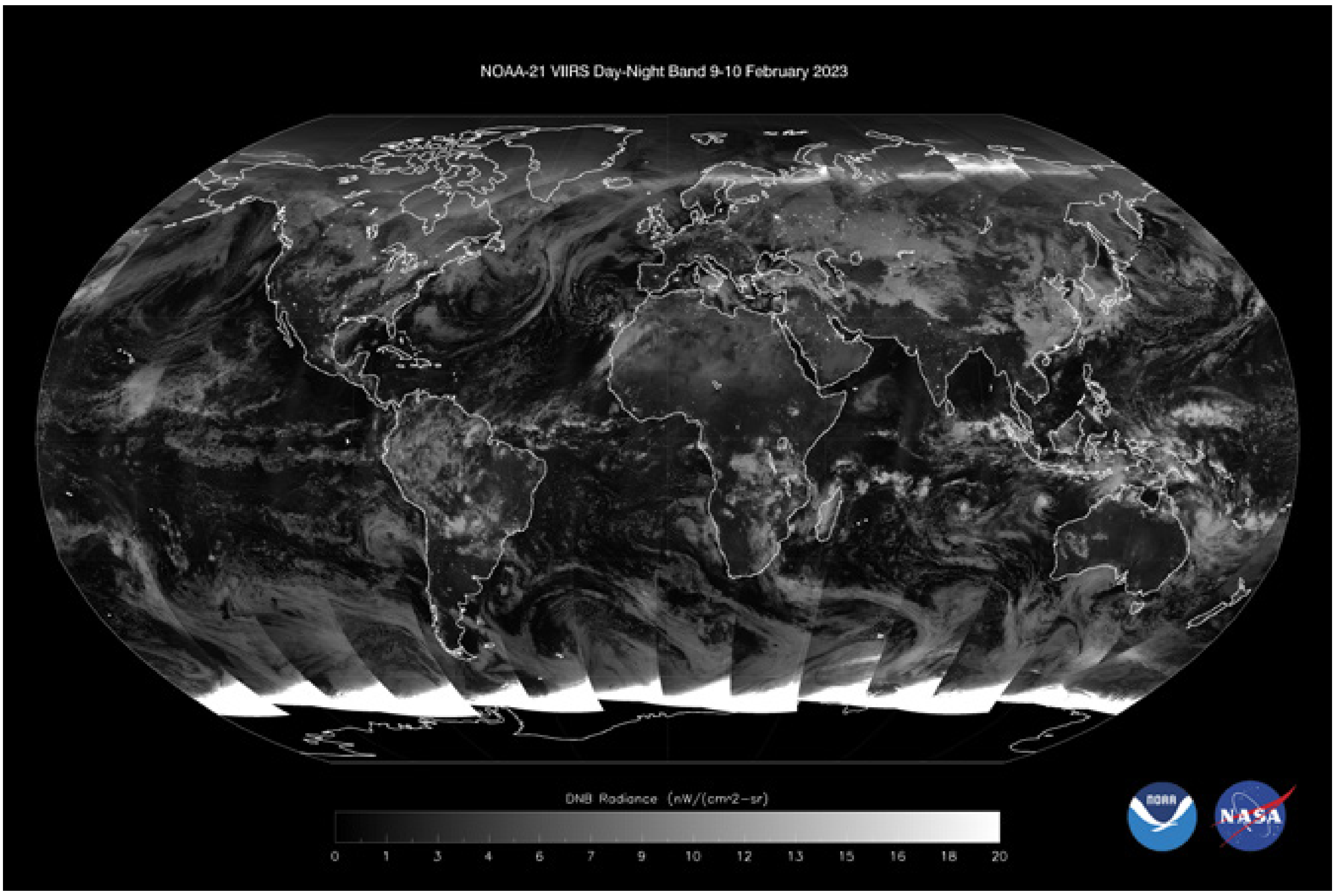
The Visible and Infrared Imaging Radiometer Suite (VIIRS) on the recently launched NOAA-21 satellite started collecting Earth science data from its Day-Night Band (DNB) and its Thermal Emissive Bands (TEB) on Feb. 9, 2023. This comes three months after the satellite launched from Vandenberg Space Force Base on Nov. 10, 2022.

Thermal Emissive Band imaging data has several important applications: It allows for measurements of sea and land surface temperatures, wildfire intensity, and the detection of clouds. This image, captured on Feb. 9 and Feb. 10 shows cold objects such as clouds, snow and ice as blue, and warm surfaces such as deserts in shades of red.

VIIRS on NOAA-21 also started acquiring data in its unique "Day-Night Band (DNB)" on Feb. 9, 2023. Since its debut on VIIRS on the Suomi National Polar-orbiting Partnership (SNPP) satellite more than 10 years ago, the DNB has revolutionized how we view the Earth from space at night. The DNB is a unique VIIRS capability that measures low signals of reflected light illuminated by the moon at night and is used for detecting nighttime clouds and fog. Illumination from manmade sources such as city lights, flaring from natural gas wells, and shipping vessels can also be seen via the DNB.



The following image was created by stitching together the orbit swaths collected from Feb. 9–10, 2023. City lights all over the world are clearly visible in this image. Clouds that are illuminated by the moon are seen in shades of white depending upon the opacity and thickness of the cloud cover. Over Siberia, one can see the aurora borealis (northern lights) as a bright streak. Note that the south polar region is daytime this time of the year and thus is very bright.



Images are generated by the NOAA/NESDIS/STAR/JPSS Sensor Data Record Science Team.

STORY SOURCE

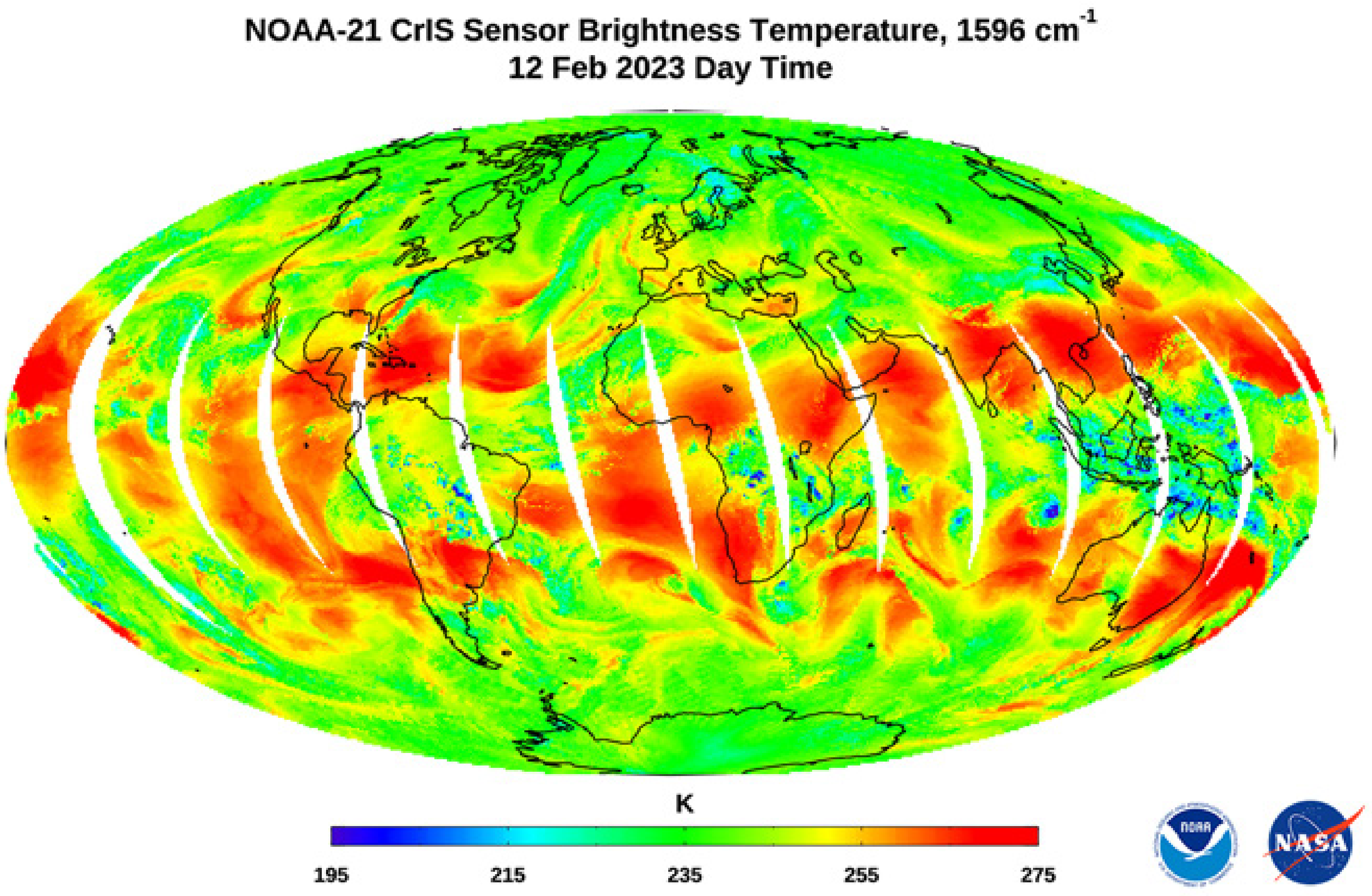
This story was originally published on the NOAA NESDIS website at https://www.nesdis.noaa.gov/news/viirs-sensor-noaa-21-now-collecting-new-imagery

FEBRUARY 16, 2023

FIRST GLOBAL IMAGE FROM NOAA-21'S CrIS INSTRUMENT

Jenny Marder
Lead Editor, Earth Science News Team
NASA Goddard Space Flight Center

Three months after the NOAA-21 satellite launched from Vandenberg Space Force Base, an instrument onboard that provides valuable weather forecasting measurements to global weather models sent back its first science data. The data from the new Cross-track Infrared Sounder (CrIS) instrument will continue the critical infrared soundings that play an important role in numerical weather prediction.



The first light image in brightness temperature was captured by the NOAA-21 CrIS sensor at the 1596 cm-1 water vapor channel on February 12, 2023. This image shows the large-scale waves of upper tropospheric water vapor and clouds over the Earth's globe. Image generated using NOAA-21 Preliminary, Non-Operational Data. Courtesy: NOAA/NESDIS/STAR/CrIS SDR team.

The infrared map above shows water vapor in the troposphere, the lower part of the atmosphere where we live and where weather happens. The red on the map likely indicates areas of drier air, where you're seeing deeper into the atmosphere, said David Johnson, NOAA's Joint Polar Satellite System's (JPSS) CrIS instrument scientist.

"There's that red area that's over Hispaniola that's about 275 degrees Kelvin and you go north of that off the mid-Atlantic coast and it's about 240 degrees Kelvin, so that's higher up in the atmosphere," Johnson said. "That's a region where there must be more water vapor in the atmosphere, since we cannot see through it to warmer air below."

The CrIS sensor provides hyperspectral infrared observations from more than 2,211 channels with high radiometric and spectral accuracy. CrIS measures atmospheric temperature, surface temperature, and several trace gases in the atmosphere, including Carbon Dioxide (CO_2), Ozone (O_3), Methane (CH_4), Sulfur Dioxide (SO_2), Carbon Monoxide (CO), and Nitrous Oxide (N_2O).

The CrIS sensor measures infrared spectra in three spectral bands: the long-wave IR (LWIR) band from 650 to 1095 cm-1, mid-wave IR (MWIR) band from 1210 to 1750 cm-1 and short-wave IR (SWIR) band from 2155 to 2550 cm-1.

