2022 NESDIS Science Report

Use-Inspired Science: Creating Output That's Usable, Useful and Used

May 2023

Notice

This report is a work of the United States Government authored as part of official duties of employees of the National Environmental Satellite, Data, and Information Service. Any findings, as well as views or opinions expressed in this report, are those of the authors and do not constitute a statement of policy, decision, or position on behalf of the Department of Commerce/ National Oceanic and Atmospheric Administration/ National Environmental Satellite, Data, and Information Service.

ACKNOWLEDGEMENTS

EDITORS

Price, Julie
McHansen, Brooke
Rubenstein, Benjamin

CONTRIBUTORS (SCIENCE HIGHLIGHTS)

Azeem, Irfan
Blunden, Jessica
Boyer, Tim
Brewer, Michael J
Brucker, Ludovic
Byrne, Deirdre
Carignan, Kelly
Csiszar, Ivan
Daniels, Jaime
Forsythe, John
Garcia, Hernan
Gleason, Karin
Heim, Richard
Helfrich, Sean
Huang, Boyin
Jankot, Josh
Jencks, Jennifer
Kalluri, Satya
Key, Jeff
Knaff, John
Kondragunta, Shobha
Kozyr, Alex
Kulie, Mark
Lance, Veronica
Larsen, Kirsten
Laszlo, Istvan
Leuliette, Eric
Lindsey, Dan
Line, William
Liu, Xiaoming
Meng, Huan
Noh, Yoo-Jeong
Pavolonis, Michael
Pryor, Ken
Rachmeler, Laurel
Reagan, James
Redmon, Rob
Rudlosky, Scott
Silva, Jim
Smith, Adam
Straka, William
Street, Davida
Talaat, Elsayed
Wang, Menghua
Webster, Jennifer
Williams, Andrea
Xie, Pingping
Yan, Banghua
Yu, Yunyue
Zhan, Xiwu
Zhang, Huai-min
Zhao, Xuepeng
Zhou, Lihang
Zou, Cheng-Zhi

COVER IMAGE

Tiffany Small

We thank: The authors and editors, Bailey McCarthy Riley and Amanda Keener, for their eagle-eyed checking of the proofs, and Tiffany Small for her terrific graphic design skills.

From the NESDIS Assistant Administrator

As climate change continues, NOAA's satellite observations, data, and scientific experts are needed more than ever. They are critical components of NOAA's mission and of the security, safety, and prosperity of the nation. With advances in technology, NOAA can build the observing system we need—one that supports our vision to create an integrated digital understanding of Earth's environment and that evolves quickly to help our communities adapt and thrive.

2022 was a busy year for NESDIS. The GOES-T satellite was launched in March and completed its journey to a stable geostationary orbit. Now known as GOES West, it joins a vibrant family of satellites providing life-saving and climate-critical observations and information. The satellite instrument Argos-4, developed under a joint agreement between NOAA and the French Space Agency, Centre National d'Etudes Spatiales, was successfully launched in October. Argos-4 joined a network of other Argos instruments onboard other polar-orbiting satellites to help provide a better understanding of Earth's physical and biological environment and assist with maritime security, offshore pollution, and humanitarian assistance. And the Joint Polar Satellite System's (JPSS) NOAA-21 (previously called JPSS-2), the third in a series of five advanced polar-orbiting satellites, was successfully launched in November. Our JPSS satellites provide up to 80% of the data that NOAA's National Weather Service uses for its numerical weather prediction models.

Satellite launches inspire awe and catch our attention. However, the products and services that analyze the satellite data are also worth the costly investment. Our NESDIS mission requires us to meet the demands of providing better information to the world about our changing climate. This, in turn, provides essential support to all segments of the U.S. economy. This is why NESDIS' scientific efforts are critical components of the NOAA Strategic Plan; these efforts are critical components to building a Climate-Ready Nation.

Looking forward, NOAA is investing in the next generation of satellites, infrastructure, products, and services

to meet demands for more accurate and expanded environmental information and services for the American public. Additionally, NESDIS will better understand and meet user needs. Ultimately, NESDIS will continue providing existing satellites and information services while also utilizing observations from our partners and developing cutting-edge products and services.

With the support of NESDIS' science, NOAA will improve Earth and space weather forecasting, expand capabilities for extreme weather, ocean, air quality, and climate observations, and continue the long-term monitoring that is essential to understanding our changing environment.

Our science enables our mission. With this inaugural report, we are underscoring the progress we have made in science from leveraging observations from satellites and other sources to help make NOAA's achievements as beneficial to society as they are.

From the NESDIS Senior Scientist

I am honored to share with you the inaugural 2022 NESDIS Science Report, which presents some of the scientific wisdom we gained last year. We also share groundbreaking discoveries, advances, mission milestones, notable papers, and much more. The science that NESDIS conducts enables the creation of information products and services, which feed into NOAA's support for healthy oceans, resilient coasts, and climate readiness. Our information, which supports a range of applications and decision-making services, comes from environmental data from in situ observations and various operational and research satellites, including those operated by our partners, commercial operators, and NOAA.

Science encapsulates nearly all facets of the NESDIS enterprise and lifecycle. Examples include: preparing to acquire satellite components; characterizing satellite instruments before they are launched; assessing the launch afterward; developing the products our data users use; and transforming satellite observations into information and knowledge. Generally, our science supports NOAA's mission: science, service and stewardship.

According to the World Meteorological Organization Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2019), over the past 50 years, communities in the U.S. and nations around the world have endured on average one disaster related to a weather, climate or water hazard every day. These disasters account for more than 100 fatalities and over $200 million in losses daily. Many of the solutions to the challenges these disasters create are rooted in science. At NESDIS, we depend on science to transform observations from satellite instruments and other sources into timely, actionable and reliable environmental information.

NESDIS's science products contribute to the quality of NOAA's forecasts, alerts, warnings, and assessments. These help us better understand the weather within our atmosphere and in space, the ocean, the climate, and climate change. Our products help drive short-

term weather forecasts and severe weather warnings. They are used to detect and monitor environmental hazards like wildfires, smoke, dust, volcanic ash, drought, and flooding, and support applications that provide advanced warning to decision-makers. NESDIS science products also play an important role in monitoring and analyzing the global ocean environment. The U.S. economy is highly dependent on healthy coastal and ocean resources. NESDIS provides a plethora of ocean-based products that help scientists better understand ocean dynamics and marine ecosystems. These include ocean surface winds, wave height, ocean color, chlorophyll, ocean depth, sea ice, and sea surface height. NESDIS science products are also important for other marine purposes such as assessing the productivity and health of oceans and the quality of coastal and inland water, managing aquaculture and fisheries, navigation, and providing warnings of hazards such as harmful algal blooms. NESDIS science products also provide global measurements of variables such as sea surface temperature that are required for global numerical weather prediction and climate applications.

Part of NOAA's mission is to monitor space weather and provide timely, accurate warnings to help our nation prepare for and minimize potential impacts to people, property and the economy. Space weather events, such as coronal mass ejections, can create intense geomagnetic storms that disrupt systems on Earth, including satellite and power system operations. NESDIS products contribute to NOAA's space weather initiatives, which help protect electric power grids, communication and navigation systems, and national security.

As you will see in this report, we've had many scientific triumphs. I want to first thank all the people who made all these triumphs possible. I would especially like to thank the NOAA Cooperative Institutes who play an incredibly important role in supporting NESDIS science activities and innovations. Without them, many accomplishments highlighted in this report would not have been possible. Here then, are just a few of the highlights featured in the report. We developed a long-term dataset of upper atmospheric temperatures using NOAA's microwave and infrared satellite measurements, which is showcased on page 21. We improved estimates of wildfire smoke and air quality predictions—see page 24 for more on that. We developed a machine learning model that helps predict lightning activity over the next hour (page 32), developed multi-satellite blended sea winds in support of the blue economy and offshore wind energy (page 49), global daily gap-free ocean color products (page 56), and a global marine microplastics database and map portal (page 57). The highlight on page 63 describes our researchers' explorations to construct geomagnetic field models for navigation purposes, and the one on page 75 provides an excellent example of our contribution to space weather monitoring.

We also made indirect scientific advancements. We started the NESDIS User Engagement Council to better commit to our users and the Earth System Integration Board to help advance the outcomes defined in NOAA's Weather, Water, and Climate Strategy.

Those and so many other achievements described in this report demonstrate NESDIS' scientific contributions. I hope that all readers find that these achievements strongly demonstrate significant societal impacts and benefits.

And then, after appreciating our past accomplishments, we're onto the future, especially given that NOAA released its Strategic Plan for fiscal years 2022-2026. NESDIS is working across NOAA with partners and allies to deliver on the new priorities identified in the Strategic Plan. These include building a Climate Ready Nation, advancing the blue economy, and working with underserved communities. We're also developing the NESDIS Science Innovation Plan, which will guide calls for outside-the-box proposals to both develop new capabilities and extend existing capabilities beyond their expected lifespan.

This 2022 NESDIS Science Report, along with our five-year product and science innovation plans, shows us where our science is today and points to where we need to lean towards tomorrow. This report reflects the breadth of our work in satellite remote sensing of the Earth's atmosphere, surface, and climate. It also demonstrates how we advance NOAA's foundational mission to "understand and predict changes in climate, weather, ocean and coasts; share that knowledge and information with others; and conserve and manage coastal and marine ecosystems and resources." As the NESDIS senior scientist, I offer my congratulations to all those involved in the initiation, planning, execution, and delivery of these important scientific achievements. Thank you.

Mitch Goldberg, Ph.D.
Senior Scientist, National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration

Contents

Our Mission

NOAA's National Environmental Satellite, Data, and Information Service (NESDIS), provides secure and timely access to global environmental data and information from satellites and other sources to promote and protect the nation's security, environment, economy, and quality of life.

The National Oceanic and Atmospheric Administration's (NOAA) mission is to understand and predict changes in climate, weather, oceans, and coasts, to share that knowledge and information with others, and to conserve and manage coastal and marine ecosystems and resources as the nation's authoritative environmental intelligence agency.

About This Report

The NESDIS Science Report identifies important gains in science at NESDIS in 2022. This report celebrates and shares highlights that effectively exhibit the breadth, relevance and application of NESDIS research to NOAA's mission of Science, Service and Stewardship. It covers NESDIS science activities across three primary thematic product areas: foundational, geophysical and analytical.

This report is divided into three main sections. The first section, which provides context to who we are and what we do, is an introduction that focuses on our science drivers, the types of research and development activities we sponsor and oversee, our offices, and thematic product areas. The second and main section of the report highlights our science and innovation accomplishments from the past year. These accomplishments cover several product categories and are presented under foundational, geophysical and analytical thematic product areas. The third and final section of the report gives the reader glimpses of our work toward future products and services.

This report complements other reports and communications materials issued by NESDIS and NOAA including the NESDIS Year in Review, NOAA Science Report, and Center for Satellite Applications and Research (STAR) annual report.

Introduction

The National Oceanic and Atmospheric Administration's mission is focused on science, service and stewardship.

1. To understand and predict changes in climate, weather, oceans and coasts;
2. To share that knowledge and information with others; and
3. To conserve and manage coastal and marine ecosystems and resources.

The National Environmental Satellite, Data, and Information Service (NESDIS) is the arm of NOAA that is responsible for the secure and efficient operation of some of the most sophisticated polar-orbiting and geostationary weather satellites in the world. NESDIS is also responsible for the development and distribution of high-quality satellite-derived science data and information products and services, and stewardship of the nation's environmental data. In addition to its satellite missions, NESDIS' remote sensing capabilities include observations from operational and research partner satellite programs[1] as well as partner satellite technology and commercial distribution with relevant applications to NOAA's mission service areas.

NESDIS fulfills NOAA's threefold mission through its own mission, which is to "provide secure and timely access to global environmental data and information from satellites and other sources to both promote and protect the nation's environment, security, economy and quality of life." This mission is deeply rooted in science, which transforms the data from satellite instruments and other sources into timely, actionable and reliable environmental information. This information not only seeks to address needs across NOAA but also forms the basis for many secondary products and product types that NOAA's stakeholders in the public and private sector's develop to suit their specific needs.

1 Such as the National Aeronautics and Space Administration (NASA) research satellites, Department of Defense (DOD) operational satellites, Japan Meteorological Agency, Japan Aerospace Exploration Agency (JAXA), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), European Space Agency, and others.

SCIENCE DRIVERS

NOAA's mission of science, service and stewardship is the cornerstone of NESDIS science. As the first pillar in NOAA's mission, science is a central focus for NESDIS and forms the basis of our products and services.[2] NESDIS science is dedicated to advancing NOAA's foundational mission to "understand and predict changes in climate, weather, ocean and coasts; share that knowledge and information with others; and conserve and manage coastal and marine ecosystems and resources."

NESDIS science activities seek to address NOAA's mission priorities:

- to build a Climate Ready Nation to establish that NOAA is the authoritative source for climate products and services that can be applied to a diverse range of missions;
- to cultivate a Blue Economy based on data, information and knowledge—to sustain communities both economically and ecologically;
- for environmental justice to address the needs of vulnerable communities as they often bear the brunt of extreme weather and climate impacts; and,
- to incorporate equity into all aspects of NOAA's work to display the Administration's promotion of diversity, equity, inclusion, and accessibility in the workforce, and provide equitable access to our products and services.

This means considering how NESDIS engages with communities and how its products and information are packaged and accessed in order to meet user needs. NESDIS science activities also seek to address a range of challenges related to extreme, high-impact weather, water, and climate events, and cascading hazards; competing demands for limited resources such as fresh water; and, threats to the health and existence of ecosystems.

2 Note: Adapted from written statement of Dr. Richard W. Spinrad, Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator "On The Advancing Earth System Science And Stewardship At NOAA," before the House Committee On Science, Space, And Technology Subcommittee On Environment September 23, 2021, https://science.house.gov/hearings?ID=45FB2C9D-B7FA-4123-A497-67BAFD4F332C.

Technological drivers, such as current and future observations and data systems, high-performance computing capacities, artificial intelligence (AI) and machine learning (ML) tools, provide opportunities for NESDIS science to enhance existing or develop new products and applications across a variety of mission areas.

Technological drivers enable NESDIS science to translate these advances into numerous real-time and research applications that benefit society.

NOAA's Satellite and Information Service operates many environmental satellites including its own fleet of 11 satellites:

- Five geostationary (GOES-14, -15, -16 [East], -17 and -18 [West])
- Five polar-orbiting (NOAA-15, -18, -19, -20 and -21)
- One deep space satellite (DSCOVR), and

six satellites, which are owned by other U.S. federal government agencies or foreign governments. These include:

- NOAA/NASA joint Suomi National Polar-orbiting Partnership (Suomi NPP)
- Jason-3
- Three Defense Meteorological Satellite Program (DMSP) satellites (F-16, F-17, F-19), and
- the former GOES-13 and current U.S. Air Force Electro-optical Infrared Weather System Geostationary (EWS-G1).