When combined with measurements from the Advanced Technology Microwave Sounder (ATMS), these two instruments provide high quality measurements of atmospheric temperature and water vapor, which allow forecasters to predict extreme weather events like thunderstorms and atmospheric rivers, along with daily weather.

"CrIS takes detailed profiles of temperature and water vapor that forecasters use to measure atmospheric instability," said NOAA's JPSS Program Scientist, Dr. Satya Kalluri.

These first global images are part of a series of events that includes instrument activation, intensive calibration and validation activities that occur before the satellite is declared fully operational.

Together, NOAA and NASA oversee the development, launch, testing, and operation of all the satellites in the Joint Polar Satellite System program. NOAA funds and manages the program, operations, and data products. On behalf of NOAA, NASA and commercial partners develop and build the instruments, spacecraft, and ground system, and launch the satellites.

STORY SOURCE

This story was originally published on the NOAA NESDIS website at https://www.nesdis.noaa.gov/news/first-global-image-noaa-21s-cris-instrument

FEBRUARY 24, 2023

OZONE-MEASURING INSTRUMENT ON NOAA-21 SATELLITE CAPTURES ITS FIRST IMAGES

Jenny Marder
Lead Editor, Earth Science News Team
NASA Goddard Space Flight Center

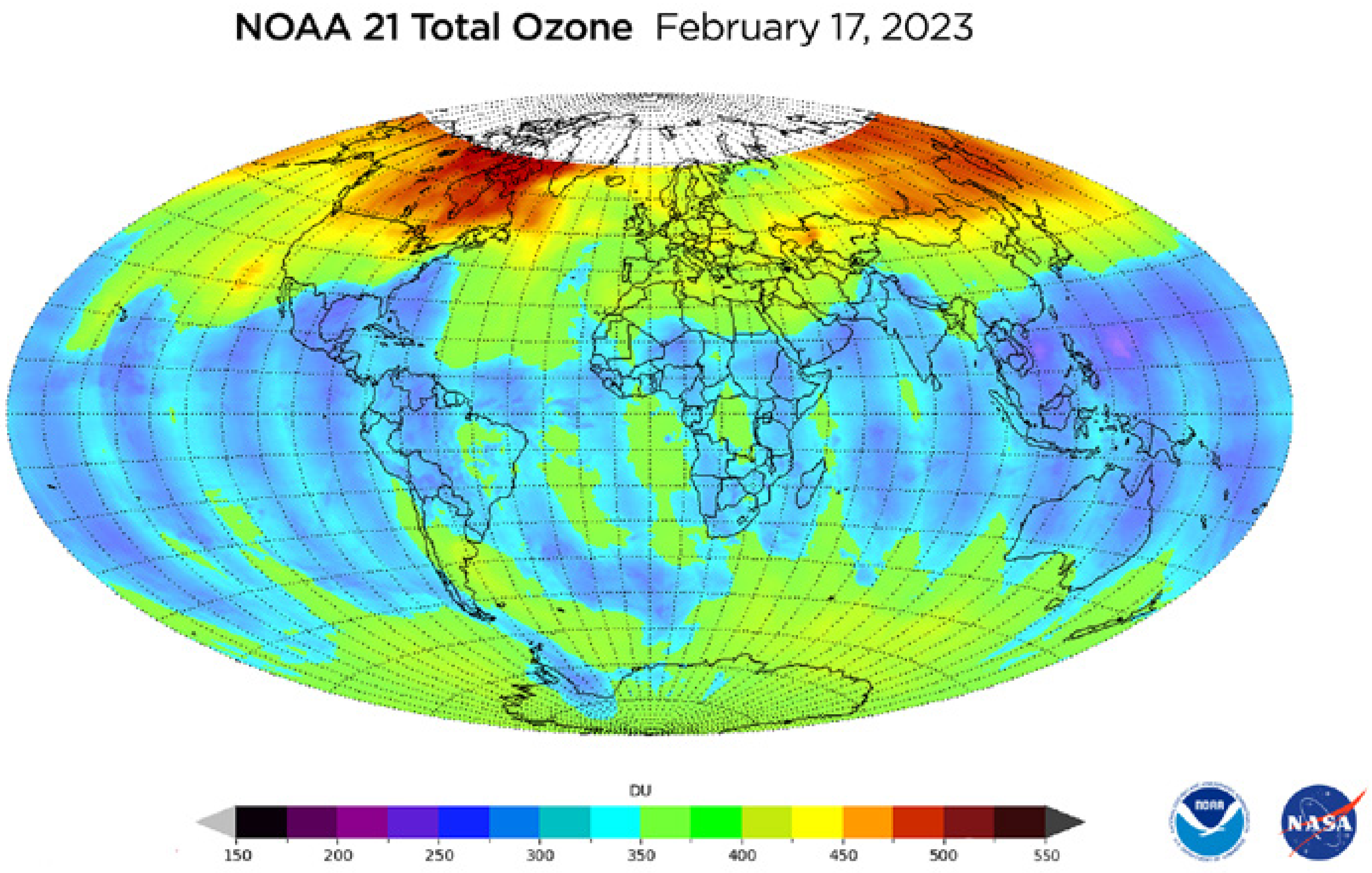


Figure 1. Total ozone measured by the OMPS NM on February 17, 2023. Credit: NASA/NOAA/JPSS

On Feb. 9, an ozone-measuring instrument on the NOAA-21 satellite opened its doors and, about a week later, captured its first global image since the satellite's Nov. 10 launch. The Ozone Mapping and Profiler Suite (OMPS) consists of a set of three sensors that are vital for monitoring the Earth's ozone layer and tracking its recovery as the amounts of atmospheric ozone-depleting chemicals decline.

The top image shows total ozone in the atmosphere distributed across the globe. Higher ozone levels are concentrated near the North Pole, which is typical for this time of year.

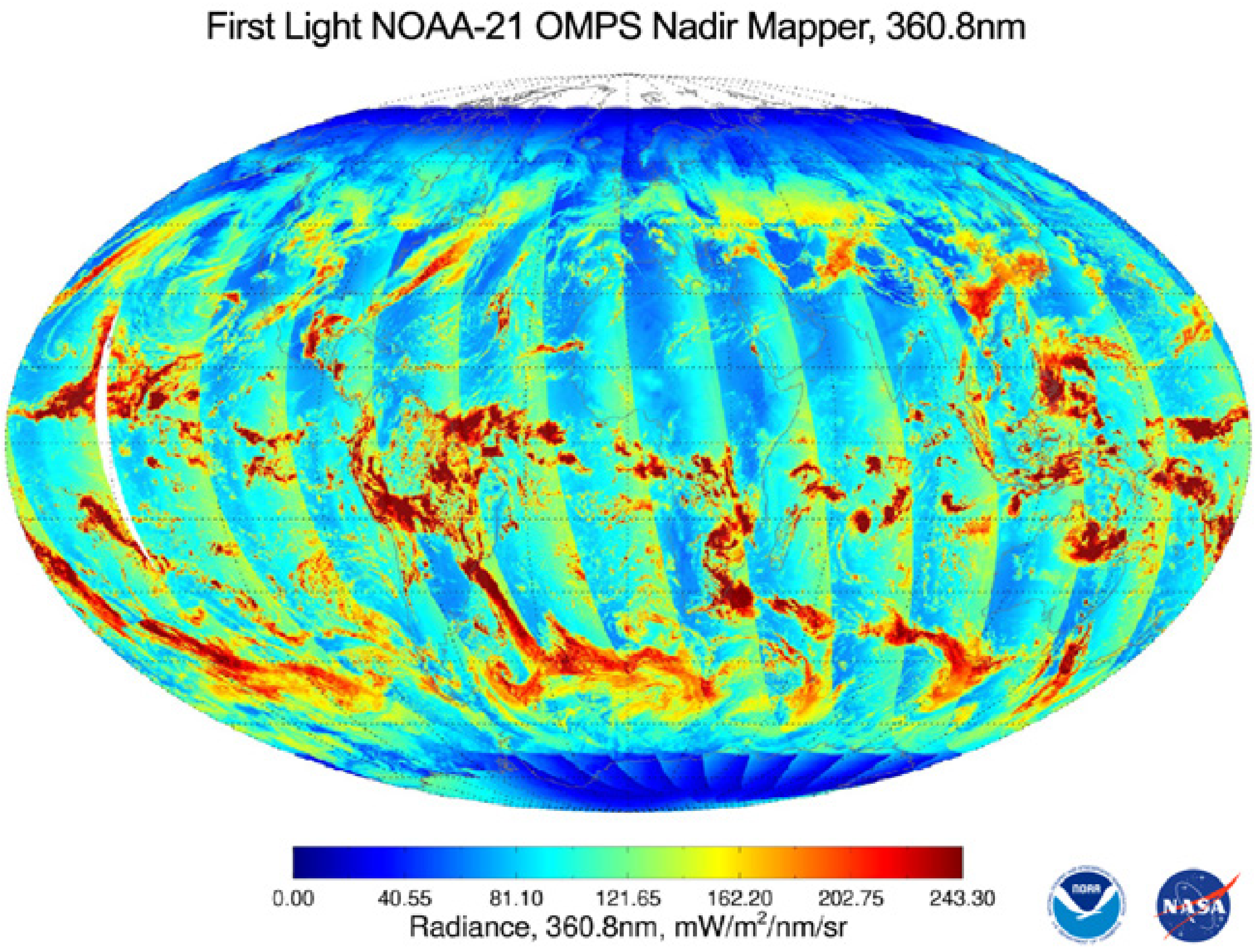


Figure 2. OMPS Nadir Mapper image from February 17, 2023 at 380 nm Credit: Banghua Yan, Likun Wang, Trevor Beck and Ding Liang, NOAA/NESDIS/STAR, JPSS OMPS SDR Team

The image above (Figure 2) shows a global mosaic of observations, taken on February 17 by the instrument's Nadir Mapper. The highest radiances are associated with bright cloud tops. The cloud reflectivity channel is one of the five primary channels used to estimate total ozone concentration.

On the same day, NOAA-21's OMPS also detected volcanic aerosols left over from the massive Hunga Tonga underwater volcano that began powerfully erupting in the South Pacific a year ago, spewing water vapor and sulfur dioxide into the stratosphere (See Figure 3).

OMPS was originally designed to measure ozone high in the atmosphere, which protects humans and other life on Earth from the harmful effects of ultraviolet radiation.