Figure 1. NOAA Satellite Observatories

Individually and collectively these environmental satellites (Figure 1) and their new instruments have significantly improved NOAA's capabilities for monitoring the atmosphere and detecting environmental events that impact the environment, public safety, and the nation's economic health and prosperity.

GUIDING PRINCIPLES

WHAT KINDS OF RESEARCH AND DEVELOPMENT DOES NESDIS SUPPORT?

> NESDIS science activities focus ultimately on providing improved products and services for the measurable benefit of our communities.
>
> Steve Volz, NESDIS AA

NESDIS science is linked to satellite in situ and remote sensing of the Sun and space, and the Earth's magnetosphere, atmosphere, surface, and climate. It covers many different variables, including those related to the atmosphere—temperature, humidity, winds; the hydrologic cycle—precipitation, clouds, water vapor; land surface—vegetation, snow and ice cover; climate—greenhouse gases, ozone, aerosols, the Earth radiation budget; space weather—solar images and irradiance, plasma, magnetic field; as well as environmental hazards from factors such as wildfire and dust emissions, heavy rainfall, harmful algal blooms, and extreme heat events.

NESDIS science also crosses into satellite instrument calibration; research to operations; radiative transfer model development for numerical weather prediction data assimilation and re-analysis; developing and analyzing long-term satellite data sets for studying and assessing climate change; and planning and preparing for new satellite instruments.

OUR OFFICES

NESDIS is made up of numerous offices, each managing different areas of satellite operations and acquisitions as well as environmental data and information.

Center for Satellite Applications & Research

OUR SCIENCE: Focuses on decoding raw satellite data into environmental measurements; improving the quality of NOAA satellite data, products and services; and providing the foundational information to support the development of future satellite instruments.

THE IMPACT: STAR research and development activities are integral to understanding and extracting the best and most useful information from our satellites to help our communities adapt and thrive.

National Centers for Environmental Information

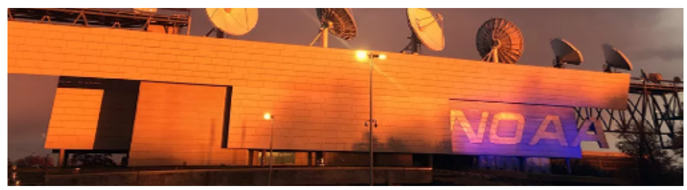
OUR SCIENCE: Explores the full spectrum of Earth data NOAA collects to develop scientific products and services that are valuable resources for public and private decision-makers. This includes industries affected by weather, space weather, and climate conditions, extracting natural resources, or other aspects of the Blue Economy.

THE IMPACT: NCEI data and access tools are used in both public and private sectors throughout the U.S. economy to address specific challenges and use cases, reduce risk and exposure to environmental hazards, sustain natural resources, and improve environmental literacy.

Office of Projects Planning & Analysis

OUR SCIENCE: Covers two important aspects: space weather and safeguarding society.

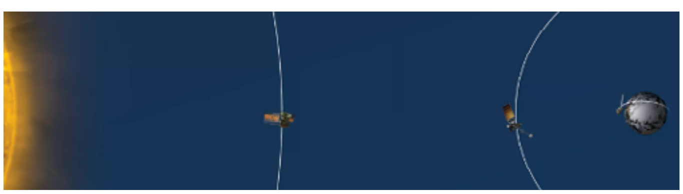
THE IMPACT: Enables the growth of new satellite products from inception through formulation and facilitates the management of existing satellite projects from formulation to launch, including technical requirements.



Office of Satellite Ground Services

OUR SCIENCE: Supports the sustainment of product processing and distribution systems, archive systems, and the cloud infrastructure.

THE IMPACT: Enables the development of an agile, scalable ground capability to improve efficiency and effectiveness of service delivery.



Office of System Architecture & Advanced Planning

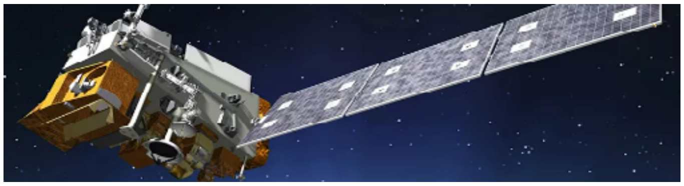
OUR SCIENCE: Helps us design and develop the next generation of Earth observations and data information services.

THE IMPACT: Leads enterprise planning that will optimize next-generation architecture in order to deliver sustainable, robust and adaptable systems and services that meet evolving user needs.

Office of Satellite & Product Operations

OUR SCIENCE: Manages satellite transmissions, provides automated satellite products and interpretative analyses of environmental hazards, and ensures advanced satellite data and analysis techniques are incorporated into NOAA's numerical model activities.

THE IMPACT: Primary intermediary between civil sector users of data and operational environmental satellites, providing continuity of measurements from polar orbits, cost sharing, and improved forecast and monitoring capabilities through the introduction of new technologies.



GOES-R and GeoXO Programs
<u>OUR SCIENCE:</u> Supports the development and/or the enhancement of products and services to enable fuller utilization and extension of GOES-R capabilities.

<u>THE IMPACT:</u> Provides constant vigil to identify and track severe weather conditions and environmental hazards like fires, smoke, dust storms, fog, and volcanic ash, as well as mapping total lightning activity and monitoring of solar activity and space weather.

Joint Polar Satellite System Program Office
<u>OUR SCIENCE:</u> Dwells at the forefront of JPSS mission spacecraft and their instruments, which provide global imagery, and meteorological observations that feed the nation's forecasting models.

<u>THE IMPACT:</u> Provides sophisticated meteorological data and observations of the atmosphere, ocean, and land for short-term, seasonal, and long-term monitoring and forecasting and allows for early warnings that enable emergency managers to make timely decisions to protect American lives and property.

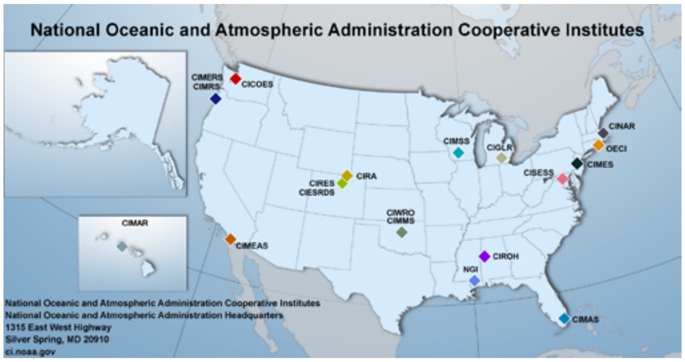
Each Office Provides A Unique Contribution To NESDIS Science And Research

Translating the bits and bytes from satellites into usable information and science lies in the work of STAR, the Office of Satellite and Product Operations (OSPO), and the National Centers for Environmental Information (NCEI). The STAR portfolio includes instrument science related to pre- and post-launch activities, the most recent of these carried out on the newest prized additions, the GOES West and NOAA-21 satellites. Science at STAR also involves the use of algorithms to derive products from satellite observations. Examples include ocean color algorithms for ocean and coastal users; multi-satellite fire emissions algorithms such as the Regional Hourly Advanced Baseline Imager and Visible Infrared Imaging Radiometer Suite Emissions, or RAVE, which has demonstrated improvements in estimates of wildfire smoke and air quality prediction; and satellite-derived precipitation models to better detect and monitor extreme rainfall and flooding events.

Engineers and scientists at OSPO command and control 17 satellites, including those operated by our partners, commercial operators, and NOAA, leveraging data from domestic and international sources to develop satellite products from data merged from GOES East or GOES West and polar-orbiting satellites. These merged products provide the information that is required by the National Weather Service (NWS) weather forecast offices, NOAA research scientists, NOAA fisheries labs, and National Ocean Service programs.

NCEI is unique in providing long-term archive and access to products and satellite data for retrospective, historical analyses. NCEI is also continuing to ramp up its development of climate datasets and products, and climate services through the regional climate services directors, regional climate centers, state climatologists, and other regional NOAA programs. Additionally, NCEI provides algorithms, product development, calibration and validation, and scientific expertise related to NESDIS's space weather portfolio.

Research Partnerships



NOAA Cooperative Institutes (CIs) are academic and non-profit research institutions that undertake a large and diverse set of research tasks—ranging from atmospheric research to oceanic exploration—that help address NOAA's mission and strategic goals. Many of the CIs are co-located with NOAA research laboratories or other NOAA facilities, supporting strong, long-term collaborations between NOAA and university scientists. Currently, NOAA supports 19 Cooperative Institutes consisting of 80 universities, and research institutions across the country, as well as the District of Columbia, US Territories, and Canada.

Product Categories

NESDIS aligns the work of these organizations to a product category framework, which improves the planning and management of resources across the defined collections of observing systems. In this report, we highlight the three main thematic product areas: foundational, geophysical and analytical—as presented in the NESDIS portfolio for science data and information products and services. These thematic product areas cover several product categories as shown in Figure 2 below.

Dive Into Our Data Archives

Looking for environmental information from one of the most significant data archives on Earth? Take a look at the breadth of oceanic, atmospheric, and geophysical data and products, as well as their impacts, from NCEI. Users can also view changing conditions from a historical perspective and directly access data through NCEI. For additional assistance, the contact page allows citizens to reach service professionals who can connect them to the information that they need for relevant decision-making and problem-solving.

You can learn more about other NESDIS products and services.

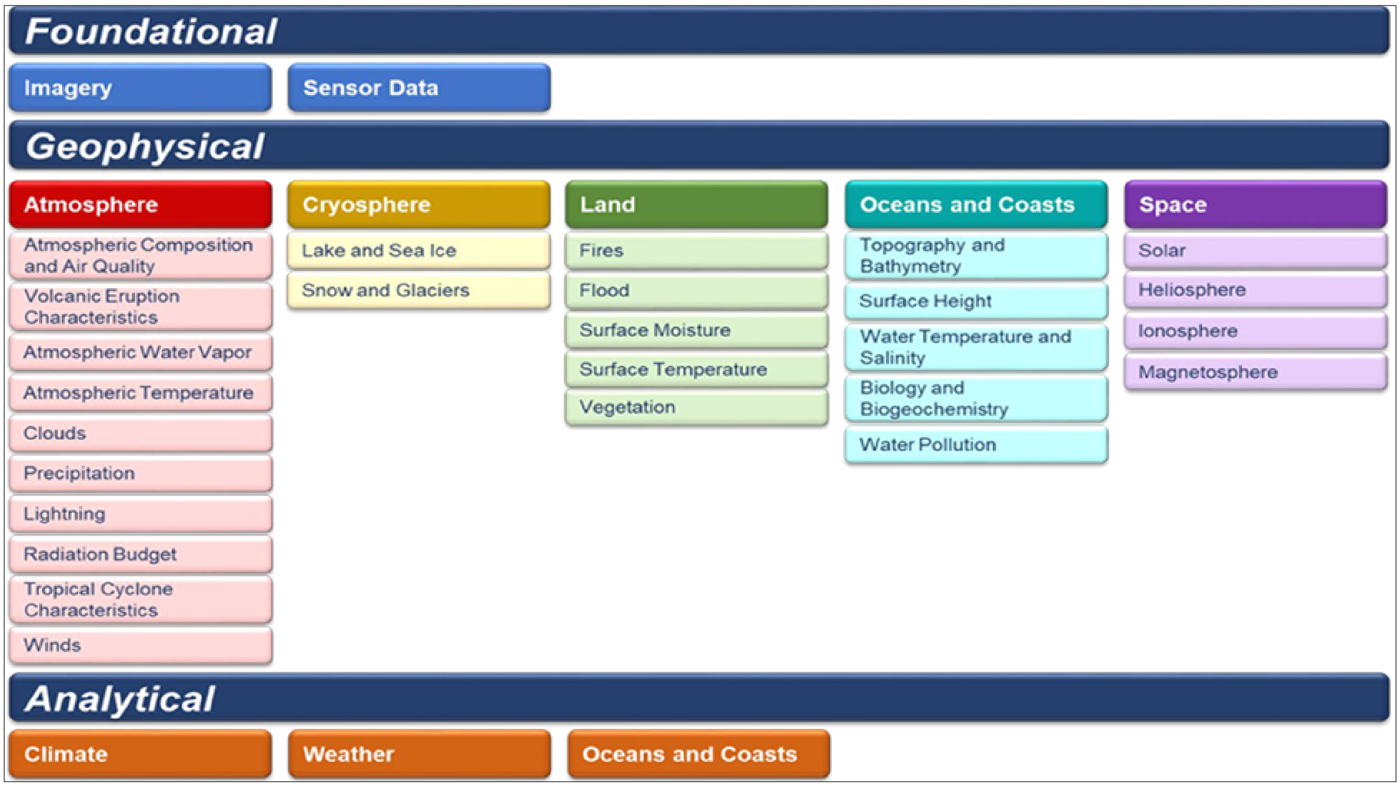


Figure 2. Thematic Product Areas and Product Categories

Foundational

Foundational products include imagery and sensor data. They describe the raw sensor data. They describe the raw sensor data generated from a satellite observing system to include calibration and geolocation information. The products are instrument specific and serve as building blocks for the NESDIS geophysical products and user applications.

The following are foundational themed areas organized according to product categories of the NESDIS portfolio for science data and information products and services.

IMAGERY

Remote sensing instruments, such as weather satellites, are among the most important tools in earth observations. Weather satellites generate many vital outputs. Among them are imagery products that are used in many key applications across the globe including forecasting weather, analyzing climate, studying the Ocean, and monitoring hazards. The type of imagery weather satellites produce is based on a number of factors including their orbits, instrumentation, and the spectral, temporal, radiometric, and spatial resolutions in which they view the Earth's surface.

NESDIS imagery products have historically been used in mesoscale and short-range weather warning and prediction[3]. And while they continue to provide vital information that enables us to detect, observe and track weather phenomena and environmental events, the evolution of NOAA satellites in the past few decades has enabled extension into applications well beyond meteorology. In addition to providing vital information for forecasting weather, analyzing climate, and monitoring hazards, NESDIS satellite imagery is also used to monitor the space environment, track volcanic eruption ash clouds, conduct maritime surveillance, map floods, view power outages following severe weather events, observe crop health and so much more.

NESDIS imagery products[4] include but are not limited to visible, near-infrared, infrared, microwave and solar imagery at multiple wavelengths. They are available in various formats, which include but are not limited to direct interpretation of single-channel images and processed multi-channel images such as multispectral compositing, temporal combination of animated sequences, and multi-satellite mosaics. Imagery products are especially important for defining features in areas where conventional data is sparse, such as mountainous or remote regions, or over the open ocean. The GOES-R satellites provide high temporal resolution imagery of the Western Hemisphere, allowing for real-time application, while the JPSS satellites, which orbit the entire Earth from distances relatively close to its surface, provide images of higher spatial resolution.

The applications of NESDIS imagery products are numerous and the benefits are enormous—with imagery being used to monitor, map, and study severe weather, wildfire, clouds, crought, lightning, snowpack, power outages, and more.

First Data from GOES West

GOES-T, the third of four GOES-R series satellites, launched on March 1, 2022. It reached its destination orbit on March 14, and is now GOES West. On May 3, the spacecraft's Space Environmental In-Situ Suite (SEISS) released its first data, followed by the new Magnetometer, on May 4. These instruments monitor proton, electron, and heavy-ion fluxes in the magnetosphere and measure the magnetic field around the Earth. On May 11, the Advanced Baseline Imager (ABI) provided its first public image, along with a series of spectacular animations highlighting the capabilities to

3 National Academies of Sciences, Engineering, and Medicine. 1997. Continuity of NOAA Satellites. Washington, DC: The National Academies Press. https://doi.org/10.17226/5588.

4 A categorized product list and other details such as specifications/attributes can be viewed at: https://nesdis-prod.s3.amazonaws.com/2022-12/NESDIS-REQ-1002-2.pdf?_ga=2.77862812.949917742.1678102358-2062665021.1660934711.

observe clouds, storms, fires, smoke, and many other phenomena on Earth. In early June, imagery from the Geostationary Lightning Mapper (GLM) showcased the GOES West satellite's ability to capture the evolution of lightning-producing storms on Earth. On July 13, data from the Extreme Ultraviolet and X-Ray Irradiance Sensor (EXIS) indicated two solar flares, and data from Solar Ultraviolet Imager (SUVI) released on July 19 captured a Coronal Mass Ejection (Figure 3). Solar storms can cause radio communications blackouts, disruptions to electric power grids, degradation or denial of GPS navigation service, and hazards to satellites and astronauts, which makes the instruments on the GOES-R series mission-critical monitoring tools.

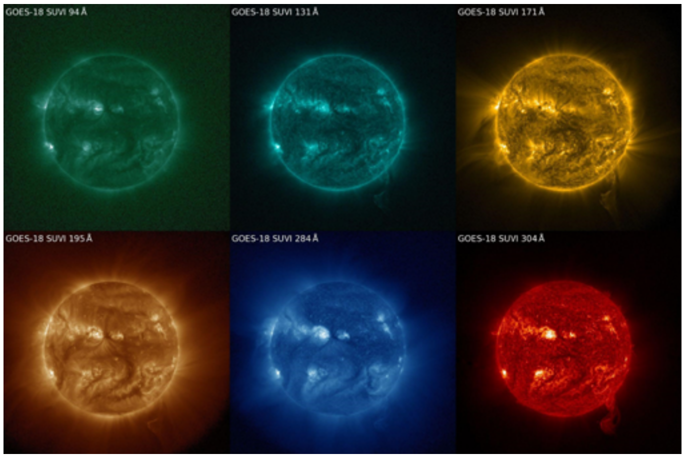


Figure 3. Coronal Mass Ejection, as captured by the GOES-18 SUVI instrument on July 10. The clearest depiction of the CME is shown in the 304 Å channel (lower right).

Light Emissions

The same technology that made nighttime imaging possible with the Defense Meteorological Satellite Program (DMSP) Operational Line-Scan System (OLS) was used with the Day Night Band (DNB) sensor on the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument onboard currently flying spacecraft in the JPSS mission. The DNB however, offers a substantial number of improvements over the OLS. These include superior spatial and radiometric resolution, better sensitivity to low levels of light, and calibrated nighttime visible measurements. Since its introduction in 2011, applications of the DNB sensor have diversified and brought forth innovations in various areas including wildfire monitoring, detecting power outages following high-impact events such as severe storms, observing marine bioluminescence, revealing the human footprint at night, and many more. Forecasters in Alaska utilize it during polar nights to help identify features such as clouds and the Arctic ice pack. Additionally, the capability to identify illegal fishing activity has made the DNB a valuable tool in fisheries enforcement. The DNB is also making it easier to detect nighttime clouds during moonlit conditions, especially during the winter months. In other application examples, the emitted light from fires and volcanoes can be used to identify fire perimeters, and when coupled with reflective moonlight, this can enable forecasters to see the smoke plumes at night.

One of the biggest improvements of VIIRS over DMPS is the ability to see features in moonless conditions. Clouds, for example, reflect light from the mesosphere, which makes it possible for the DNB to capture them even when there is no moonlight. In addition, light emissions from the chemical-luminescence in the mesosphere enable the DNB to reveal features such as airglow and gravity waves from convection, volcanic eruptions, and other sources. This is extremely important in understanding the energy budget of the atmosphere. One other unique feature that has been seen in both the OLS and DNB is bioluminescence (milky seas). However, the important difference is that the DNB is better at identifying the occurrence of these features and with higher resolution. Finally, the DNB has been able to show the northern lights, or the aurora borealis at night. This imagery, when used along with photos from citizen scientists, provides the unique ability to view simultaneously the aurora light displays from both the ground and space perspectives.

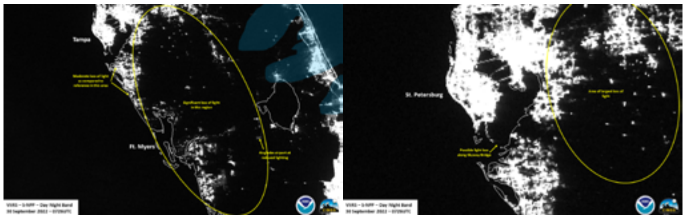


Figure 4. Imagery over Florida after Hurricane Ian on 30 September 2022 with notations of where significant differences in light amount were occurring due to power outages.

Volcanic Eruptions

Most of Earth's volcanoes sit on a stretch of islands along the rim of the Pacific Ocean—a remote area known as the Ring of Fire. Satellites in the Low Earth Orbit (LEO) such as NOAA-20 and 21, which cover the Earth two times a day; and in geostationary orbit such as GOES East and GOES West, which orbit 22,236 miles above Earth's equator, at the same speed Earth rotates, provide the best means to monitor isolated locations such as this. The ability to continuously view the same area makes geostationary satellites ideally suited for monitoring the rapid formation and expansion of volcanic clouds.

Volcanic Ash Advisory Centers (VAACs) as their name indicates, provide formal notices and recommendations regarding volcanic ash events. Imagery and other data from satellites help these centers monitor clouds whose location, evolution and/or spectral properties support volcanic activity. The Washington VAAC is located with OSPO's Satellite Analysis Branch.

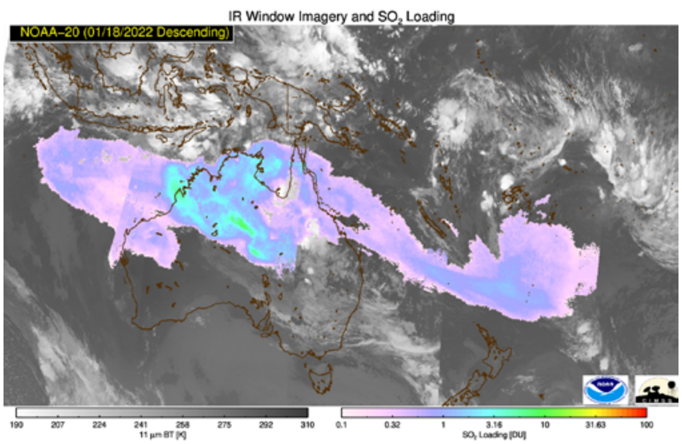


Figure 5. SO2 emissions derived from the Cross Track Infrared Sounder and VIIRS instruments on NOAA-20

In January, an underwater volcano erupted in the South Pacific Ocean. Imagery from multiple satellite instruments, including the ABI on NOAA's GOES-17[5] and VIIRS on Suomi NPP and NOAA-20, helped reveal various atmospheric features associated with the eruption, including the extraordinary amount of steam, ash, and sulfur dioxide it unleashed into Earth's stratosphere. For example, the Cross Track Infrared Sounder (CrIS) and VIIRS instruments tracked plumes of ash and volcanic sulfate aerosol from January 16-20 as they moved westward across the Pacific Ocean towards Australia through to the Indian Ocean (Figure 5). Nighttime observations from the VIIRS I-5 band showed clear tropospheric gravity wave, features at the fine resolution of 375 m while the DNB, which also captured the tropospheric gravity wave showed ash clouds. In addition to VIIRS, GOES-17 imagery of the event showed crescent-shaped shock waves and lightning strikes.

5 The operational GOES West at the time

Flood Inundation Mapping

NOAA's satellite imagery continues to play a significant role in flood detection, monitoring, and assessment. Products such as the VIIRS-ABI flood maps are now being provided routinely to federal partners such as the Federal Emergency Management Agency (FEMA) and U.S. weather forecast offices.

In addition to VIIRS and ABI, NESDIS scientists are integrating more sources—including Synthetic Aperture Radar (SAR), which penetrates cloud cover—to create visuals that are more accurate and representative of actual scenes on the ground, such as the false RGB (red-green-blue) imagery shown below (Figure 6). By integrating SAR, NESDIS is able to develop street-level flood maps from satellite and provide early response flood inundation mapping.

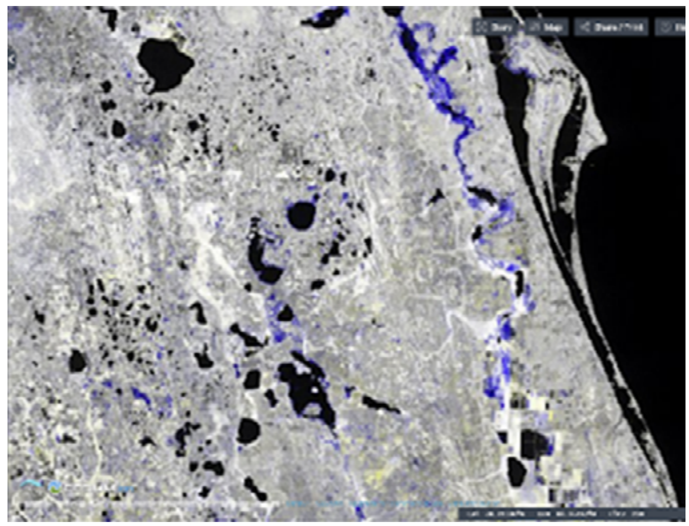


Figure 6. False RGB imagery from April-May, 2022 depicts areas of flooding advancing downstream on the Red River of the North near Bowesmonth basins in Minnesota and North Dakota.

In the next example from Hurricane Nicole, which made landfall along the coast of Florida on 10 November, NESDIS and its supporting contractor generated RGB imagery that allows for flood identification using all available SAR instruments. In this case, the image (Figure 7) shows a combination of Radarsat-2 (2022-11-11 23:17 UTC [RG]) with Sentinel-1 baseline (B) RGB composite that allows for identification of flooded locations using two disparate SAR satellite instruments. Blue colors reflect significant backscatter drop (e.g. due to flooding) while yellow colors show significant backscatter increase (e.g. from enhanced soil moisture or urban flooding).

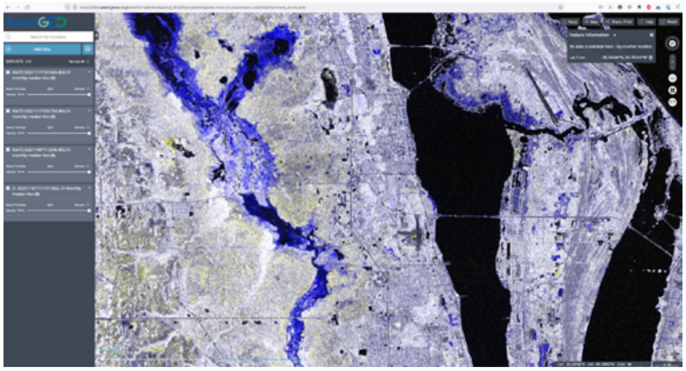


Figure 7. Radarsat-2 (from November 11, 2022) and a baseline (clearly seen) from Sentinel-1 RGB composite which depicts the flooding (in blue) in Florida along the St. Johns River from 11 November 2022.

Other significant highlights included the transition to operations for the VIIRS Flood product, and a reprocessed record from 2012 to 2020, of the NOAA VIIRS flood product. In early October 2022, NOAA's flood products supported FEMA's response efforts to Hurricane Ian. NOAA's downscaled (30m) flood maps from VIIRS, which helped assess where the flooding was occurring, were a big contribution to this effort. The map on the left (Figure 8) from 1 October 2022 shows the flooding along the St. Johns River, an area that flooded again after Hurricane Nicole 43 days later.

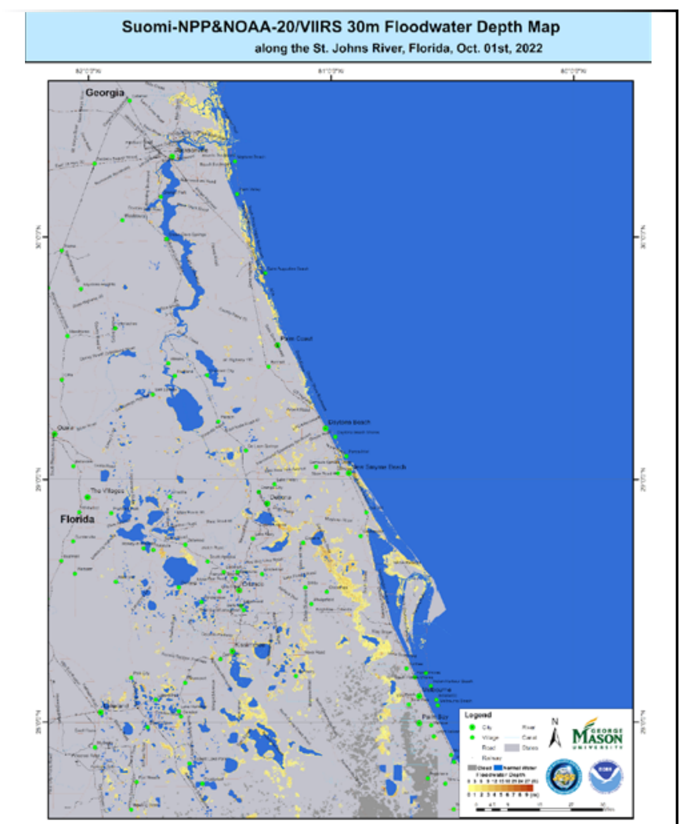


Figure 8. Suomi NPP and NOAA-20 VIIRS 30m floodwater depth map from Oct.1, 2022, shows flooding along the St. Johns River.