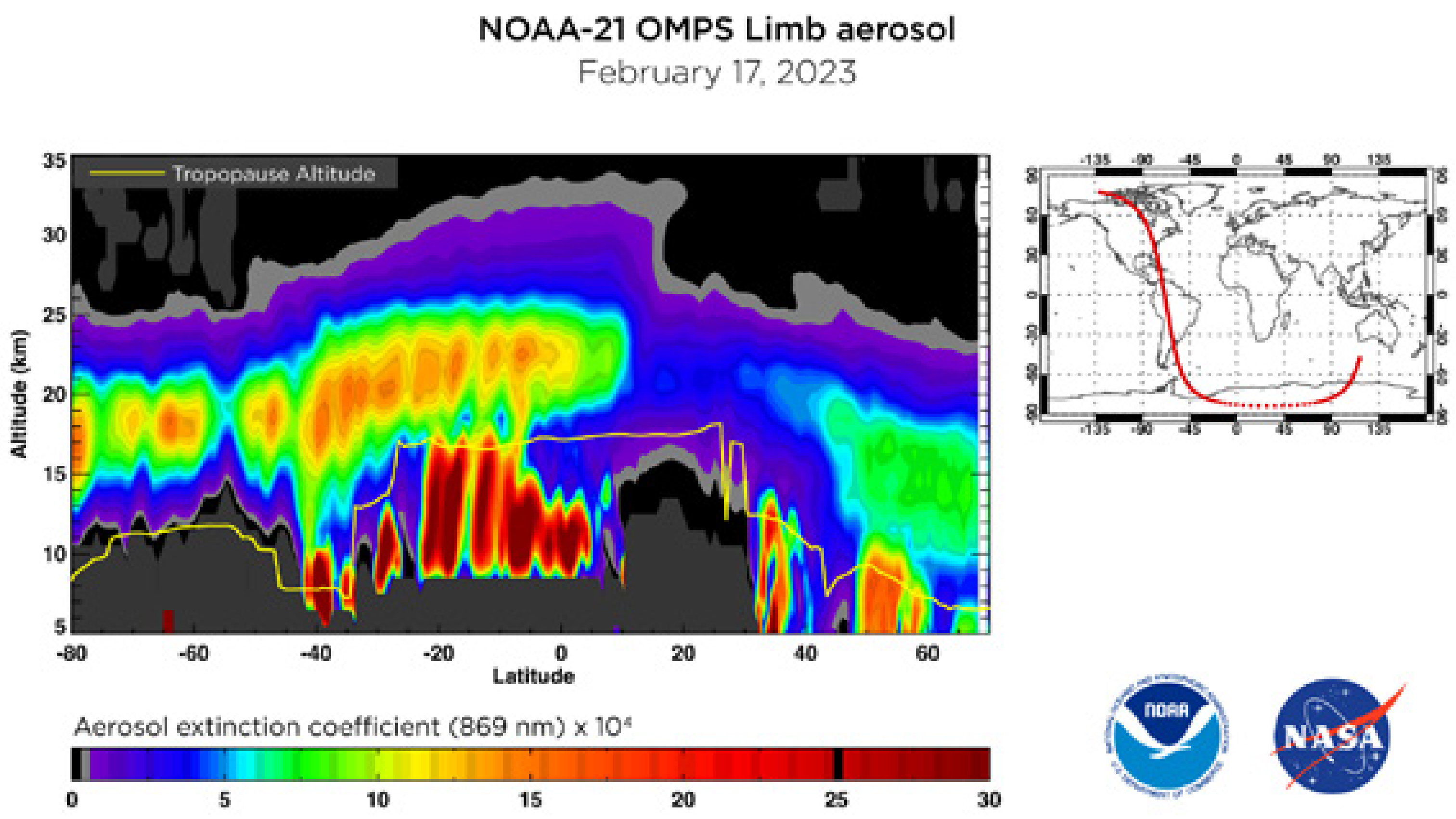


Figure 3: The OMPS limb instrument on the NOAA-21 satellite on Feb. 17 detected sulfates remaining from the January 2022 Hunga-Tonga volcanic plume eruption between an altitude of 12 to 15 miles in the tropics. Credit: NASA/NOAA/JPSS

“The goal was to be able to really make very precise measurements of ozone over long timescales,” said Glen Jaross, the OMPS instrument scientist for NOAA's Joint Polar Satellite System (JPSS). “We want to be able to measure ozone changes to a percent or better over a 10-year timescale.”

Over time, the OMPS instrument's capabilities have expanded to include other aerosols, such as smoke from wildfires and sulfur dioxide and ash from volcanoes.

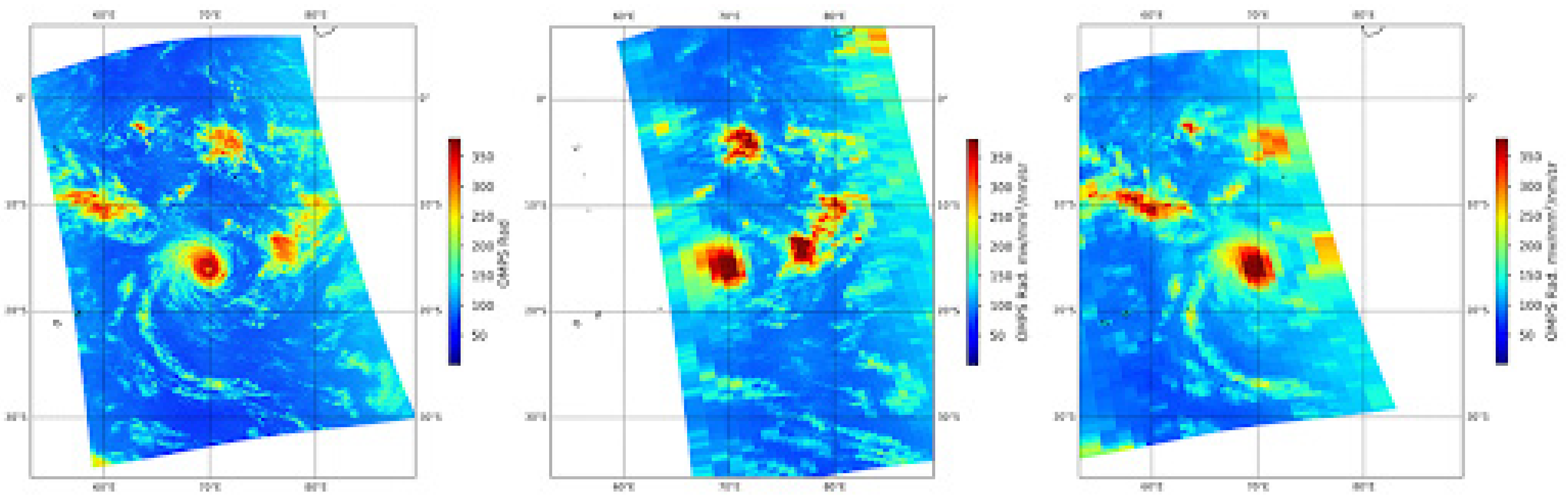


Figure 4: Image on the left is from the OMPS Nadir Mapper at 380nm on NOAA-21, the middle image is from NOAA-20 and the one on the right is from Suomi NPP. All three images were taken on February 18, 2023, over a tropical storm in the Indian Ocean around 70E longitude, and 16S latitude. Credit: Banghua Yan, Likun Wang, Trevor Beck and Ding Liang, NOAA/NESDIS/STAR, JSTAR OMPS SDR Team

OMPS can also capture the cloud structure of severe weather events. The three images above (Figure 4), were taken on February 18, 2023, over a tropical storm in the Indian Ocean. The image on the left is from NOAA-21's OMPS instrument and the picture on the right is from OMPS on NOAA-20. The cloud structure is more clearly visible from OMPS on the NOAA-21 satellite compared to those from NOAA-20 and Suomi NPP. This is due to the improved spatial resolution of the latest instrument.

NASA began measuring ozone from space in 1970, not long before scientists discovered that harmful chemicals called chlorofluorocarbons, or CFCs, result in a dangerous depletion of atmospheric ozone. By the mid-1980s, scientists discovered a hole in ozone in the stratosphere over the Antarctic. A global effort to ban these gases has resulted in the stabilization of ozone levels over the past three decades, with recent measurements indicating ozone levels are beginning to increase.

OMPS instruments, which also fly on NOAA-21's sister satellites, NOAA's Joint Polar Satellite System's NOAA-20 and Suomi-NPP, along with an instrument aboard the Aura satellite, showed that between Sept. 7, 2022, and Oct. 13, 2022, the Antarctic ozone hole had reached an average area of 8.9 million square miles, an area slightly smaller than last year, continuing a shrinking trend.

Last week, engineers sent a command to OMPS, directing a mechanism to open the nadir and limb sensor doors, according to Natalie Ciampa, the OMPS instrument manager for JPSS. This allowed the instrument to start collecting data.

OMPS detects what's known as "backscattered" light from the atmosphere. That's sunlight that reflects off either the atmosphere or the Earth's surface. OMPS does this by looking at the sun and measuring the direct solar signal and then turning to Earth to measure the fraction of that signal that gets reflected back.

Think of the Earth as a laser shining on a disco ball, Jaross said. The sun is like a laser, and all the sparkles are light reflected off the Earth. "And OMPS is sitting out there, and it's picking up all that light."

OMPS measures atmospheric ozone in two ways, by mapping total ozone over the globe using the Nadir Mapper, and by probing the atmosphere vertically to collect precise measurements at different altitudes using the Nadir Profiler and the Limb Profiler. The suite's nadir instrument (NM), operated by NOAA, points directly down at Earth, and the limb instrument (LP), operated by NASA, measures from an angle. And this latest version on NOAA-21 has some improvements.

The spatial resolution on NOAA-21's OMPS mapping instrument has improved. While the nadir footprint of the Suomi-NPP satellite was about 30 by 30 miles, the resolution on NOAA-21 OMPS can now measure about 6 by 6 miles. The latest instrument also provides the capability to measure nitrogen dioxide, a precursor to ground-level ozone, the primary ingredient in smog. This is not to be confused with stratospheric ozone high in the atmosphere that protects humans and other life against ultraviolet rays.

"Quantifying these atmospheric species is important for a variety of reasons, including monitoring the ozone layer and its interactions with climate change, tracking volcanic sulfur dioxide and ash for air traffic safety, and identifying pollution sources and levels for general air quality health assessments," said JPSS Program Scientist Satya Kalluri.

Together, NOAA and NASA oversee the development, launch, testing, and operation of all the satellites in the Joint Polar Satellite System 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.