NESDIS is in the process of migrating GOES flood mapping and blended VIIRS/GOES flood mapping into operations. The use of GOES ABI offers significant benefits due to the high frequency of observations, while the combined blended VIIRS/GOES flood products allow for applying the strengths of both VIIRS and ABI for daily flood identification. GOES ABI contributed to generating flood maps during and shortly after Hurricane Ian's landfall on September 30, 2022.

NESDIS satellite flood products are also used around the world via mechanisms such as the International Charter Space and Major Disasters. Examples from 2022 include a large-scale flood event that occurred in Pakistan in August in which imagery (Figure 9) from the Suomi NPP and NOAA-20 VIIRS instruments showed satellite-detected water extents between 3 to 23 August in the region.

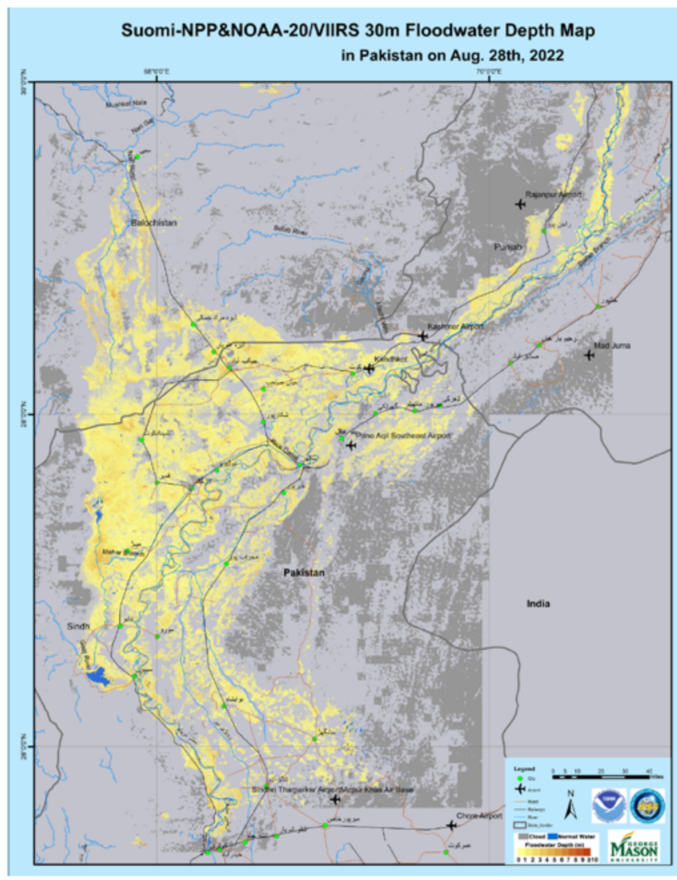


Figure 9. Suomi NPP and NOAA-20 VIIRS 30m floodwater depth map from Aug 28, 2022, shows flooding extent in Pakistan.

The United Nations Satellite Centre, or UNOSAT, also heavily utilizes the VIIRS flood products to produce population impacts for flood events, especially those from the International Charter. The August flood event impacted more than 33 million people. In addition, UNOSAT derived another unique product showing the evolution of the flood by utilizing the daily products from VIIRS, as shown in Figure 10[6].

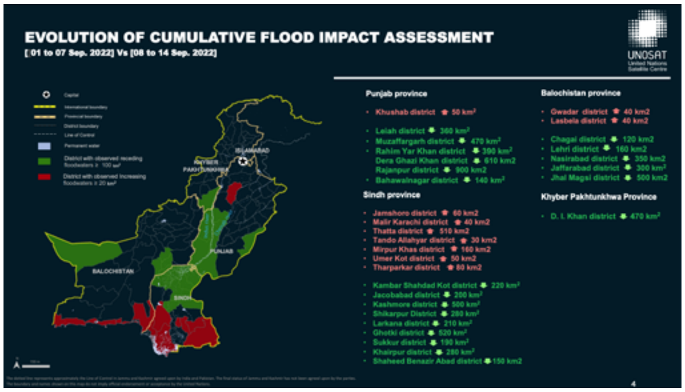


Figure 10. VIIRS flood product shows the evolution of Pakistan's August 2022 flooding event.

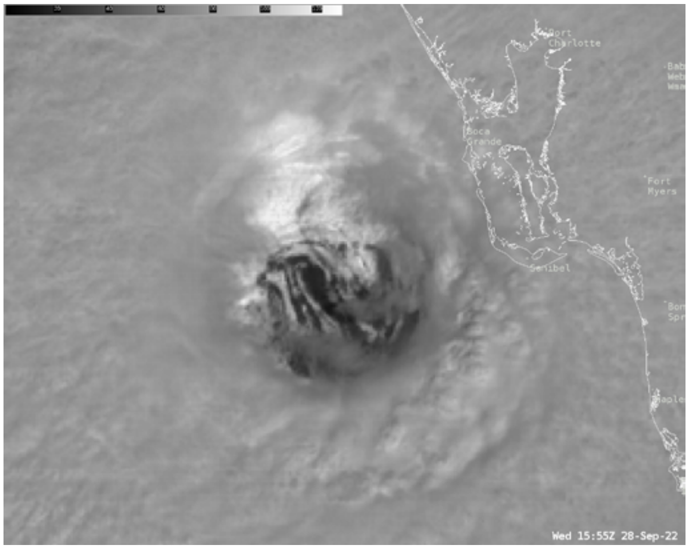


Figure 11. 1555 UTC 28 Sep 2022 GOES-East 30-sec Visible Satellite Imagery centered over the eye of Hurricane Ian three hours prior to landfall in southwest Florida.

2022 Hurricane Seasons

The Atlantic had a near-average season, with 14 named storms and eight Hurricanes, while the Pacific was slightly active, with 19 named storms and 10 Hurricanes. Forecasters leverage imagery from NOAA's geostationary and polar-orbiting satellites to provide timely and accurate forecasts and services related to tropical systems. Specifically, the high temporal resolution from the GOES ABI allows forecasters to center-fix tropical systems and track their movement and intensity in near-real-time. As storms impact land, GOES imagery is leveraged to assess the timing of landfall, and to monitor the development of thunderstorms, potentially tornadic, within the outer rain bands. Imagery from the JPSS VIIRS instrument provides very detailed views of tropical systems, in high spatial resolution, as well as unique "visible imagery at night" from the DNB.

Hurricane Ian was perhaps the most memorable storm from the 2022 Atlantic Hurricane Season, peaking in intensity as a 155 knot category 4 Hurricane. Ian made landfall in southwest Florida as a category 4 Hurricane, causing over 150 deaths and billions of dollars in damage. During Ian's evolution, NOAA positioned GOES-East 1-min, and at times 30-second, sectors over its location, providing forecasters with rapid updates on the storm's movement and intensity. In fact, GOES-East 30-second imagery tracked Hurricane Ian as it made landfall near Cayo Costa, FL on 28 Sep 2022 (Figure 11).[7]

Hurricane Darby developed into a strong Category 4 Hurricane in the eastern Pacific on 11 July 2022. Early that morning as the storm strengthened rapidly, the Suomi NPP and NOAA-20 VIIRS DNB Near Constant Contrast product provided detailed views of the storm, including a clearing eye, thunderstorms in the eyewall, and transverse banding within some of the outer cirrus cloud bands (Figure 12). Even though GOES-18 was undergoing post-launch testing during the hurricane season, it provided 30-second imagery of the hurricane to complement the 1-minute scans from the then-operational GOES West (GOES-17).

6 Source: International Charter

7 Additional NOAA satellite imagery of Hurricane Ian, and how it was used by forecasters, can be found at https://satelliteliaisonblog.com/2022/09/28/hurricane-ian/.

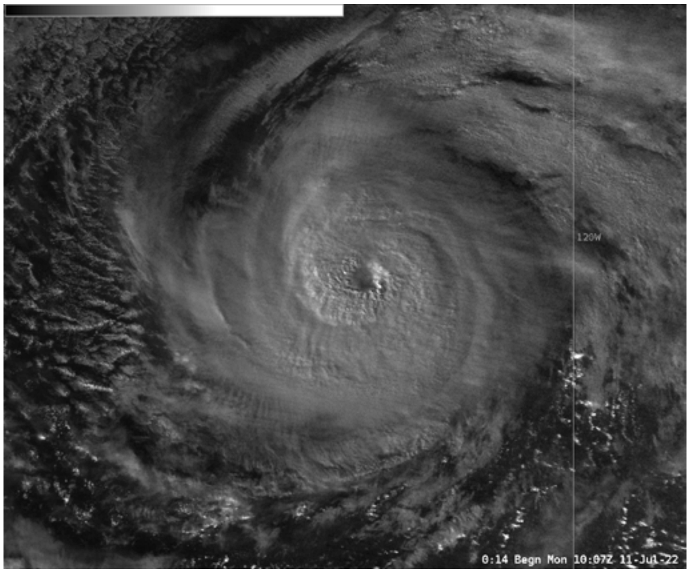


Figure 12. 1007 UTC 11 July 2022 NOAA-20 VIIRS DNB Near Constant Contrast Imagery centered over Hurricane Darby in the eastern Pacific Ocean

Sensor Data

NESDIS Sensor Data can be used to develop scientific products and services that are valuable resources for a myriad of industries affected by weather and climate conditions, reduce risk and exposure to environmental hazards, and address specific challenges such as extreme events & hazards, coastal resilience, the changing ocean, water availability & quality, effects of space weather, and climate change mitigation.

Sensor Data products include but are not limited to radiances, radar/lidar backscatter amplitudes and phases, backscattered radiation, brightness temperatures, sensor radiometric calibration information and geolocation, and in-situ observations such as electrons, ions, and electric and magnetic fields, etc.

Observing Atmospheric Temperature Trends

Satellite instruments are important sources of the measurements used to monitor atmospheric temperature. Scientists from the NESDIS STAR developed a science-quality long-term dataset of upper atmospheric temperatures from NOAA's microwave and infrared satellite measurements. The dataset includes observations from several instruments including the Microwave Sounding Unit (MSU), Advanced Microwave Sounding Unit (AMSU), and Stratospheric Sounding Unit (SSU) onboard 16 historical and currently operational NOAA and JPSS polar-orbiting satellites. These observations provided information on atmospheric temperature conditions from the lower troposphere through the upper stratosphere. This dataset, which allows researchers to perform upper-air temperature trend assessments (as shown below in Figure 13), also holds the first-ever multi-decadal global temperature measurements from the lower atmosphere to the upper stratosphere.

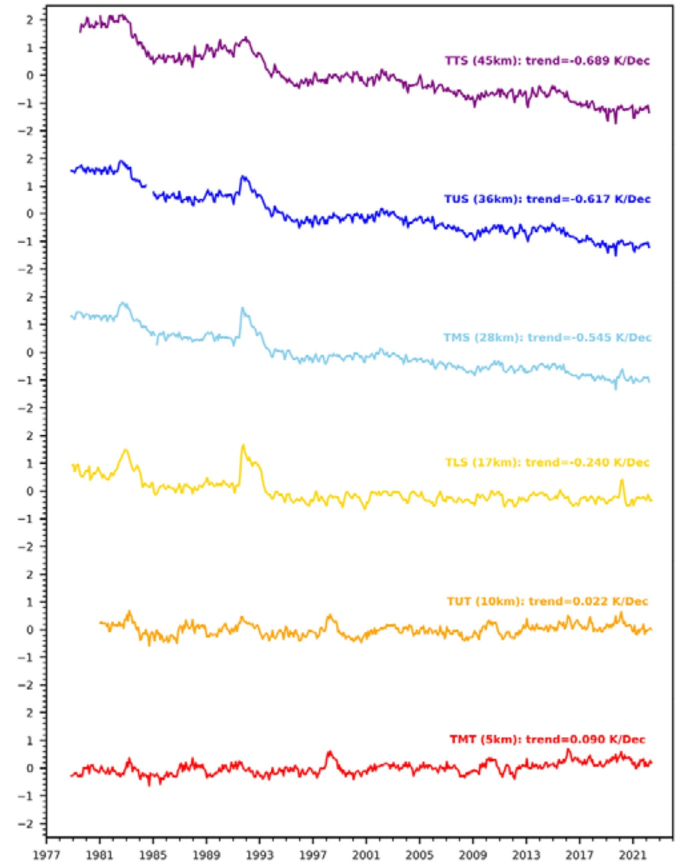


Figure 13. Deseasonalized monthly global mean temperature anomaly time series and trends for the mid-troposphere (TMT), upper-troposphere (TUT), lower-stratosphere (TLS), mid-stratosphere (TMS), upper-stratosphere (TUS), and top-stratosphere (TTS). The heights in the brackets above each time series represent the peak levels of weighting functions for each instrument channel measuring the temperature index time series. Trends were calculated for the period from January 1979 to June 2021.

Improving Numerical Weather Prediction

Numerical Weather Prediction (NWP) uses mathematical equations—of all the dynamic and physical processes in the atmosphere—to generate a forecast. NWP enables observed data to be converted into information and services such as forecasts and warnings for tropical cyclones, winter storms, and convection, which is extremely important on all scales from local (towns) to global (earth). Over 85 percent of the observations ingested as initial conditions in NWP come from passive infrared and microwave instruments. Forecast Sensitivity-based Observational Impact (FSOI) assessments of various observations including aircraft, buoy, and dropsondes have shown that among all satellite observations, those from microwave (MW) sounders have the largest impact in reducing forecast errors. This is in part due to their ability to operate in almost all weather conditions including through non-precipitating cloud layers, and also because more MW sensors are operating compared to IR sounders. However, hyperspectral IR satellite data, as shown in Figure 15, make up the largest proportion of observations assimilated into NWP models.

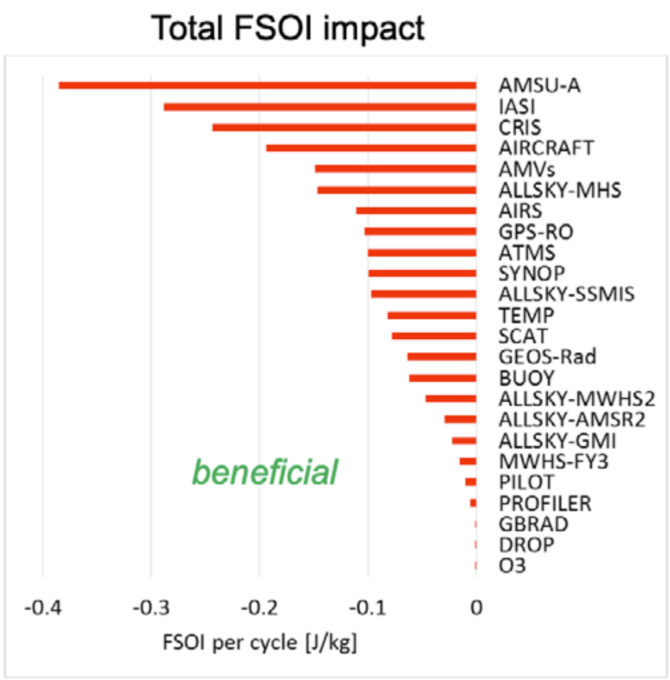


Figure 14. The total beneficial contribution of forecast sensitivity to observation of various assimilated observations on forecast errors.

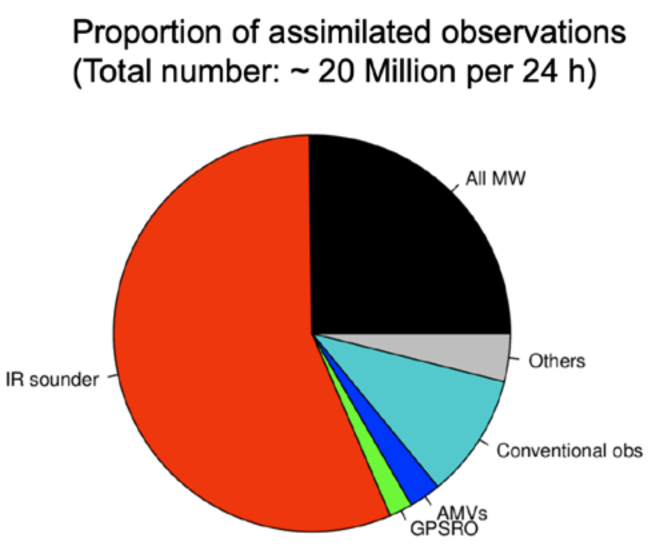


Figure 15. Proportion of observations assimilated into NWP models.

Three-dimensional Views of a Tropical Cyclone's Warm Core Features From the Advanced Technology Microwave Sounder

Tropical cyclones are warm-core, non-frontal synoptic-scale systems, originating over tropical or subtropical waters with organized deep convection and a closed surface wind circulation about a well-defined center. The Advanced Technology Microwave Sounder (ATMS) instrument is very sensitive to warm-core heating in the middle and upper troposphere. The STAR Integrated Calibration and Validation System (ICVS) Long-term Monitoring System (LTM) scientists have established a well-validated gap-free ATMS 3D hurricane warm core animation system (HWCAS) that can visually monitor vertical and horizontal warm core features of hurricanes particularly in both the North Atlantic and North Pacific Ocean basins. Besides the ATMS temperature sounding changes from channels 5 through 12, this new tool uses an existing penalized least square (PLS)-Discrete Cosine Transform (DCT) method to fill in both intrinsic gaps between successive orbits and missing points near the swath edges in the gridded ATMS data, thus ensuring the spatial consistency of realistic hurricane warm core structure. Figure 16 is an example from Hurricane Ian, which was close to category 5 just before landfall, and is also considered one of the most powerful hurricanes to strike the U.S. in decades. The cross-section image shows the ICVS-HWCAS observations for Hurricane Ian during the period of three days from 26 September to 29 September 2022, where the hurricane gradually strengthened. The 3D observations from the ATMS closely match the 2D observations from the VIIRS. This example further evidences the high quality of the JPSS ATMS and VIIRS SDR data products that are highly capable for extreme event monitoring applications. More details, images, and animations can be found at https://www.nhc.noaa.gov/archive/2022/IAN.shtml. The reference of the used algorithm is referred to Yan et al. (2020; Earth and Space Science, 7, e2019EA000961. https://doi.org/10.1029/2019EA000961)

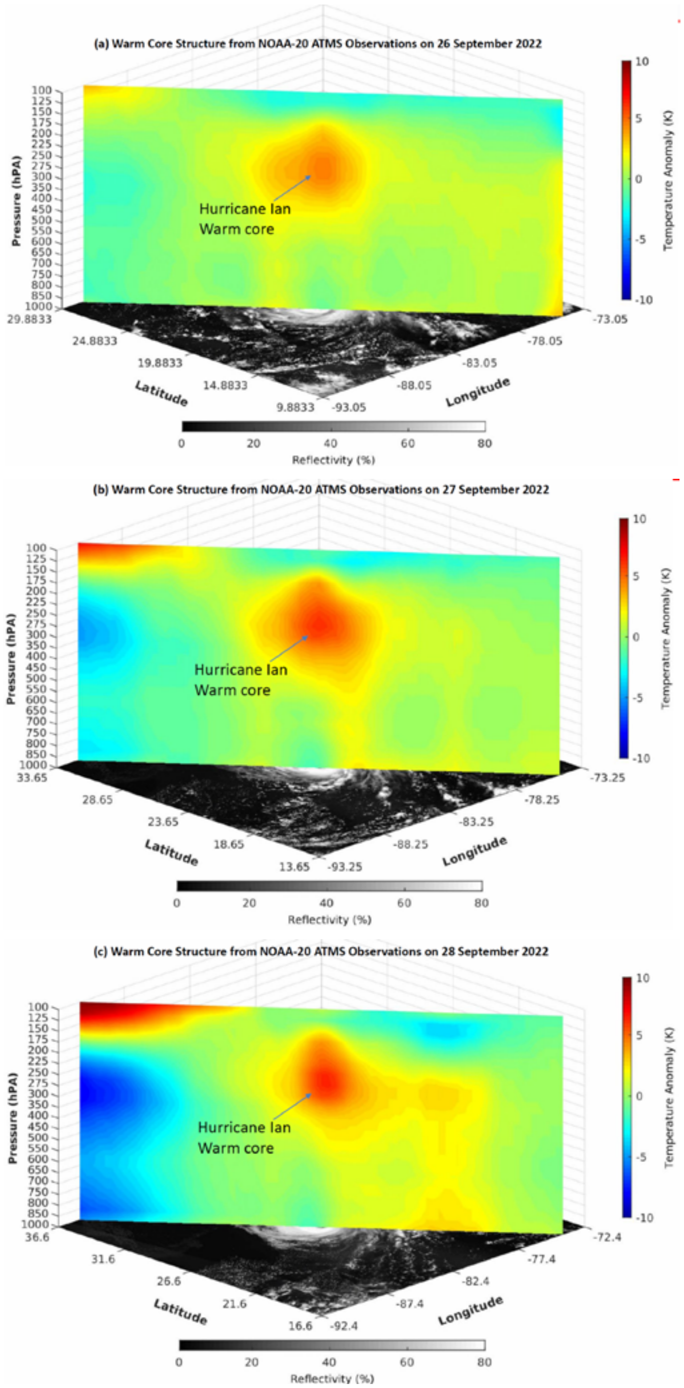


Figure 16. The upper-level warm core structure of 2022 Hurricane Ian on 26 September in (a), 27 September in (b), and 28 September in (c), which are produced by the ICVS Hurricane Warm Core 3-D Animation System (HWCAS). Each event includes the daytime 3-D animation by using NOAA-20 ATMS data along with the NOAA-20 VIIRS I1 reflectivity as the background in the 3D animation images.

Geophysical

Geophysical products help describe the earth, athmosphere and surrounding space environment. They are derived through mathematical algorithms that process observing system foundational data. They are designed to support user need in weather, climate, cryosphere, oceanic and space forecast and monitoring.

The following are geophysical-themed areas organized according to product categories of the NESDIS portfolio for science data and information products and services.

Atmosphere

NESDIS atmospheric products provide important information on the Earth's atmosphere, including winds, aerosols, trace gases, retrieved temperature and water vapor profiles, and lightning detection. They are used for a variety of applications including to: determine atmospheric stability; forecast severe weather; to assess the intensity of tropical storms; study climate change; and monitor and help predict air quality.

ATMOSPHERIC COMPOSITION AND AIR QUALITY

The atmosphere is composed of a mixture of trace gases and aerosol particles, many of which can lead to poor air quality that is harmful to human health and the environment. Accurate and timely air quality information is critical to public health. NOAA has a robust capability for observing and predicting air quality and atmospheric composition. This includes continuous observations and measurements of atmospheric composition from NESDIS space-based assets, which are used in air quality monitoring and forecasting applications. These observations and measurements also provide the inputs needed to design mitigation strategies at the local, state, and federal levels.
NESDIS generates several atmospheric composition products that have relevance for air quality and climate monitoring and forecasting applications, including but not limited to aerosol detection, optical depth, particle size, height, ozone, methane, carbon monoxide (CO), carbon dioxide (CO2), and other trace gases. For example, Aerosol Optical Depth (AOD), which is a measure of the amount of aerosol in a vertical column from the Earth's surface to the top of the atmosphere, enables scientists from NESDIS STAR to derive surface particulate matter concentrations key for the Environmental Protection Agency (EPA) designated criteria pollutant, PM2.5 (particles < 2.5 micrometers in median diameter). Exposure to certain aerosols can impact human health by exacerbating certain health conditions such as asthma and heart disease. Aerosol composition by mass and size distribution is one of the key pieces of information that scientists use to help them understand the links between aerosols and health, weather, and climate outcomes.

NOAA Satellites Improve Estimates of Wildfire Smoke, Air Quality Predictions—RAVE

Wildfires are a source of harmful air pollutants including smoke, various volatile and semi-volatile organic compounds, and nitrogen oxides that form ozone and PM2.5. PM2.5 is especially concerning because those particles penetrate deep into human lungs and cause various upper respiratory diseases, including premature death. A team of scientists from NESDIS and South Dakota State University developed more accurate wildfire emissions of trace gases and PM2.5 to predict the impacts of wildfire smoke on air quality. These efforts stem from the Disaster Relief Act of 2019, in which NOAA's Office of Oceanic and Atmospheric Research (OAR), NWS, and NESDIS partnered to deliver improved forecasts of wildfire smoke impacts on air quality. The method known as Regional Hourly ABI and VIIRS Emissions, or RAVE, combines observations from the instruments for which it's named, which can detect heat signature, or fire radiative power, from wildfires. It is an upgrade to the current benchmark, the NESDIS Global Biomass Burning Emissions Product, that the NWS uses as input to the Community Multi-scale Air Quality (CMAQ) modeling system, providing predictions of surface PM2.5 that are much closer to the true values and accurate predictions of National Ambient Air Quality Standard (NAQS) for PM2.5. The

NAQS designated by the EPA is a 24-hour average of 35 µug/m3. Compared to fire emissions information from polar-orbiting satellite instruments, RAVE's hourly fire emissions resulted in reductions in false alarms by a factor of 100 because the diurnal changes of emissions data associated with highs and lows of fire activity are now captured by the model. NWS will continue to test the RAVE emissions product to determine its performance for different types of fires ranging from small-scale agricultural fires to large-scale multi-day wildfires.

In addition to the CMAQ model, the RAVE data will be ingested into the Rapid-Refresh Forecasting System (RRFS) for high-resolution smoke forecasting over North and Central America. The experimental RRFS model is currently being developed for weather and smoke forecasting at NOAA's Global Systems Laboratory. The RAVE data will be used to estimate the wildland fire emissions and heat fluxes in the RRFS-Smoke model. The RRFS-Smoke model will be initialized every hour, thus taking advantage of the high-frequency RAVE fire data.

Air Quality Data When You Need It: Incorporating Satellite Data Updates into EPA AirNow

The U.S. EPA uses ground-based monitors to survey and enforce the NAAQS standard for PM2.5. The network is not densely populated and mostly located in populated urban areas. While the focus on air quality issues has traditionally been in urban areas, there are increasing issues in rural areas due to wildland fires that release smoke that is transported long distances and impacts air quality regionally. Rural areas, however, lack adequate monitors. The mitigation strategies adopted by local and state agencies over the years have reduced urban air pollution from anthropogenic sources. However, pollution from smoke and dust is evolving as a major source of NAAQS violations. Adequate monitoring and issuance of public safety air quality alerts in rural areas is particularly essential due to the limited number of monitors.

In a newly funded NASA Health and Air Quality Applied Science Team (HAQAST) project, AirNow is being complemented with NOAA's geostationary satellite data, specifically focused on providing PM2.5 derived from aerosol optical depth on an hourly and daily scale in near-real time. This timeliness is especially useful for public communication of ongoing air quality risks, by improving both the local accuracy and timeliness of the information, so people can make the most informed decisions to manage their risk. Satellite observations also provide a unique bird-eye view of the entire continental region, which can help monitor transport of pollution from region to region, specifically during air quality events such as fires and dust storms. In the recently published study by Zhang et al. (2022), it was pointed out that the geostationary satellite-based PM2.5 estimates inform the public of harmful air quality ten times more than standard ground observations (1.8 vs. 0.17 million people per hour). In partnership with STAR scientists and using the data provided by Zhang et al. (2022), public health researchers at the George Washington University School of Public Health found that in the year 2020 alone, geostationary satellite observations provided 350 million more person-alerts compared to polar-orbiting satellite observations that led to ~1000 averted deaths estimated at $10 billion (Figure 17) due to alert-informed human behavior modification.

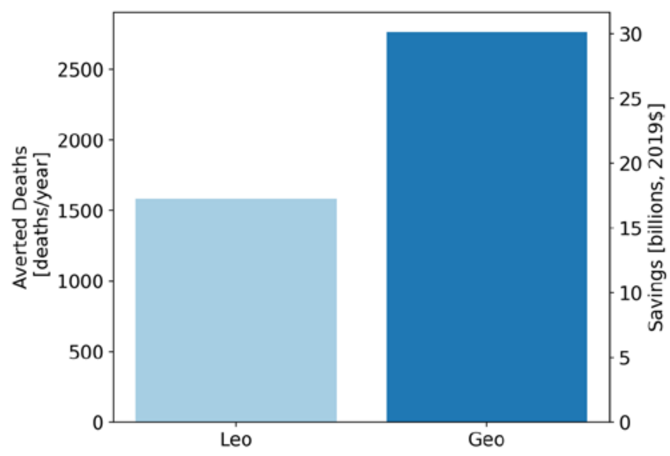


Figure 17. Deaths prevented by and Economic savings from person alerts derived from geostationary satellite observations. Figure from O'Dell et al. Fall 2022 AGU presentation.