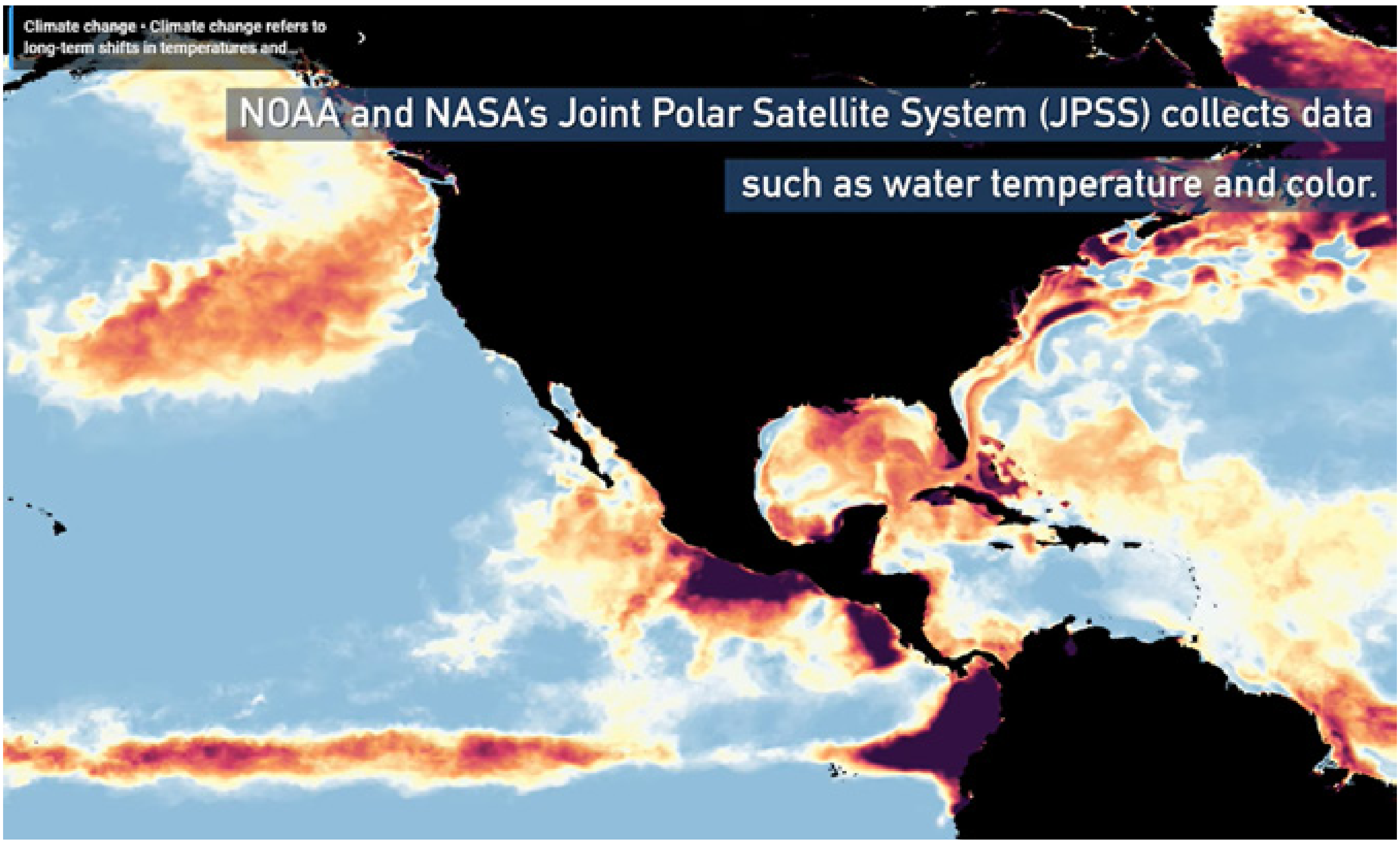
STORY SOURCE

This story was originally published on the NOAA NESDIS website at https://www.nesdis.noaa.gov/news/ozone-measuring-instrument-noaa-21-satellite-captures-its-first-images

AUGUST 18, 2023

EXTREME OCEAN TEMPERATURES ARE AFFECTING FLORIDA'S CORAL REEF

Sara Leeds, Amanda Keener
Science Writer and Social Media Specialist
NOAA NESDIS



Since April 2023, NOAA has been monitoring a steady rise in ocean temperatures, which is resulting in unprecedented heat stress conditions in the Caribbean basin, including waters surrounding Florida and the Gulf of Mexico. On Thursday, August 17, 2023, NOAA scientists provided a briefing on how these record-breaking warm ocean temperatures have stressed, bleached, and in some cases, killed corals within the 3,800 square miles of the Florida Keys National Marine Sanctuary.

Coral reefs are often referred to as the "rainforests of the sea," due to their incredible biodiversity and ecological importance. They provide vital benefits as part of marine ecosystems by sustaining habitats for marine life, buffering the harmful impacts of storms on coastal communities, and supporting local economies through tourism and fishing.

According to the briefing, a large-scale heat stress and coral bleaching event is underway, impacting two ocean basins and multiple countries. Five countries in the Eastern Tropical Pacific have confirmed coral bleaching, including Mexico, El Salvador, Costa Rica, Panama, and Columbia. Seven countries/territories/states in the Atlantic have confirmed bleaching as well, including Florida, Puerto Rico, the U.S. Virgin Islands, Mexico (both sides of the Yucatan), Panama, Belize, and Cuba.

Throughout the Caribbean and Atlantic, sea surface temperatures are as high or higher than ever before in satellite records, and heat stress has developed five to six weeks earlier than ever seen in the record.

Essentially, corals around Florida are experiencing extreme levels of heat stress that have never been recorded before. All of the Florida Keys are at Alert Level 2 for bleaching conditions, which means severe, widespread bleaching and significant mortality are likely. Some sites have already been exposed to two times greater the amount of heat stress than when mortality is expected to begin, and so far, the most extreme heat stress is in the lower and middle Florida Keys.

NOAA's current modeled Outlook predicts that a Caribbean-wide mass bleaching event may begin in a matter of days to weeks, and Alert Level 2 conditions are predicted for the majority of Caribbean coral reef sites by the end of September.

NOAA scientists and partners are employing various methods to restore Florida's Coral Reef, but it's a race against time. They are assessing how different genotypes (genetic individuals) of coral tolerate different environmental conditions; developing ways to naturally prepare corals for stress in the wild; and are working to automate certain processes to increase efficiency and decrease costs.

In July, ocean temperatures near Florida crossed into the triple digits. A sensor in Manatee Bay near Everglades National Park recorded 101.1 degrees Fahrenheit at 6 p.m. after a morning low of 91 degrees. For comparison, the average hot tub temperature is 100 to 102 degrees. Other readings included a buoy near Johnson Key that reached 98.4 degrees while others in the area reached or surpassed 95 degrees during the day. In these cases, the water temperatures were even higher than air temperatures.

Dr. Derek Manzello, who coordinates NOAA's Coral Reef Watch Program, pointed out that the "hot tub" temperatures are from locations where corals have never lived. "In other words, these environments have always been inhospitable for corals, even before climate change," he explained. Despite this, he said the highest recorded temperature that he has seen from a coral reef site was 93.2 degrees at Sombrero Reef, which is still very warm.

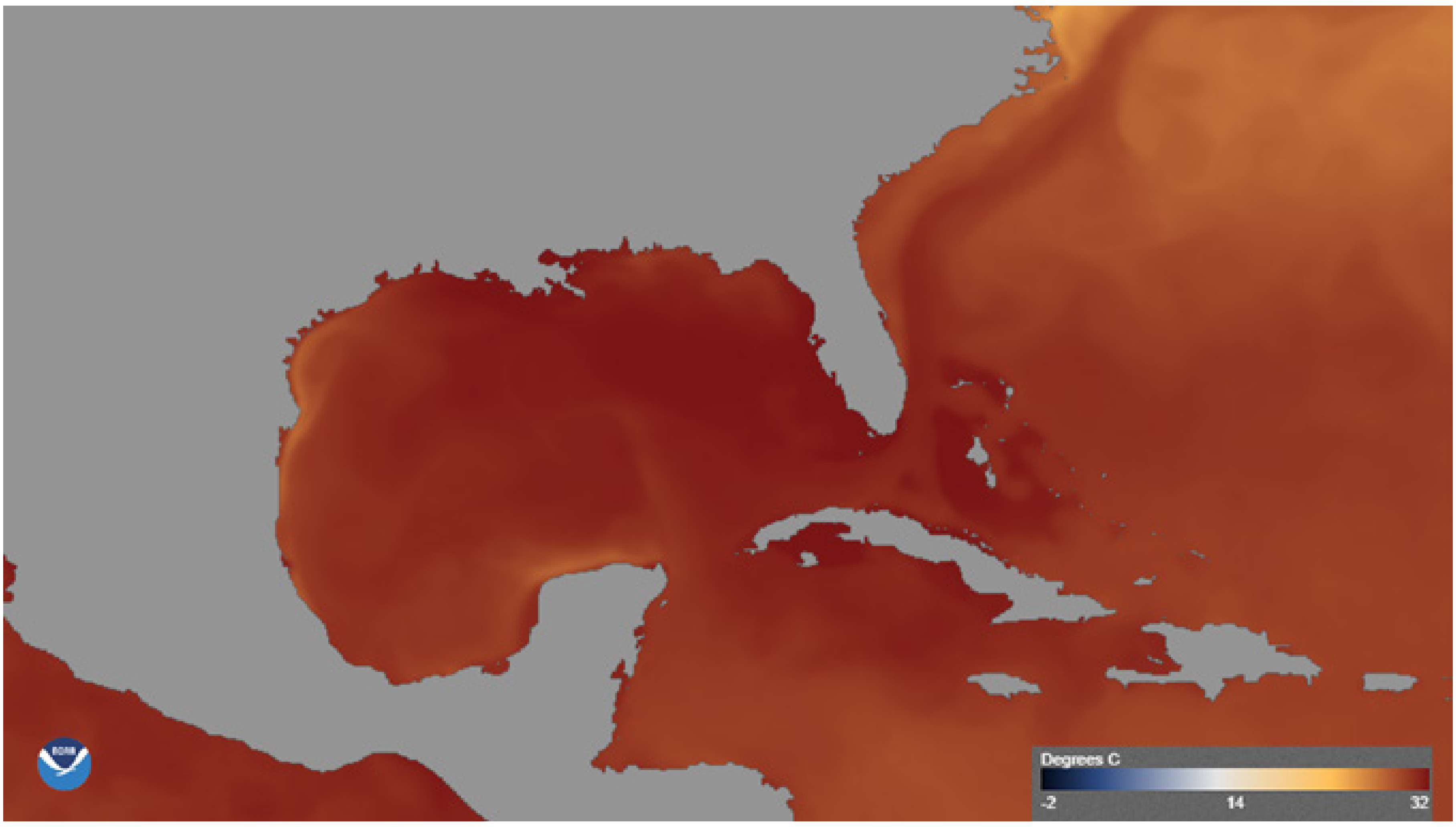
Meteorologist Jeff Masters tweeted that official sea surface temperature records are not kept, but a study published in 2020 proposed that the highest sea surface temperature reliably observed may have been 99.7 degrees in Kuwait Bay, within the Persian Gulf on July 30, 2020.

Marine heatwaves can last for weeks, months, or years, and by definition, are usually defined as any time the ocean temperature is above the 90th percentile for a specific length of time, which can vary depending on whether you are looking at daily or monthly data. Observations and measurements of marine heatwaves are made by the National Weather Service's National Data Buoy Center, which gathers data from 1,300 weather observing stations. Additionally, global ocean surface temperatures are monitored daily using a blend of geostationary and polar-orbiting satellite measurements.

In addition to the tropics, other isolated marine heatwave conditions have been detected off the Northeastern U.S. coast, along the path of the Gulf Stream. NOAA also has been monitoring a large marine heatwave in the Northeast Pacific, in the Gulf of Alaska, that has been sitting offshore since late 2022.

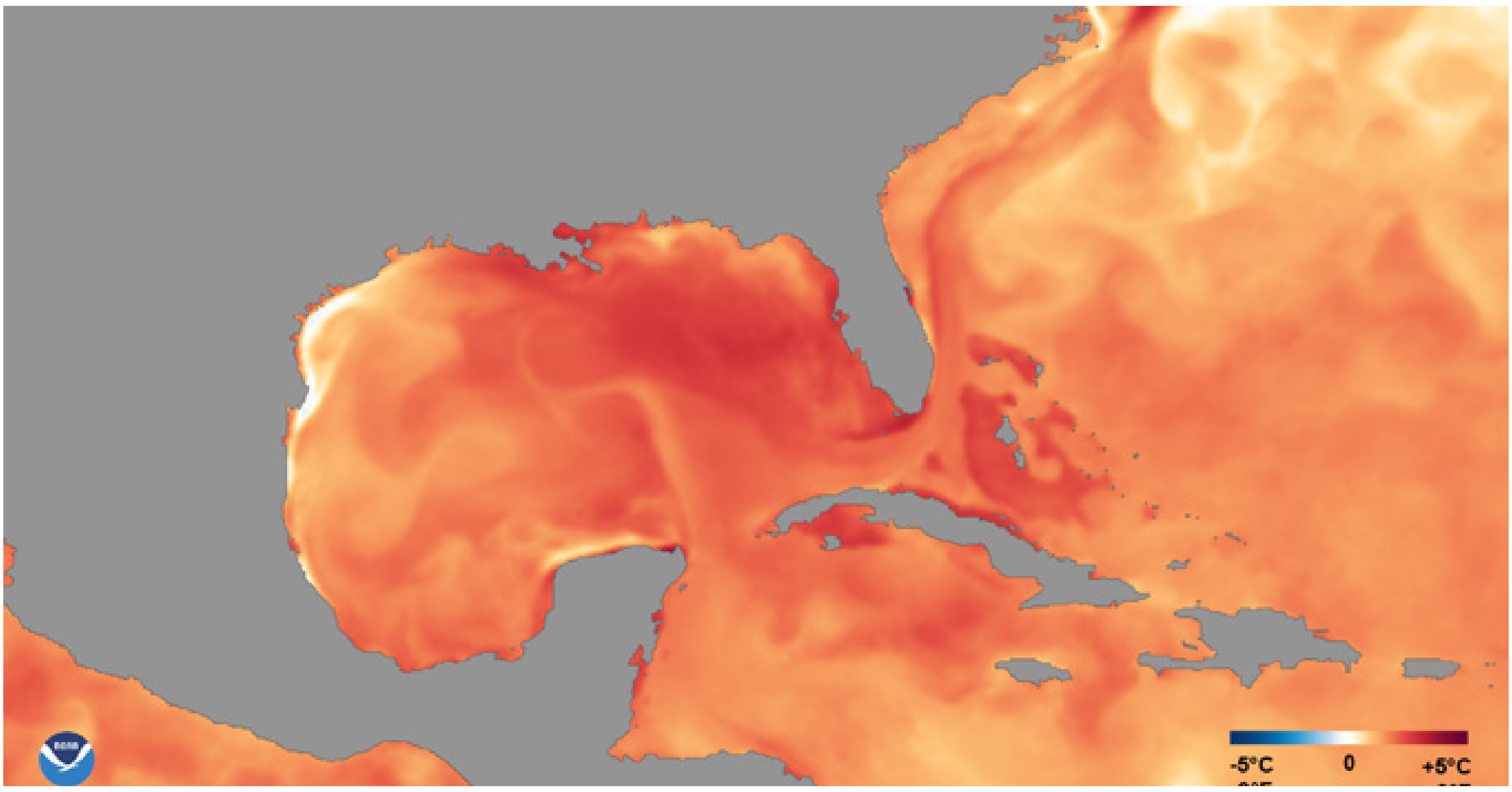
NOAA's Joint Polar Satellite System (JPSS) consists of polar-orbiting environmental satellites that circle Earth from pole to pole and cross the equator 14 times daily—providing full global coverage twice a day. They collect a variety of environmental data, including water temperature and color, which is used in many applications including monitoring of climate variability, operational weather and seasonal forecasting, military and defense operations, ocean and atmospheric models, ecosystem assessment, tourism, and fisheries. Some examples of data collected are shown below.

The image below shows sea surface temperatures from Aug. 7 to 13, 2023, with areas of darker red signifying higher temperatures. While the key is in Celsius, the darkest red temperatures are around 90 degrees Fahrenheit.



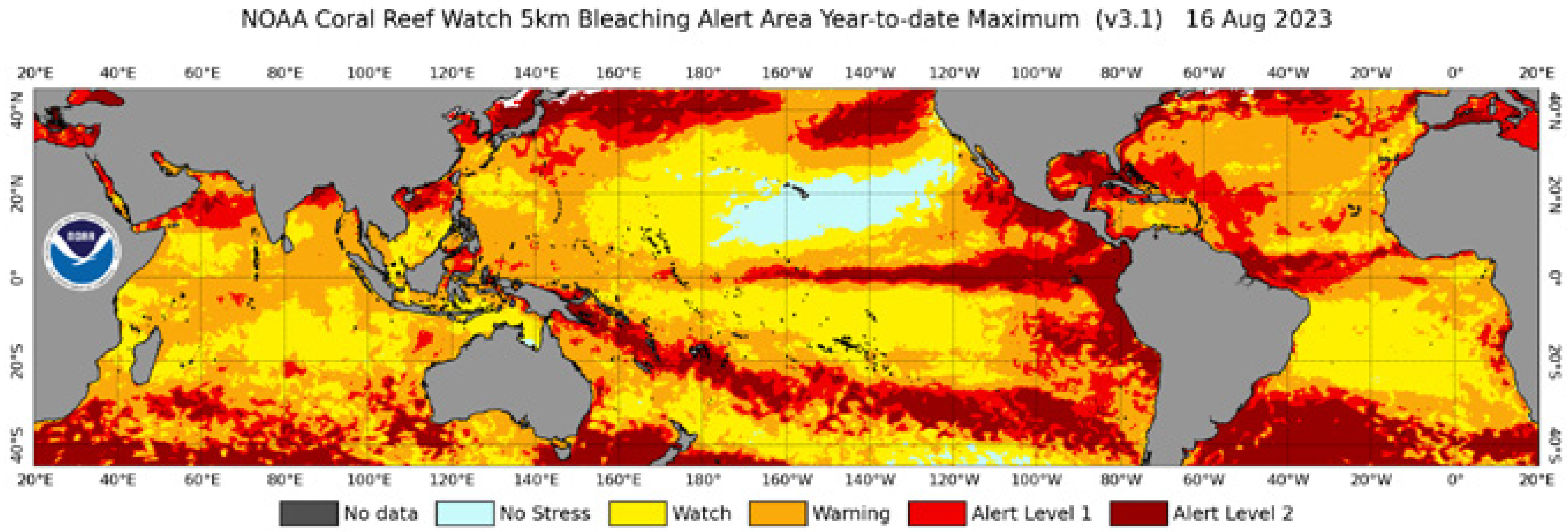
An example of sea surface temperature data that is collected by JPSS satellites. In this example from August 7-13, 2023, higher temperatures are shown by darker red colors around Florida, the Gulf of Mexico, and the Caribbean.

Satellite data can also help us visualize the difference in ocean temperatures compared to historical baseline measurements. Thus, areas with abnormally warmer or cooler temperatures can be identified. In the visualization below, historically normal temperatures would be white. Unusually warmer areas are shown as increasingly darker shades of red, and unusually cooler temperatures would be shown as increasingly darker shades of blue, respectively. You can see that areas around Florida in the Gulf of Mexico and in the Caribbean are redder, and thus higher than normal.



An example of sea surface temperature data that is collected by JPSS satellites showing historical temperatures. Historically normal temperatures appear as white, unusually warmer temperatures appear as increasingly darker reds, and unusually cooler temperatures are shown as increasingly darker blues. Here, areas around Florida, the Gulf of Mexico, and the Caribbean are redder, meaning that temperatures are higher than normal.

In addition to marine heatwaves, this type of data is also useful for identifying the onset of El Niño and La Niña cycles, the approach of potential coral bleaching heat stress, cooling effects of weather events such as tropical storms, etc.

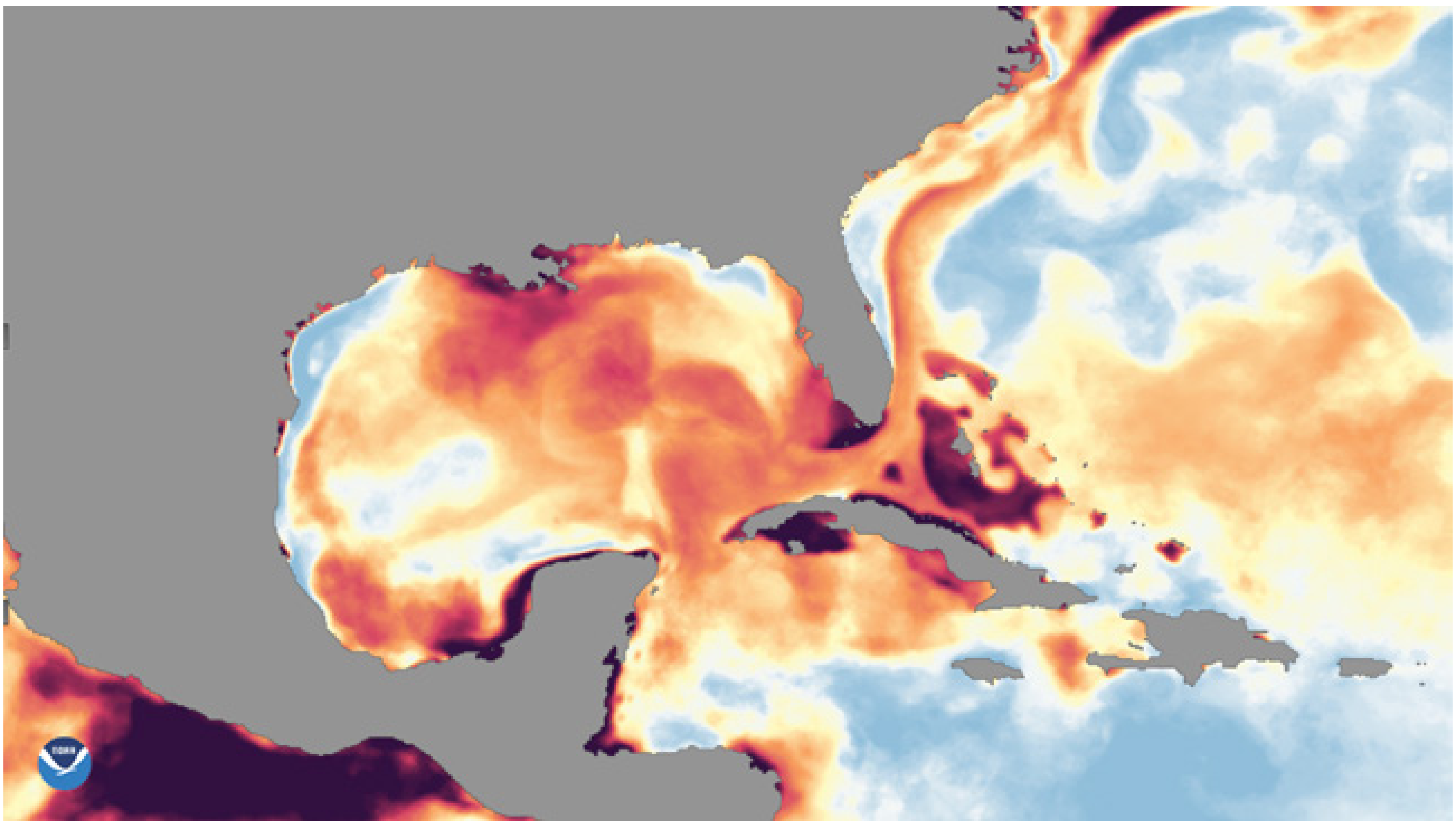


The NOAA Coral Reef Watch year-to-date Bleaching Alert Area product shows maximum global bleaching alert levels from January 1-August 16, 2023 (as of the writing of this article). The products use a variety of polar-orbiting and geostationary datasets, including data from JPSS satellites.