Satellite Aerosols and Atmospheric Composition Data Training

The STAR Aerosols and Atmospheric Composition (AAC) science team interact with a large community of end users who utilize GOES-R and JPSS satellite data in research and operations. Through outreach activities that began in the early 2010s as part of the GOES-R Air Quality Proving Ground, it became evident that there are many more potential end users who would like to use NOAA satellite products for their applications, but face a myriad of barriers. To address this need, the science team developed the STAR Atmospheric Composition Product Training program in 2020, with the goals of increasing access to aerosol, fire, and trace gas satellite data and promoting proper use of the products. These goals align with high-level directives from NOAA and NESDIS related to prioritizing user engagement and enhancing the "customer experience."

The new STAR Atmospheric Composition Product Training website is a centralized repository for training program content and resources for end users. To reach a broad swath of the user community, half-day to full-day training courses are conducted at scientific conferences; multi-day in-depth sessions are offered by request for smaller specialized groups, such as state air quality forecasters. Products covered in the training include GOES-R/ABI and JPSS/VIIRS aerosol optical depth, aerosol detection (smoke/dust mask), fire detections, and fire radiative power. Sessions on Sentinel 5-Precursor (S5P)/TROPOMI aerosol index, aerosol layer height, carbon monoxide, formaldehyde, nitrogen dioxide, and sulfur dioxide are also offered via STAR's work on the S5P validation team.

The STAR Training program features Python tutorials to demonstrate the proper workflow for satellite data. Python is ideal because it is a powerful, freely-available, and open-source language with a wealth of support available online. To foster real-world learning, training participants run live Python code on their own computers for recent smoke, dust, or haze events. First, participants download satellite netCDF (.nc) data files programmatically: ABI and VIIRS files from the GOES-R and JPSS NOAA Open Data Dissemination (NODD) archives on Amazon Web Services (AWS) and TROPOMI files from the S5P data hub. Second, participants open the downloaded satellite data files, read the metadata, and explore data variables. They learn how to identify the structured content in a netCDF4 file, including groups, variables, dimensions, attributes, and data types. This is an important step because working with the netCDF4 file structure can be a substantial hurdle for new users. Third, participants learn how to process satellite data correctly using the data quality flags appropriate for their application. As a final step, participants use Python to visualize satellite data and make professional-grade figures that can be included in presentations or papers, or posted on social media.

The STAR Training website includes all of the resources end users need to work with satellite data successfully, including documentation/user guides and detailed links to the many online satellite data archives. The website also provides short summaries of information needed to understand satellite data products, such as data processing levels, product maturity levels, and satellite filename content, as well as a glossary of satellite terminology and a list of satellite and Python reference links.

Feedback from training participants has been overwhelmingly positive, with many more requests for training that can be accommodated. The science team already has several training sessions planned for 2023, including the GOES-R/JPSS sponsored Short Course at the annual meeting of the American Meteorological Society.

VOLCANIC ERUPTION CHARACTERISTICS

Volcanic eruptions produce aerosols that pose major threats to transportation, health and infrastructure. Communities residing close to a source volcano often encounter an array of hazards, including ash fall, heated debris flows, lava flows, and poor air quality. Volcanoes also generate clouds of ash and sulfur dioxide (SO2), which are aviation hazards. Aircraft encounters with ash clouds can diminish visibility, damage flight control systems, and cause jet engines to fail. Moreover, aircraft passengers and crew exposed to SO2 and sulfate byproducts may experience irritation of the skin, eyes, nose, and throat. Given these threats, routine operational monitoring of volcanoes and volcano byproducts, such as ash and SO2 clouds, is critical to protecting life and property, improving aviation safety and efficiency, and mitigating impacts from volcanic eruption events.

NESDIS products in the Volcanic Eruption Characteristics sub-category include those that detect, track, and characterize volcanic emissions (primarily ash and SO2), and volcanic heat signatures (lava, hot gases, and incandescent material). Specialized multi-spectral imagery and volcanic event-centric eruption attributes, such as source volcano, eruption timing, cloud height, mass of emissions, and cloud microphysical properties, are also part of the NESDIS product suite.

Revolutionizing Volcanic Eruption Detection With AI

Volcanic ash is a major aviation hazard. Volcanic Ash Advisory Centers (VAACs) are responsible for issuing volcanic ash advisories to aviation when airborne volcanic ash is present. VAACs primarily rely on satellite data to detect and track volcanic ash clouds. In order to help VAACs shift through thousands of new satellite images acquired each day, NESDIS developed the VOLcanic Cloud Analysis Toolkit (VOLCAT). VOLCAT, which is powered by AI, automatically detects new volcanic eruptions and tracks volcanic ash clouds. Through automated identification of subtle eruption indicators in satellite images, for example, as shown in Figure 18, VOLCAT enables VAACs to consistently issue timely volcanic ash advisories. VOLCAT alerts have been cited in over 12,000 volcanic ash advisories, which illustrates the value of AI as a force multiplier for hazard detection.

ATMOSPHERIC WATER VAPOR

Water vapor is a natural and very important component of the Earth's atmosphere. Its distribution influences many physical and chemical properties of the atmosphere, including weather, clouds, precipitation, radiation balance, convective uplift, lightning generation, and ozone chemistry including the Antarctic ozone hole. Variations in the amounts of water vapor in the atmosphere are natural and normal, but changes in its vertical distribution, especially in the upper troposphere and lower stratosphere, may be indicative of changes in the Earth's climate. For this reason, there is great interest in long-term measurement records of water vapor vertical distributions as they may reveal changes in atmospheric dynamics resulting from climate change.

Multi-Satellite Advected Layer Precipitable Water

NESDIS generates several atmospheric water vapor products including moisture profiles, total precipitable water, total precipitable water anomaly and stability indices. These products are used by weather forecasters to view pipelines or rivers of moisture which may transport water vapor thousands of miles and fuel destructive floods. Under the JPSS Proving Ground, a Cooperative Institute for Research in the Atmosphere (CIRA) team created a multi-satellite Advected Layer Precipitable Water (ALPW) water product which is currently being transitioned to NWS operations. Profiles of water vapor are derived via passive microwave retrievals (NOAA Microwave Integrated Retrieval System) from several polar orbiting spacecraft. Model winds move the satellite water vapor fields to a common time, which allows forecasters to see the flow of water vapor in three dimensions.

While ALPW processing is being transitioned to NESDIS operations to commence in 2023, CIRA produces and distributes ALPW to the NOAA Weather Prediction Center (WPC), National Hurricane Center and 27 Weather Forecast Offices. WPC routinely uses ALPW to assess the moisture environment and flow at various layers to warn of potential flood threats in Mesoscale Precipitation Discussions. Figure 19 shows an example of ALPW usage at WPC for flash flooding over the Desert Southwest on 13 September 2022.

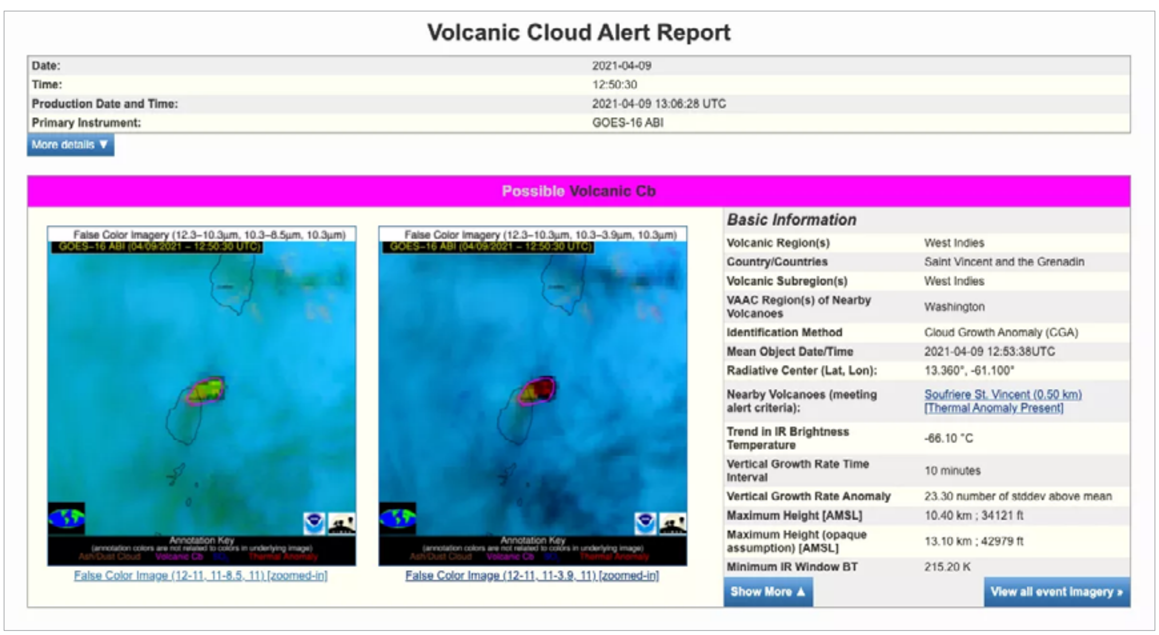
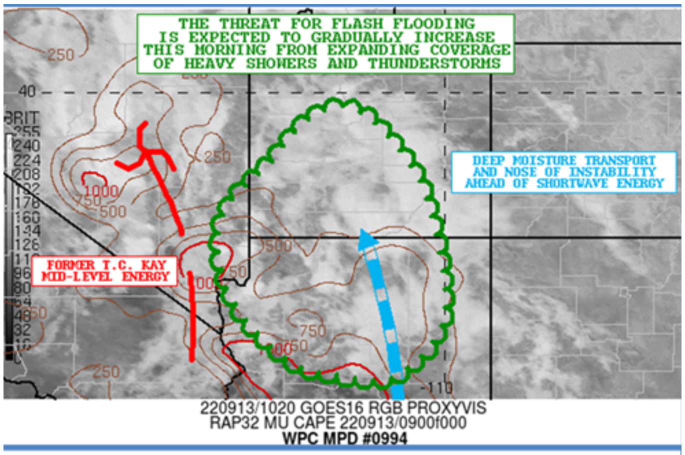


Figure 18. An example VOLCAT ash emission alert report derived from GOES-16 ABI data on 9 April 2021



Mesoscale Precipitation Discussion 0994
NWS Weather Prediction Center College Park MD
642 AM EDT Tue Sep 13 2022

...

Concerning...Heavy rainfall...Flash flooding likely

...

DISCUSSION...The latest GOES WV and Proxy Vis satellite imagery shows a very well-defined shortwave trough lifting north-northeast across the southern Great Basin and adjacent areas of the Southwest out ahead of upstream shortwave/jet energy crossing the West Coast. This energy advancing into the Intermountain West is largely the remnants of former T.C. Kay and is also bringing a significant surge of mid and high-level tropical moisture along with it. The latest CIRA-ALPW data sets validate this.

Figure 19: Example of ALPW usage at WPC for flash flooding threat over the Desert Southwest on 13 September 2022. Mid- and high-level moisture from former Tropical Cyclone Kay fueling the event is depicted in ALPW.

The NOAA operational blended Total Precipitable Water (TPW) product has been operational since 2009 and is being upgraded using science results supported by NESDIS from teamwork by CIRA and CIMSS. A key advance is combining advection of the Low Earth Orbiting satellites (MIMIC technique) with TPW fields from the GOES satellites in the operational data processing system. In NWS testbed experiments, users ruled these enhancements to be an improvement over the current product. These upgrades are currently being transitioned to operations with a target implementation date of Summer 2023.

ATMOSPHERIC TEMPERATURE

Profiles of temperature in the troposphere, stratosphere and temperature of deep atmospheric layers are among Essential Climate Variables in the upper atmosphere. Observations from the satellite microwave sounders, especially AMSU and ATMS onboard NOAA, NASA, and EUMETSAT satellites provide global atmospheric temperature observations for long-term climate change monitoring.

CrIS and ATMS NUCAPS Soundings Capture Powerful Arctic Cold Front

The CrIS and ATMS instruments on board JPSS satellites are critical to the operational data assimilation of numerical weather prediction (NWP) models. They are also used by NUCAPS algorithms to produce temperature, water vapor, and trace gasses products operationally.

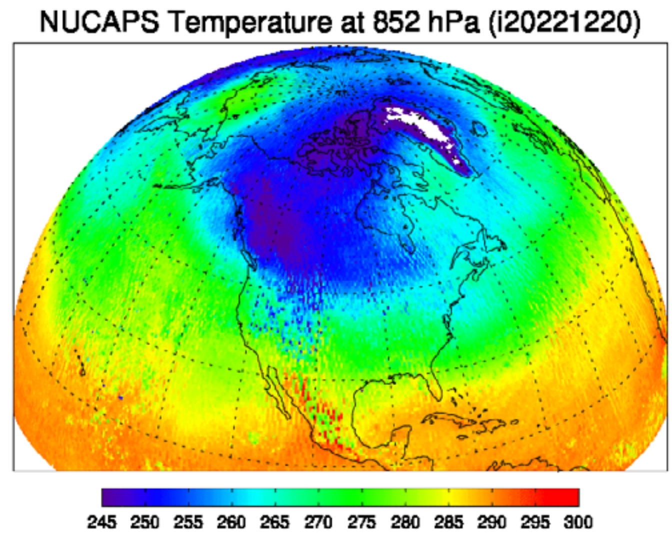


Figure 20. CrIS and ATMS NUCAPS Soundings capture bomb cyclone. Credit. NESDIS/STAR, NASA GMAO and Joshua Stevens

In late December 2022, the NWP models, aided by CrIS and ATMS, accurately predicted the onset of a polar vortex that caused a bomb cyclone over the northern latitudes. The NUCAPS temperature image (Figure 20) shows the progression of the cold front as it moved from the Arctic and Canada to the CONUS areas of the United States. The storm caused severe disruptions during the winter holidays, particularly in the transportation and aviation sectors. The global coverage of the JPSS/LEO satellites is crucial in enabling NWP models to provide the necessary information to prepare for and respond to severe weather events like this.

CLOUDS

Clouds cover almost two-thirds of the Earth's surface on any given day. They serve several important purposes including helping maintain the Earth's energy balance by trapping heat near the surface and reflecting solar radiation back to space. They are also fundamental features of the hydrological cycle, which replenishes the Earth's water supply.