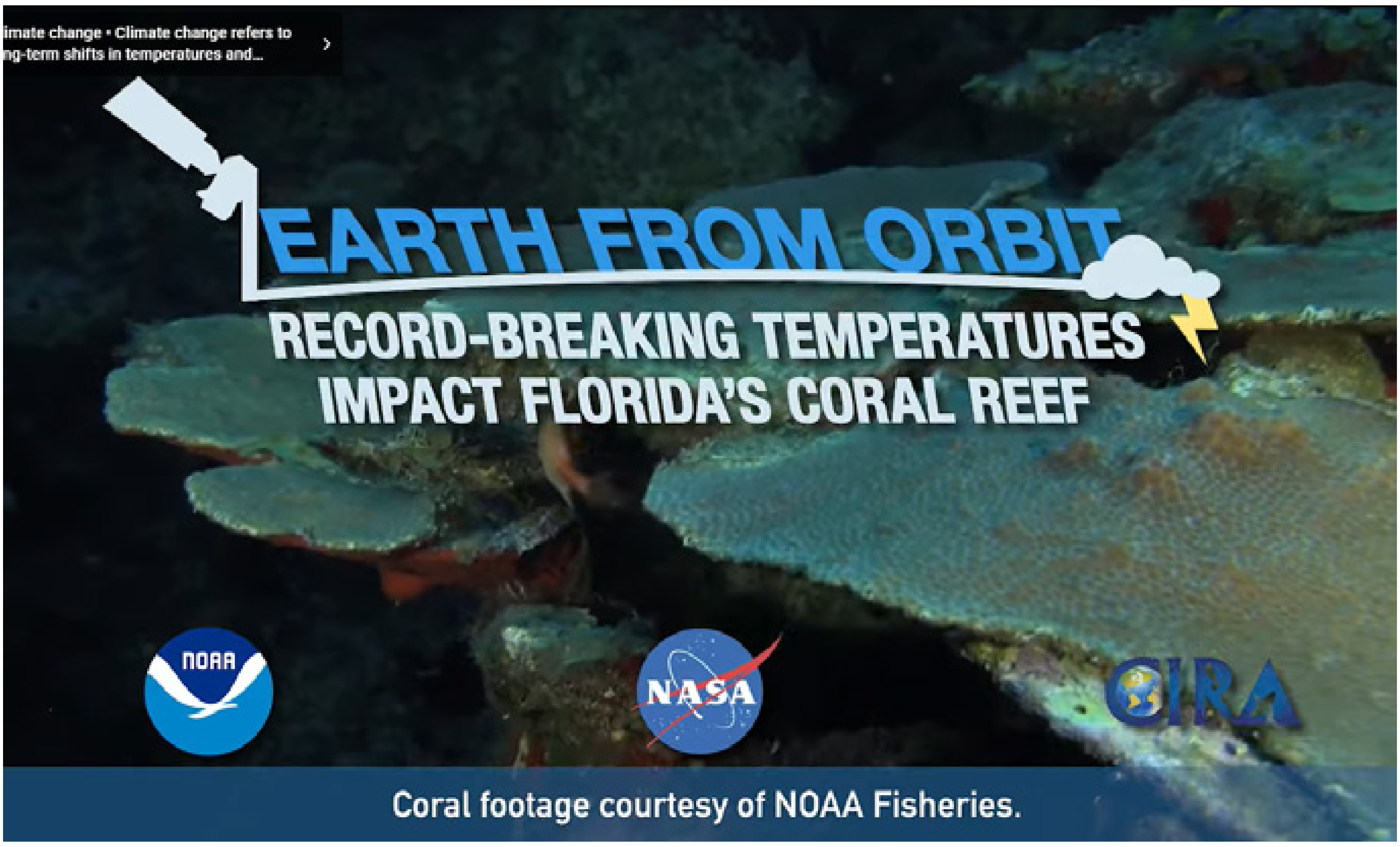
We also use NOAA data to visualize accumulated heat stress, a major factor that can lead to coral bleaching. Shown here is the year-to-date Bleaching Alert Area product from NOAA Coral Reef Watch, which shows the maximum bleaching alert levels experienced around the world since the start of 2023. Areas with high heat stress, shown as dark reddish and brown areas on the map above, can cause severe coral bleaching and death.

If we take a closer look at Florida and the Caribbean on the following page, we can see areas where corals have been exposed to the highest accumulated heat stress (dark red) from Aug. 7 to Aug. 13, 2023.

The alarming rise in extreme ocean temperatures is pushing coral reefs to the brink of collapse. NOAA and our global partners will continue to monitor the situation and work to promote global solutions and efforts to protect our reefs. The fate of coral reefs is intertwined with the health of our planet, and by taking collective action, we must strive to ensure a sustainable future for these vital and breathtaking marine wonders.



An example of heat stress data from NOAA's Coral Bleaching Heat Stress product from Coral Reef Watch. This example from August 7-13, 2023, shows areas around Florida, the Gulf of Mexico, and the Caribbean where corals have been exposed to the highest accumulated heat stress as indicated by darker red colors.



Watch the Earth From Orbit video, available from NOAA NESDIS.

STORY SOURCE:

This story was originally published on the NOAA NESDIS website at https://www.nesdis.noaa.gov/news/extreme-ocean-temperatures-are-affecting-floridas-coral-reef

SOCIAL MEDIA *Highlights*

Harnessing the power of social media, the LEO Communications Team takes on the mission of informing and captivating the public by sharing inspiring JPSS news, data in action, STEM activities, and fun facts through JPSS Facebook and X (formerly known as Twitter) channels. Below is a collection of the most popular JPSS social media 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

X
@JPSSPROGRAM

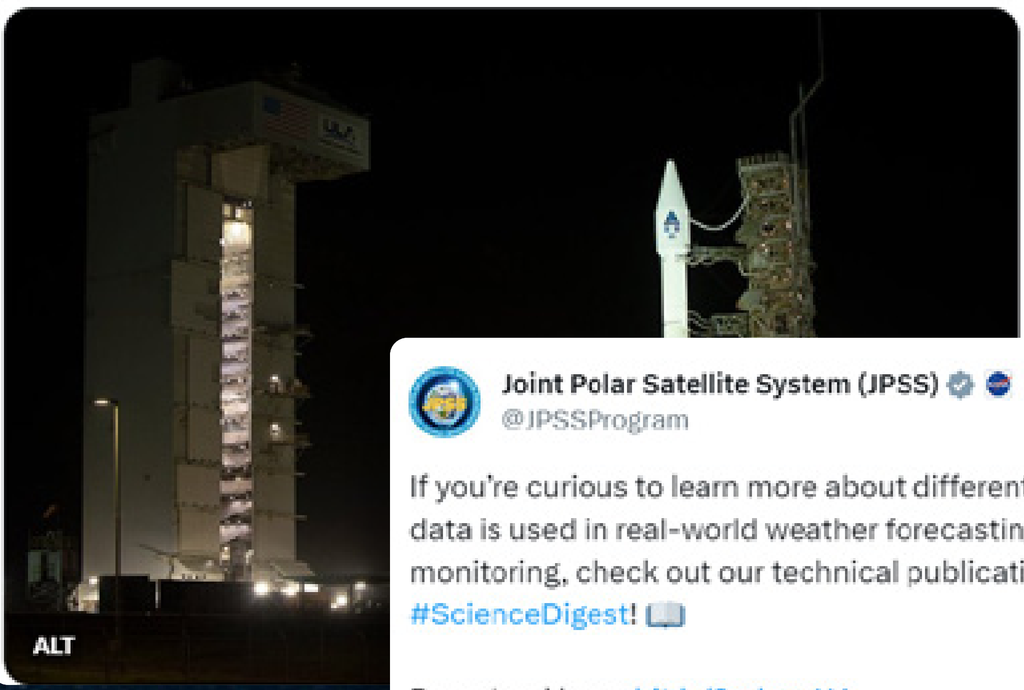
JPSS NEWS

Click on an image to view original post.

Joint Polar Satellite System (JPSS)
@JPSSProgram

.@ulalaunch's #AtlasV rocket carrying @NOAA's #JPSS2 satellite and its rideshare, #LOFTID, is now secured into its launch position for liftoff later this morning. 🚀

#JPSS2Launch #CountdownToLaunch



Joint Polar Satellite System (JPSS)
@JPSSProgram

If you're curious to learn more about different ways that JPSS satellite data is used in real-world weather forecasting and environmental monitoring, check out our technical publication, the 2022 #JPSS #ScienceDigest! 📖

Download here: bit.ly/3mkcmXA

10:00 AM · Jul 31, 2023 · 7,104 View

Joint Polar Satellite System - JPSS
September 27 ·

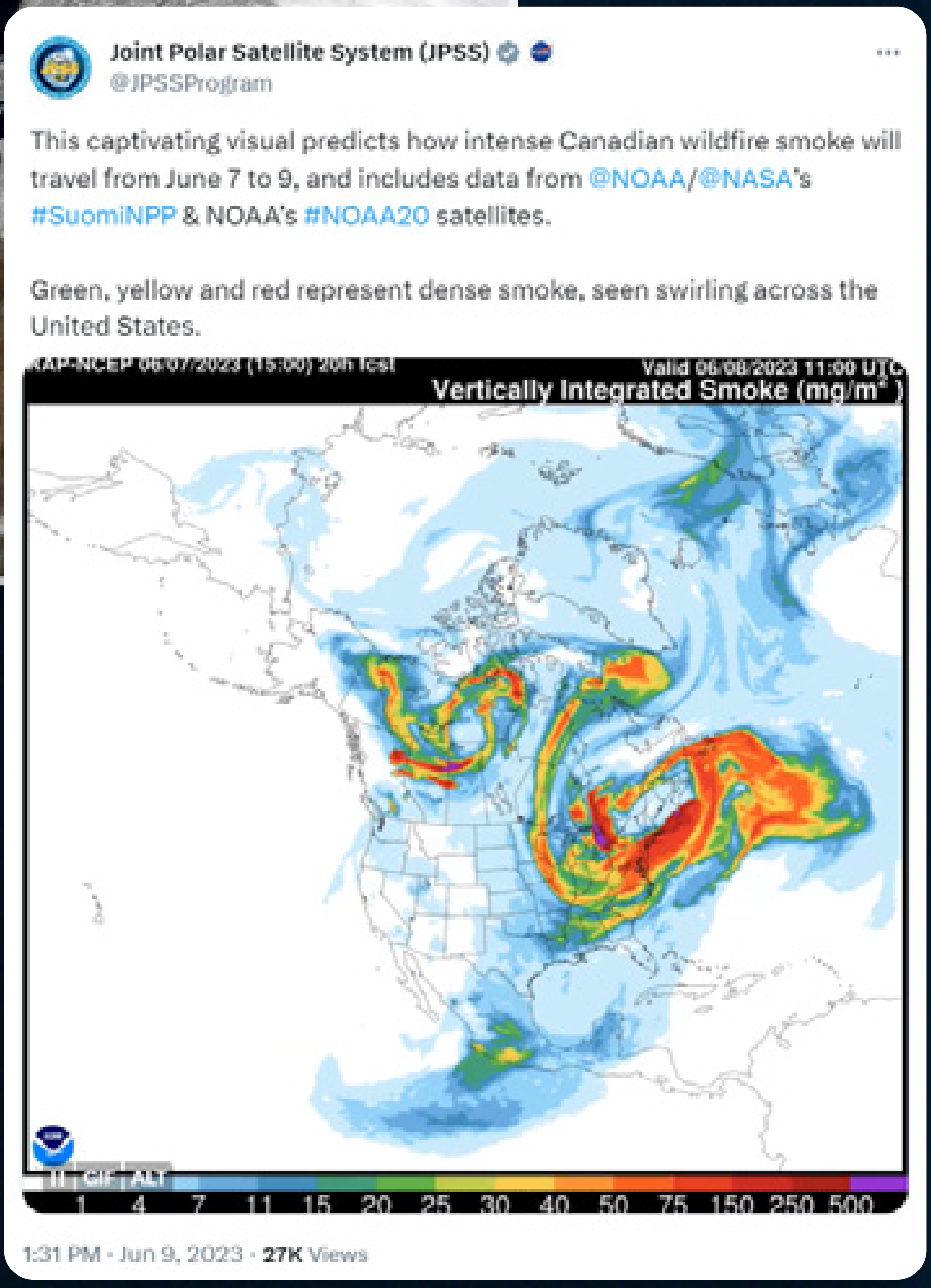
For #HispanicHeritageMonth, we're shining the spotlight on JPSS Satellite Liaison and Cooperative Institute for Research in the Atmosphere (CIRA)/CO State Univ. (CSU) affiliate, Jorel Torres!