Cloud products are used in various applications, which include nowcasting severe weather to better understand tropical systems, and to determine potential aviation hazards. They are also used by numerical weather prediction models for model verification and data assimilation. Cloud products also provide long-term environmental datasets that are critical to understanding the earth's energy balance and climate.

Earth observation satellites, including geostationary and polar-orbiting satellites, are the primary instruments to observe and document global cloud radiative properties.

The cloud product suite includes cloud occurrence (also called the cloud mask), cloud type, cloud emissivity, water/ice path, height (top and base), layers, optical depth, phase, particle size, cloud probability, cloud IR microphysical index, and more. These products provide information on cloud structures, forms, and microphysical properties. Other products in this portfolio include radiative flux and outgoing longwave radiation (OLR) data that are used to verify climate models and theories. These data are also used by the energy and financial sectors for planning, locating, and validating new capabilities for solar farms.

Understanding vertical cloud layer conditions is important for flight planning and in-flight adjustments to operate aircraft in different weather conditions.

Alaska Cloud Product Demonstration

A new Cloud Vertical Cross-section (CVC) product was recently developed that provides vertical cloud information along flight paths for the Alaska region, recognizing the needs of aviation users for enhanced weather information in this data-sparse region. This experimental product obtained from NOAA satellite cloud products with supplementary data such as temperature, terrain, and pilot reports (turbulence and icing) is a new approach to provide vertically extended cloud structure information that forecasters and pilots can easily access, interrogate, and interpret for aviation applications. Figure 21 shows the vertical distribution of clouds along two flight routes. It also depicts the state of the clouds in terms of water, ice or supercooled liquid. The graphic also displays a cross-section of the terrain and an estimate of the freezing level. The top graphic uses data extracted from the VIIRS instrument, while the bottom graphic uses data from the ABI instrument.
In support of this JPSS Aviation Initiative engaging the aviation community, the product has been demonstrated through a user interactive website (https://aviation.cira.colostate.edu/) and improved based on user feedback. In response to user requests, the JPSS Aviation Initiative also launched the CVC CONUS domain with the addition of GOES East ABI observations. The products have been used as additional observational data for National Transportation Safety Board (NTSB) aviation accident investigations. Aviation users will continue to be engaged through direct communication, social media, and online surveys, reflecting our goal of increasing the utility of NOAA satellite cloud products to users.

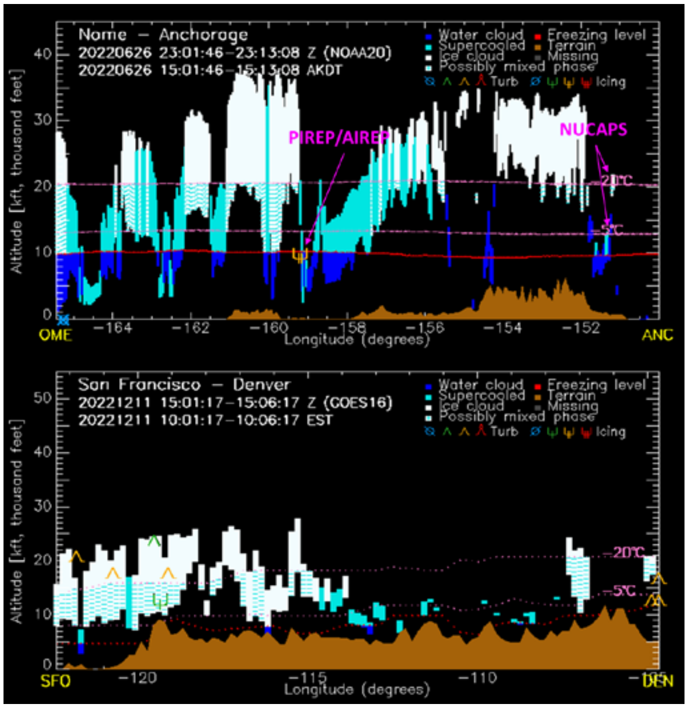


Figure 21. Cloud vertical cross-sections between Nome and Anchorage, Alaska from NOAA-20 VIIRS (top) and between San Francisco and Denver from GOES East (-16) ABI (bottom).

PRECIPITATION

Precipitation is a crucial link in the hydrologic cycle that supplies the Earth's atmospheric water. Its large spatial and temporal variations are drivers for regional hydrology and global fresh water balance. Accurate knowledge of the timing and spatial distributions and amount of regional rainfall is essential to make accurate short-term forecasts—providing the information needed to make sound decisions to protect life and property. Precipitation products are important for assessing threats from extreme rainfall events, particularly flash flooding.

CMORPH Integrated Satellite Global Precipitation Estimates

Several years ago NOAA scientists developed a technique that constructs high-quality, high-resolution global precipitation analysis. The technique, known as the Climate Prediction Center (CPC) Morphing (CMORPH) integrates cloud and precipitation retrievals from satellite observations and numerical model forecasts (Xie et al 2017). A second version, CMORPH2, developed several years ago with the support from the NESDIS JPSS and a couple other programs, produces precipitation estimates on a 0.05olat/lon grid over the entire globe with greatly improved quality in representing heavy rainfall and cold season precipitation. Inputs to the CMORPH2 include rainfall and snowfall rate retrievals from passive microwave (PMW) measurements aboard all available low earth orbit (LEO) satellites, precipitation estimates derived from infrared (IR) observations of geostationary (GEO) and LEO platforms, and model precipitation forecast from the National Centers for Environmental Prediction (NCEP) operational global forecast system (GFS).

CMORPH BASICS

Inputs from the various sources are first intercalibrated to ensure quantitative consistency. The intercalibrated PMW retrievals and IR-based precipitation estimates are then propagated from their respective observation times to the target analysis time along the cloud motion vectors. The propagated PMW and IR-based precipitation estimates are finally integrated into a single field of global precipitation through the Kalman Filter framework. In addition to the total precipitation, a fraction of solid precipitation is computed from the surface air temperature and other surface meteorological variables.

During 2022, the real-time production system for the CMORPH2 was constructed and migrated to the NCEP Central Operations(NCO)/CPC Compute Farm (CF). CF is an operational platform maintained 24/7 by the NCEP/NCO. The migration ensures that CMORPH2 is accessible to all NWS operational prediction models, operational centers, as well as NWS field offices on a real-time basis. The real-time version, which is pushed to a NESDIS web portal for public release, is generated at a very short latency of one hour. It also refreshed once every 30 minutes with any newly available inputs until 12 hours after the target analysis time (Figure 22).

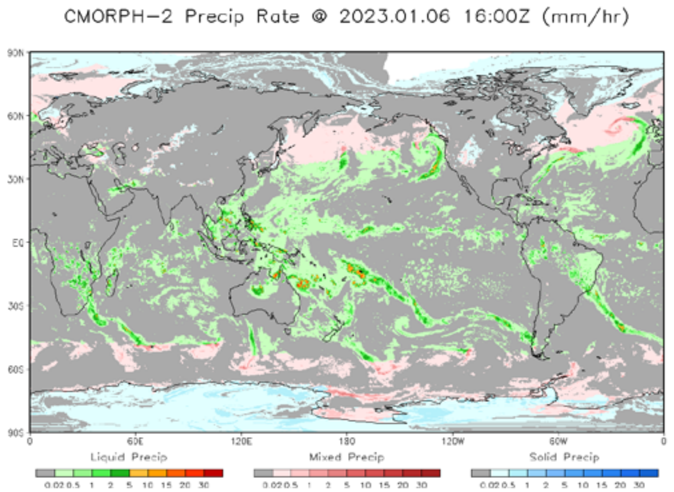


Figure 22. Global precipitation intensity (mm/hr) for a 30-minute period starting at 16:00UTC, 6 January 2023, observed by the CMORPH2 real-time production. Liquid, solid, and mixed-phase precipitation intensity is displayed in different color scales as indicated at the bottom of the figure.

Key internal NOAA users include:

- The NWS/AWC for use as inputs to their prediction models for the high-impact NOAA-FAA Ensemble Prediction of Oceanic Convective Hazards (EPOCH) project;
- NWS/WPC in tests to monitor tropical precipitation and hurricanes; and
- NWS Alaska, which has been using it to monitor the weather over Alaska and is exploring a potential application to improve river forecast models with precipitation forcing from CMORPH2;

Currently, the World Meteorological Organization (WMO) is utilizing CMORPH1 as a primary tool to monitor the tropical precipitation for its Space-based Weather and Climate Extreme Monitoring (SWCEM) project, though there are discussions in place to upgrade to CMORPH2.

Satellite-Radar Merged Snowfall Rate Product

Radar is a useful tool for weather forecasting. However, radar gaps are common throughout the country especially in the western US and mountainous regions due to beam blockage, overshooting, or being out of range. With their unobstructed view of the earth, satellites provide broad spatial coverage that can effectively fill in radar gaps.

NESDIS has an operational SnowFall Rate (SFR) product that is derived from a constellation of polar-orbiting satellites including the JPSS series of satellites. A machine learning model is used to detect snowfall. Once snowfall is positively identified, snowfall rates are estimated using a physically-based inversion model. The estimates are further enhanced with a machine learning bias correction model to achieve optimal results. Extensive validation studies against ground observations and radar estimates have demonstrated that the NESDIS SFR product correlates very well with the target data. Since precipitation is a very dynamic process, observations with adequate temporal resolution are required for weather forecasting. However, it is difficult to effectively use SFR in lower latitudes because the current polar-orbiting satellites used for retrieving SFR are limited in temporal frequency.

NOAA's National Severe Storms Laboratory (NSSL) has developed a Multi-Radar Multi-Sensor System (MRMS) radar instantaneous precipitation analysis. NESDIS, with the support of scientists from NOAA's Cooperative Institute for Satellite Earth System Studies (CISESS) at the University of Maryland, has developed an SFR and MRMS (snowfall only) merged product, mSFR. It is a spatiotemporally more advanced product benefiting from the spatial coverage of satellites and the rapid update of radar. Figure 23 shows the effect of merging the two products compared to MRMS only, and demonstrates the satellite's ability of filling in radar gaps. The merged product also has a very low latency because it uses direct broadcast satellite data, which makes it especially suitable for nowcasting. This product has already been incorporated in the Advanced Weather Interactive Processing System (AWIPS) at some NWS Weather Forecast Offices and forecasters have used it to provide weather and social media updates on heavy snowfall. The mSFR product can be viewed in near real-time at http://cics.umd.edu/sfr/?page=mSFR-CONUS.

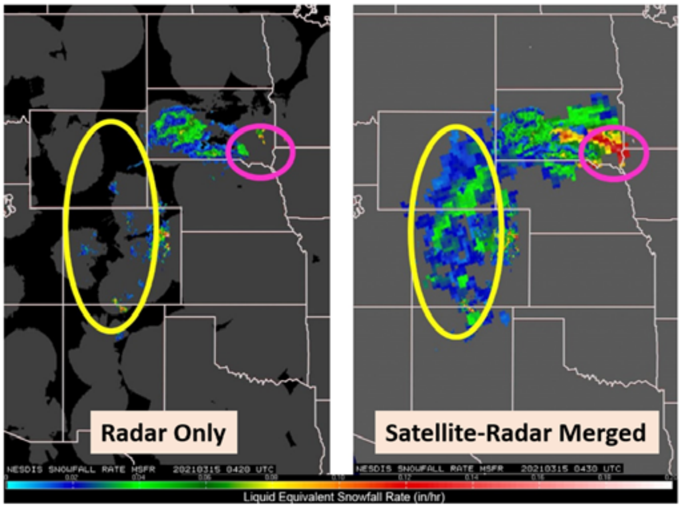


Figure 23. The NOAA NESDIS satellite-radar merged snowfall rate product fills gaps in radar-only coverage during a strong winter storm on March 15, 2021. The yellow oval indicates snowfall missed due to radar gaps, and the magenta oval shows the intense snowfall missed by radar due to precipitation phase misidentification.

LIGHTNING

Two GLMs now observe spatial and temporal lightning distributions over a vast region. The GOES-East GLM covers most land areas in the Western Hemisphere and detects ~4 times as much lightning as the GOES-West GLM. The GLM is establishing a legacy of applications likely to become ubiquitous across a wide variety of meteorological domains (Rudlosky et al. 2020). Operational users have eagerly embraced this new source of lightning information and incorporated it into their workflow. A recent GLM value assessment documented societal and economic benefits realized through GLM data use (Rudlosky et al. 2020). The GLM was shown to improve lightning safety, severe thunderstorm and tornado warnings, safety and effectiveness of wildfire response, short-term model forecasts (via data assimilation), precipitation estimation, tropical cyclone diagnosis and warning, and climate applications. The study also described the value GLM yields by filling data gaps and mitigating aviation hazards. The GLM is broadening access to lightning information beyond those who can afford to purchase data, helping people working and recreating outdoors make more informed lightning safety decisions, leading to decreased injuries and fatalities.

The GLM now provides a national and international baseline of publicly available lightning data and establishes a baseline for widespread government and industry implementation. In 2016, the Global Climate

Observing System (GCOS) added lightning to its list of Essential Climate Variables (ECVs) needed to understand and predict changes in climate. The GLM also helped inspire the most recent World Meteorological Organization (WMO) Integrated Global Observing System document (WIGOS-2040) to include "lightning imagers" alongside "high-resolution multi-spectral Vis/IR imagers" and "IR hyperspectral sounders" in their recommended backbone of the future WIGOS geostationary satellite constellation (i.e., GEO-Ring).

NESDIS generates and distributes Level 2 GLM data and recently has begun distributing gridded (accumulated) GLM products tailored for NWS users. The GLM Level 2 data are produced as points and typically lose information concerning the spatial extent. The gridded GLM products restore and disseminate the spatial footprint information while greatly reducing file size. Gridded GLM products involve re-navigating the GLM event latitude/longitude to the 2×2 km ABI fixed grid. The flash extent density (FED) product indicates the number of flashes that occur within a grid cell over a 5-minute period updating every minute. This product allows forecasters to quickly diagnose trends in lightning activity which help identify trends in storm severity. Additional gridded products provide complementary information.

The GLMs have allowed scientists to document world-record lightning flashes that were unobservable before this technology, for example, as shown in Figure 24.

To read more on the GLM's application on a world record flash, visit the story map (https://arcg.is/0Pemqj0) on the 29 April 2020 lightning flash that covered a horizontal distance of 768 km (477.2 miles).