Through his work, and his passion for meteorology, he connects the National Weather Service user community with JPSS satellite data.

Family, traveling and exercise inspire him to keep things in perspective and motivate him to be successful. For fun, Jorel loves watching and attending baseball games and he's toured 12 Major League Baseball stadiums across the U.S.! ⚾

DATA IN ACTION

Click on an image to view original post.



JUST FOR FUN

Click on an image to view original post.

Joint Polar Satellite System (JPSS)
@JPSSProgram

You've heard of Elf on the Shelf, now get ready for...

11:12 AM · Dec 19, 2022 · 43.9K V

Joint Polar Satellite System (JPSS)
@JPSSProgram

Will you be our valentine, @NASAEarth? Watching over Earth with you is such a treat! 😍 ❤️

From the North to the South Pole, and everything in between, we love how Earth-orbiting satellites work with us to make continuous observations of our planet. #ValentinesDay

12:45 PM · Feb 14, 2023 · 60.1K V

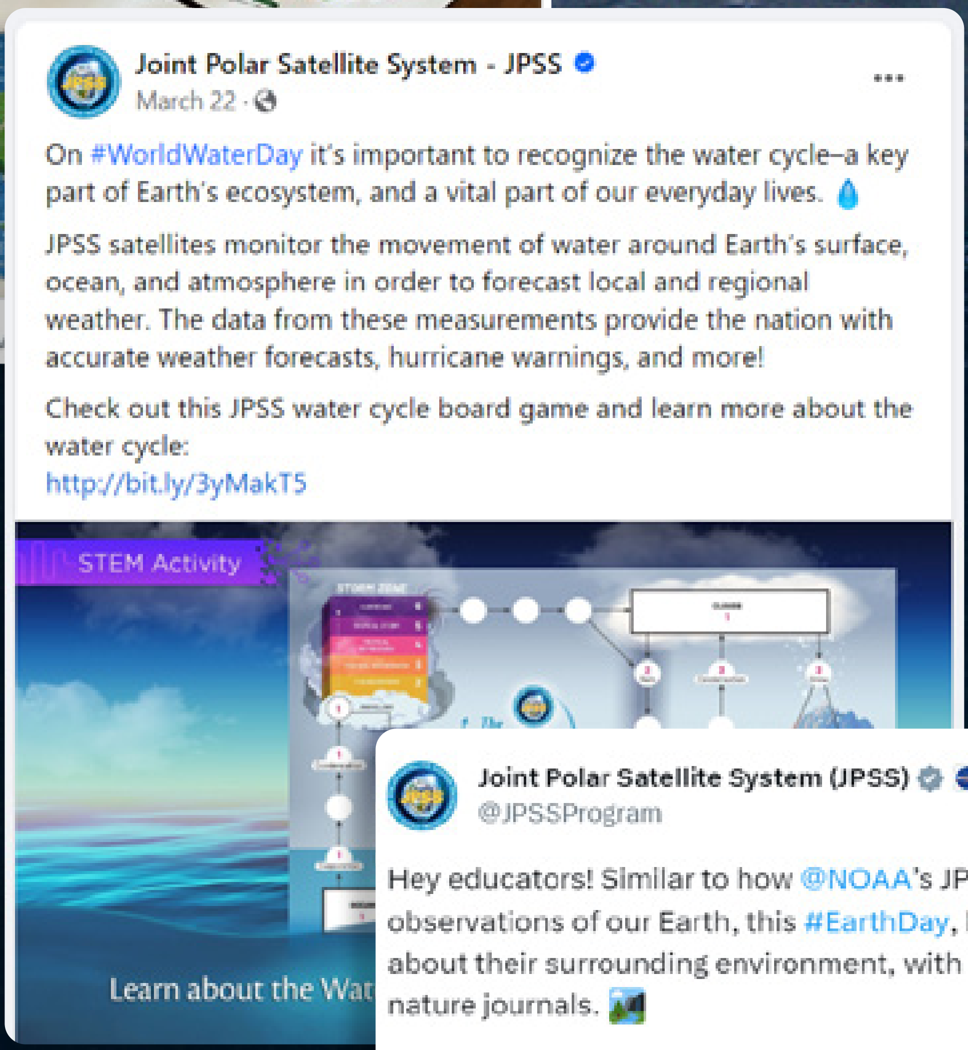
Joint Polar Satellite System - JPSS
2d ·

It's not a trick, it's a treat that JPSS is a NOAA and NASA partnership! Enjoy carving some of these JPSS jack-o-lantern stencils. 🎃 🛰️

Download here: https://www.nesdis.noaa.gov/.../pumpkin-carving-stencils

STEM ACTIVITY

Click on an image to view original post.



Highlights

from Public Outreach & STEM Engagement

Julie Hoover
Senior Communications and STEM Engagement Specialist, LEO/JPSS
NASA Goddard Space Flight Center

The Office of Low Earth Orbit Observations (LEO) is deeply committed to its mission of public outreach and STEM (**S**cience, **T**echnology, **E**ngineering, **M**athematics) education. This commitment is rooted in the belief that these efforts play a critical part in informing the public about the invaluable role of satellite data in making informed decisions about climate change, weather, disaster management, and other applications. Outreach and STEM education help to demystify science and humanize scientists—important objectives to excite and engage the community in STEM.

The LEO Communications and STEM Engagement (LEO CaSE) team prioritizes audience needs and modifies activities and events accordingly. This can be as simple as choosing a hands-on activity that fulfills the learning objectives of a classroom or as involved as planning a custom event to meet a unique set of needs. Many lesson plans and STEM activities linked to the Joint Polar Satellite System (JPSS) mission are available on the NOAA NESDIS website, which educators and learners alike can readily incorporate into their educational goals. Below are highlights from a selection of activities from the past year.

Children participate in STEM activities at the JPSS booth inside the NASA tent at the International Balloon Fiesta.

HIGHLIGHTS FROM PUBLIC OUTREACH & STEM ENGAGEMENT ACTIVITIES

Celebrating Earth Month

During Earth Month in April, the LEO CaSE team planned and supported many celebratory events. The team began the month in Las Cruces, New Mexico for the Las Cruces Space Festival, where they presented to over 250 local kindergarten and elementary school children and 500 middle school students. The team also spoke to more than 250 attendees during the festival's Career Night, and 2,500 people at Las Cruces STEAM Day (STEAM stands for **S**cience, **T**echnology, **E**ngineering, **A**rt, and **M**athematics).

Julie Hoover, Senior Communications and STEM Engagement Specialist, talks about the JPSS mission to students in Las Cruces, New Mexico.

Later in the month, the LEO CaSE team celebrated Earth Day at the Goddard Child Development Center by teaching older students about JPSS, composting, and soil health, and making a vermicompost (worm castings) bin for the school's garden. The team helped younger students learn about cloud types through a simple activity where the children made cloud shapes out of homemade "cloud dough."

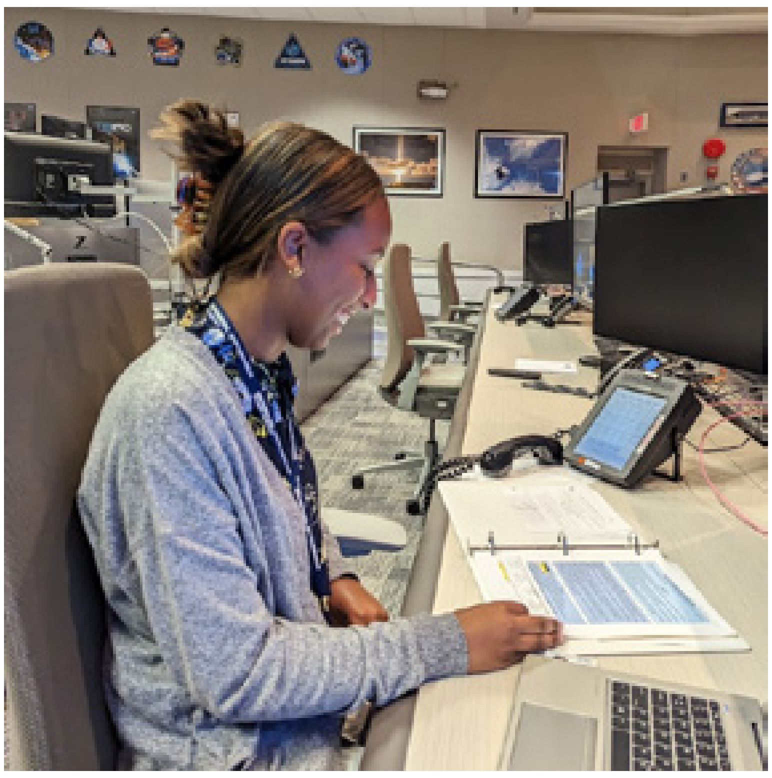
At NASA's Earth Day event held at Union Station in Washington, D.C., the team led 250 students in a hands-on tree ring print activity. They also supported Rockville Science Day at Montgomery College in Rockville, Maryland, with more than 680 guests visiting the JPSS booth. Many children helped color a custom-illustrated poster that featured JPSS satellites orbiting the Earth.

At the end of Earth Month, the LEO CaSE team supported NASA Goddard's Take Your Child to Work Day in collaboration with other NOAA and NASA outreach teams. The team offered a hands-on activity about disaster preparedness for about 200

children and their families who attended the event. The team, along with subject matter experts, also hosted a booth at Maryland Day, the University of Maryland's annual springtime open house that gets around 15,000 attendees each year. During the event, the LEO CaSE team handed out educational materials, talked to patrons about JPSS, and helped kids create their own seed balls, small bundles of seeds that are wrapped in a mixture of clay and soil or compost.

Supporting JPSS Interns

During the summer, LEO welcomed several JPSS interns who enjoyed a busy schedule of enrichment activities. Interns started the summer with a tour of the NASA Goddard Space Flight Center. Later, Tim Walsh, LEO director, and Satya Kalluri, LEO program scientist, gave a “JPSS 101” presentation to introduce the interns to the program. Two interns also had an opportunity to sit on console and speak with Flight Directors as part of the “Down to the Wire” flight controller simulation activity, held in NASA Goddard’s Near Space Operations Control Center.



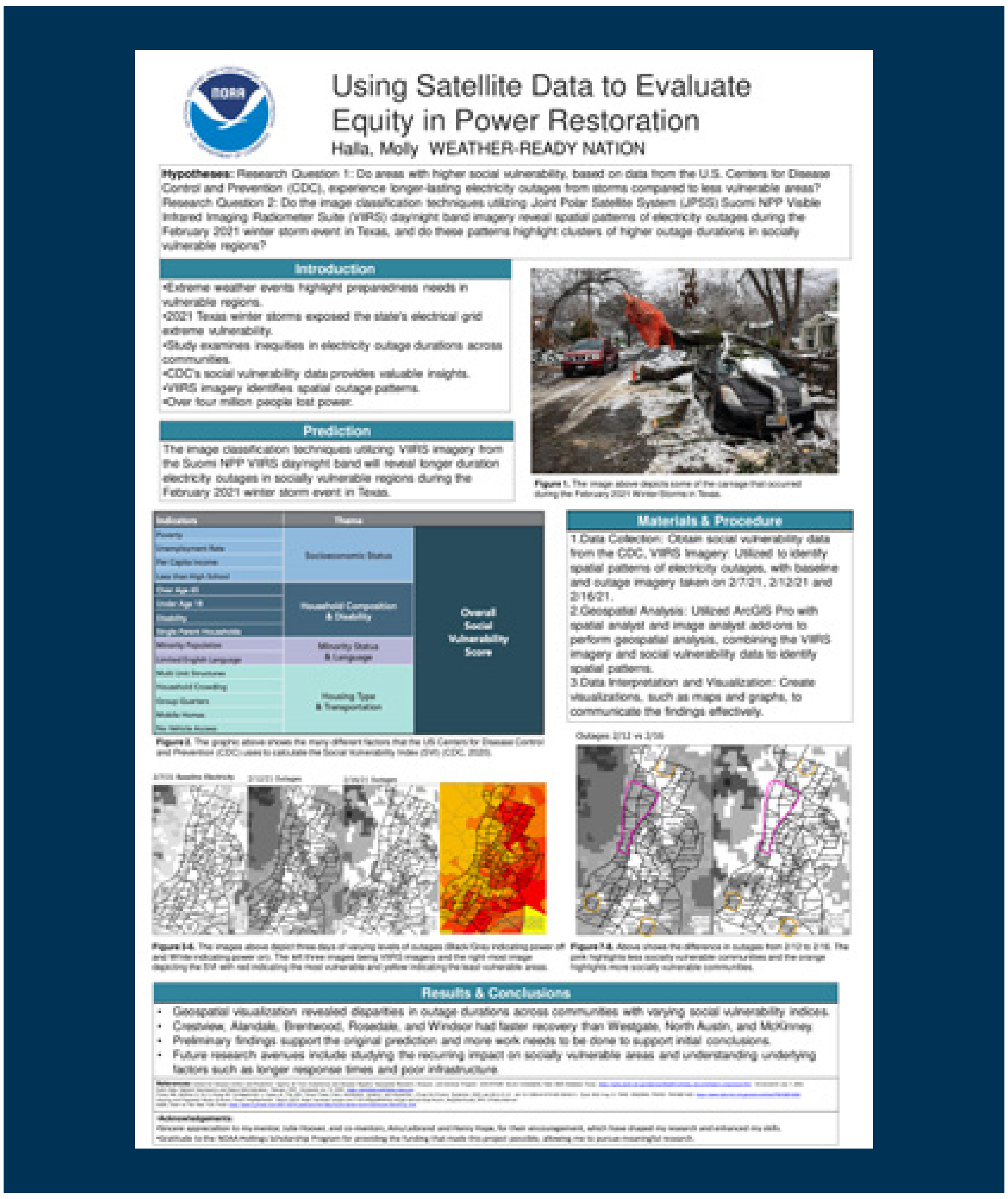
Left: A JPSS intern participates in the “Down to the Wire” flight controller simulation activity at NASA Goddard’s Near Space Operations Control Center. Right: JPSS interns visit NASA Wallops Flight Facility on Wallops Island, Virginia.

Several JPSS interns attended the Self-Advocacy in the Workplace Lunch and Learn, which provided valuable information about resume preparation, salary negotiation, career development, respectful confrontation, and handling microaggressions at work. Another Lunch and Learn introduced interns to the NASA Mission Operations Support Team (MOST), where they participated in a table read of a JPSS-2 launch script.

Later in the summer, interns took a tour of the NOAA Satellite Operations Facility (NSOF) where they met Commander James Brinkley, NESDIS/OSPO Acting Assistant Director, and traveled to Virginia for a tour of the NASA Wallops Flight Facility. At Wallops, the interns visited the Range Control Center, Fabrication, Testing & Integration building, Balloon Research & Development Lab, and Launch Pad 0A on Wallops Island. They also participated in a Lunch and Learn about internships at NASA.

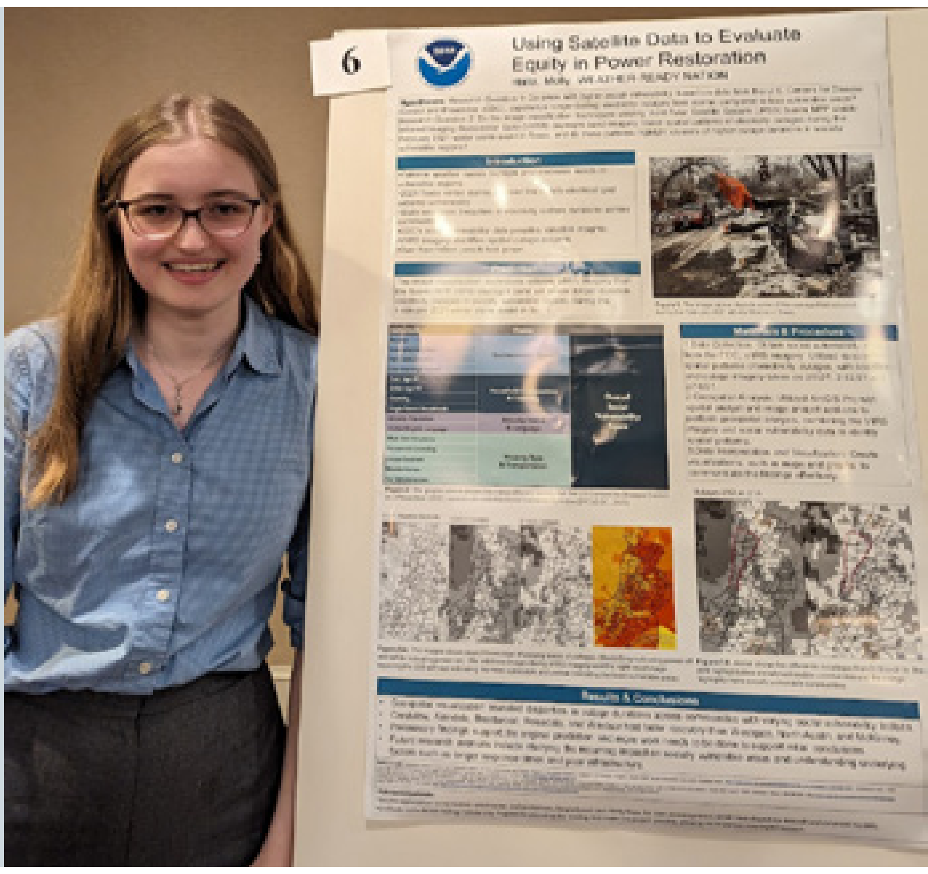
Intern Spotlight

From May 30 through August 4, the LEO CaSE team provided support to Molly Halla, a Hollings Undergraduate Scholarship1 recipient attending the University of Rhode Island. Her project, "Using Satellite Data to Evaluate Equity in Power Restoration," involved mapping data from the JPSS Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band in QGIS, a free and open source geographic information system (GIS) application that supports viewing, editing, printing, and analysis of geospatial data.



"What excites me most about this internship is the opportunity to work with advanced satellite technology and apply it to real-world problems. The ability to track the progress of power restoration after a storm event can provide valuable insights into the resilience of communities and their ability to recover. It's an exciting field that combines geospatial analysis, remote sensing, and social factors, allowing me to contribute to a more comprehensive understanding of the impact of storms on society."

Molly Halla
2023 Hollings Undergraduate Scholar



The goal of the project was to create a map that showed the restoration of power in certain areas after a major storm event. Molly examined the correlation between the economic inequality of these areas and various relevant factors, which involved extensive secondary research to understand the region, storm characteristics, and similar previous studies. The project was ultimately developed into a poster (right) that was presented to NOAA leadership, scientists, and fellow scholars at the Science and Education Symposium in Silver Spring, Maryland. The LEO CaSE team provided guidance and feedback throughout the process.

Greenbelt Farmers Market

The LEO CaSE team hosted a JPSS-themed booth at the Greenbelt Farmers Market on August 13, where they handed out JPSS recipe cards and spoke with over one hundred patrons. This was an excellent opportunity to have one-on-one conversations with an engaged audience about how NOAA and NASA satellites contribute to weather forecasting, agriculture, and Earth science data collection.

NASA Goddard Sunday Experiment

LEO hosted the Sunday Experiment on Sunday, September 17, 2023, at the NASA Goddard Visitor Center. Participants were given event "passports" to encourage participation in all available activities. People who completed six or more activities could redeem the passport for a special prize. Activities developed and facilitated by the LEO CaSE team included assembling a Corsi-Rosenthal box (a DIY air filter for eliminating wildfire smoke indoors), a puzzle challenge using imagery of the Great Lakes during the four seasons, painting a poster that shows a global view of how vegetation changes from season to season (right), and using colorful pegs with VIIRS imagery on a backlit display grid (similar to a LITE BRITETM toy) to show real locations of Canadian wildfires and lights in New Mexico at night. Patrons participated in a rousing game of the new Weather Terms Kahoot Trivia, and enjoyed a game that encouraged them to develop a household disaster preparedness backpack.

International Balloon Fiesta

At the International Balloon Fiesta held in Albuquerque, New Mexico from October 10-15, 2023, the LEO CaSE team supported several NASA-sponsored events. The Fiesta coincided with the 2023 annular solar eclipse, making the experience even more exciting for the hundreds of thousands of attendees. At the NASA tent, the team facilitated many hands-on activities, including an eclipse photo station, eclipse DIY activities, 3D Hubble experiences, astrophysics demos, real-time ozone and atmospheric particulate data collection, GLOBE temperature data collection, augmented reality with Earth data, and building virtual flight logs. Attendees were encouraged to complete at least half of the activities in their activity “passport” to receive a NASA bag and a variety of takeaways. More than 6,000 activity passports were distributed to the public and about 18,000 people visited the NASA tent. The LEO CaSE team also supported NOAA eclipse outreach by providing educational outreach materials related to JPSS for attendees.

Fun Creations

Over the past year, the LEO CaSE team created many activities and tools for STEM education, two of which are highlighted below.

Nature Journaling

This JPSS-themed Nature Journal is a downloadable journal that can be used to explore the outdoors and become more mindful of the environments, habitats, and weather in our neighborhoods. Filled with original illustrations by Wes Harvey, an illustrator, animator, and 3D model maker at NASA Goddard, this journal includes tidbits about the environment and plenty of blank space to fill with drawings and thoughts.

WeatherSats AR App

The WeatherSats AR App is an augmented reality (AR) app that creates an immersive experience for users to learn about how weather satellites like JPSS and the NOAA Geostationary Operational Environmental Satellites (GOES) monitor extreme weather and climate change. Users will be challenged to complete a series of missions, starting with an interactive journey into space where weather satellites orbit the Earth. The AR features enable users to view the satellites and their instruments up close. Play at home or play the app's six challenges at the NASA Goddard Visitor Center! The free app is available for download to mobile devices from the Apple and Google app stores.

IN SUMMARY

These represent just a fraction of the public outreach and STEM engagement initiatives developed and orchestrated by the LEO CaSE team in 2023. Events and activities like these play a pivotal role in bolstering public support and awareness of the significance and applications of low Earth orbit observations. Enhancing public understanding of LEO observations and their far-reaching benefits for the planet, humanity, and the economy has the potential to foster better-informed decision making and inspire a new generation of students to pursue STEM disciplines.

Thank you for reading the

2023 JPSS Annual Science Digest!

Learn more about JPSS and the Office of LEO Observations on our web page.

Follow us on Facebook and X to learn more about JPSS!

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