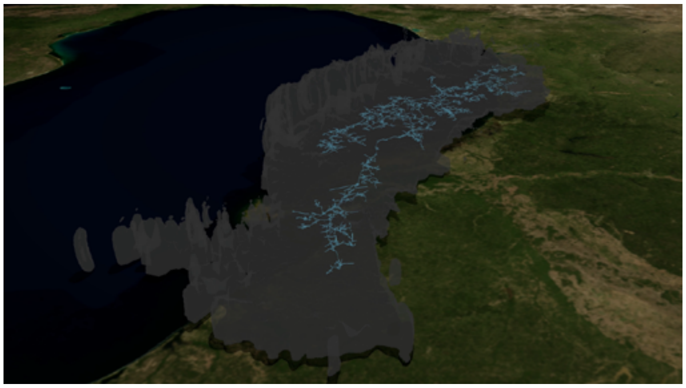


Figure 24. A 3-D depiction of a world record lightning flash as observed by the GOES-East GLM.

LightningCast—A New Machine Learning Model for Lightning Prediction

GOES-R satellite imagery not only provides forecasters with unprecedented insight into current weather conditions; with the help of machine learning, it can also predict lightning activity. The LightningCast AI model utilizes machine learning to transform GOES-R ABI data into 60-minute predictions of where lightning will be observed by the GLM. LightningCast frequently provides 20 minutes or more of lead time, which enables people to seek shelter before lightning strikes. LightningCast is powered by a deep learning technique that was trained to recognize complex patterns in satellite imagery. The NWS routinely utilizes LightningCast for Impact-based Decision Support Services, such as notifying event organizers and local emergency managers when there is a threat of lightning where large numbers of people are gathered outdoors. LightningCast is also used in support of air traffic management and airport operations.

RADIATION BUDGET

Earth's climate is determined by its energy budget, a delicate balance between how much of the sun's radiative energy is absorbed in the atmosphere and at the surface and how much thermal infrared radiation Earth emits to space. Perturbations to the radiation budget, such as those that change the amount of sunlight reaching the surface or the amount of heat trapped in the atmosphere, will shift the radiation balance and either cool or warm the Earth. Increases in greenhouse gases (e.g., CO2 and methane) have changed the composition of the atmosphere and disrupted the planet's energy budget by trapping heat that would have previously escaped back into space.

NESDIS estimates solar radiation reflected, as well as the thermal radiation emitted by the Earth's atmosphere and the surface, and solar and thermal radiation reaching the surface of the Earth from the Imager instruments onboard the NOAA polar and geostationary platforms.

Outgoing Longwave Radiation

Outgoing longwave radiation (OLR) is an essential contributor to the Earth's radiation budget (ERB) at the top of the atmosphere (TOA). OLR datasets, as generated by LEO satellite sounders, are critical for understanding climate variability due to the radiative forcing that results from energy imbalances at the TOA. OLR has been widely used in climate sensitivity studies, diagnoses, and predictions, as a proxy for deep convection and precipitation, and as an indicator of the progression of El Niño—Southern Oscillation (ENSO) cycles, and solar and monsoon variability. The CrIS instruments onboard the JPSS NOAA-20/21 satellites are currently generating near real-time OLR products, with a 2-h time latency, via the NOAA Unique Combined Atmospheric Processing System (NUCAPS). The CrIS OLR product is derived from pseudo-channels and the difference between CrIS and the AIRS radiances, and then evaluated with adjusted radiances. Recent validation analyses show that the NOAA-20 CrIS OLR products agree very well with both the Suomi NPP CrIS OLR products and the Aqua CERES OLR products at all timescales.

Recent studies have also highlighted the application of the OLR product to monitor the combined effects of ENSO and sunspot cycles on global precipitation patterns. The estimated international sunspot number ("EISN") is a daily value obtained by a simple average over available sunspot counts from stations in the Sunspot Index and Long-term Solar Observations (SILSO) network. Figure 25 compares global OLR product images during two recent phases of the solar cycle: sunspot minimum and maximum in January 2021 and January 2023, respectively. As expected from previous studies, a significant increase in convective storm activity is apparent over the equatorial and southern hemisphere tropical regions in January 2023 at the time of a sunspot maximum, contributing to an overall global decrease in OLR. This result is consistent with previously-identified OLR cycles that are roughly coincident with trends in the EISN, demonstrating the long-range predictive capability of the CrIS OLR products for anticipating large-scale heavy rainfall events.

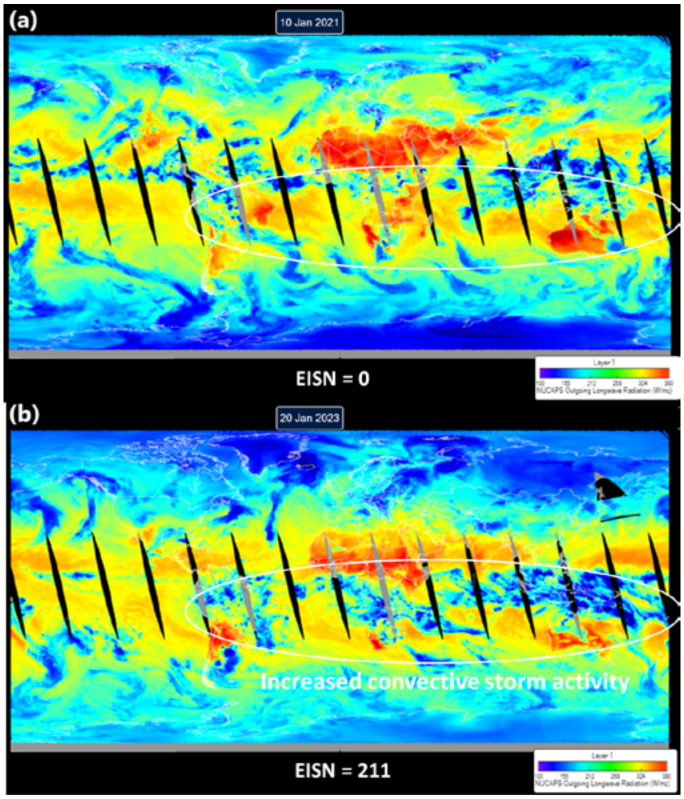


Figure 25. Comparison of global OLR product images during two recent phases of the solar cycle: (a) sunspot minimum and (b) maximum in January 2021 and January 2023, respectively.

Solar Radiation in Support of Coral Health Forecast and Drought Monitoring

An algorithm capable of retrieving shortwave radiation budget data at high spatial and temporal resolution from observations of US, Japanese, and European advanced imagers onboard geostationary satellites was developed and delivered for implementation in 2022. The delivery signifies the completion of an important milestone on the road to generating a new, global, high-resolution geostationary shortwave radiation product using state-of-the-art enterprise algorithms. The data suite provided by the new algorithm includes the downward shortwave (solar) radiation at the surface (see Figure 26 on the left for an example), the photosynthetically active radiation (see Figure 26 on the right for an example)—the portion of the solar radiation utilized by plants for photosynthesis—and the reflected shortwave radiation at the top of the atmosphere.

The downward shortwave radiation at the surface is intended for helping the Environmental Monitoring Center (EMC) of the NOAA National Centers for Environmental Prediction to verify model-predicted values

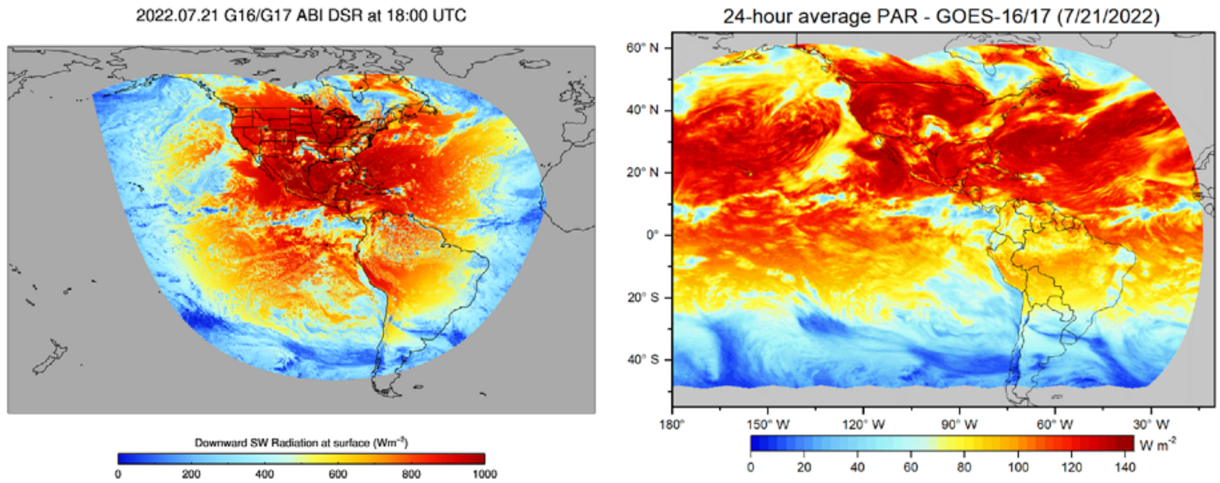


Figure 26. Instantaneous downward shortwave radiation at surface (left) and 24-hour average of the photosynthetically active radiation (right) on July 21, 2022, as estimated from the GOES East (-16) and GOES-17 satellites.

of solar radiation and to improve the modeling of the radiation and land-atmosphere interaction processes. Instead of climatology as input in their models, EMC is increasingly using observational data like the one generated by the GOES Evapotranspiration and Drought (GET-D) algorithm. GET-D ingests the downward shortwave radiation at the surface as one of its inputs. Without this input, errors in evapotranspiration could rise above 10% causing an error in the drought monitoring product for a region resulting in a light drought missed for a week that may cost farmers millions of dollars in crop yield loss.

The photosynthetically active radiation is intended to serve as input to the NESDIS Light Stress Damage algorithm of the Coral Reef Watch team, which in turn, provides input to the NOAA coral bleaching decision support system that delivers information to US and international agencies. Without this input, prediction of coral bleaching onset for ~20–30% of reefs would be significantly less accurate and would not correct most false positives seen in the current product.

The scientific basis and technical implementation of the method developed for estimating top-of-the-atmosphere reflected shortwave radiation from NOAA's GOES East (-16) satellite was documented in a journal publication in 2022. The paper also demonstrated a favorable evaluation with high-precision reference data from NASA, and thus increasing trust in the NOAA radiation product.

TROPICAL CYCLONE CHARACTERISTICS

Tropical cyclones account for more than half of the total damages attributed to billion-dollar weather and climate disasters since 1980. Although tropical cyclones typically evolve slowly, they sometimes experience rapid changes, erratic motions, and can form quickly, therefore requiring information is readily available to help diagnose current conditions, and make critical forecasts that guide mitigation activities when these changes occur.

NESDIS algorithms for tropical cyclones are used worldwide in various applications including to diagnose tropical cyclone characteristics (intensity, size and distribution of the wind field, central pressure, precipitation, etc.), tropical cyclone formation, the real-time assessment of the tropical cyclone environment (moisture, temperature, SST, ocean heat content, etc.), and for input into numerical models.

Progress on Rapid Intensification Guidance

The majority of the most intense hurricanes go through a period of rapid (95th percentile) intensification. Generally, when this occurs, warnings and mitigation activities by NOAA stakeholders dramatically change. While the environmental conditions associated with rapid intensification are fairly well known, forecasting rapid intensification events remain challenging as the thunderstorms scale, which is necessary but much more difficult to predict. Over the last several years, NESDIS/STAR scientists have been attempting to incorporate satellite-derived information related to the nature, size and vigor of convection and developing guidance on guidance methods based on machine learning. Examples include incorporating geostationary lightning information into an existing rapid intensification index at the National Hurricane Center, and developing three probabilistic forecast methods at the DoD's Joint Typhoon Warning Center-all these methods are available in these center's operations. Evidence for the impact was shown at the annual 2022 NOAA Hurricane Forecast Improvement Program where these efforts were mentioned and examples of forecast successes were highlighted by JTWC's lead scientific advisor.

New Observational Data Available For Tropical Cyclone Monitoring and Model Improvements

Existing aircraft reconnaissance from NOAA and the U.S. Air Force has been invaluable for understanding how the winds and temperatures are distributed in hurricanes. But those data, which are observed along the flight path of the storm, cannot provide instantaneous two-dimensional analyses of surface winds nor are such data available in the majority of tropical cyclone basins. The latest generation of SARs, which have cross-polarization capabilities, can provide global and instantaneous estimates of surface wind speeds up to 75 ms-1 with little precipitation attenuation. Over the last several years, NESDIS and international partners in France have coordinated with both the National Hurricane Center (NHC) and DoD's Joint Typhoon Warning Center (JTWC) to collect and disseminate high-resolution wind surface speed estimates and tropical cyclone fix (intensity and wind structure metrics) in global tropical cyclones.[8] Through coordination with Navy partners, the tropical cyclone fix and image information is made available on workstations running the Automated Tropical Cyclone Forecast software at NHC and JTWC. The 3-km averaged wind speed archive is also made available to the research community and has resulted in many important findings documented in the referred literature. An example of SAR wind speed estimates for Hurricane Fiona on 19 September 22 UTC when it was located off the coast of the Dominican Republic is shown in Figure 27, which depicts a small tropical cyclone with a 9 n. mi/ 17 km radius of maximum wind with maximum winds near 98 kt / 50 ms^{-1} .

8 NOAA/NESDIS/STAR, https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/tropical/

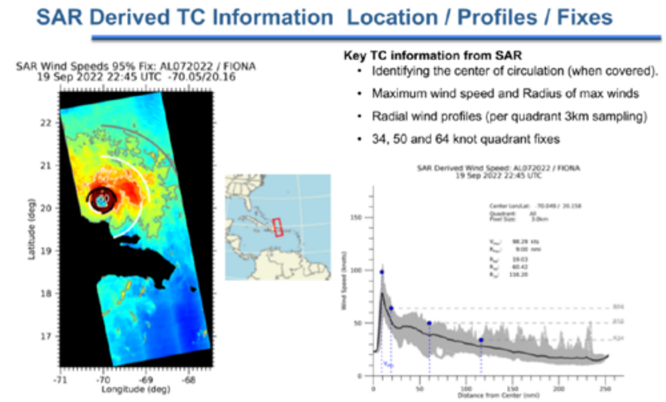


Figure 27. SAR wind speed estimates for Hurricane Fiona on 19 September 2022.

NOAA and NOAA CIs Use Machine Learning To Improve Observational Capabilities—89GHz Estimates

Tropical cyclone forecasters have long employed the 85-91 GHz (hereafter 89GHz) passive microwave imagery to monitor the convective organization of tropical cyclones and center location. Upwelled microwave signals from the ocean at 89GHz are both re-emitted by warm rain and clouds (a warm signal), and scattered by larger ice particles in deep convection (a cold signal). As these signals propagate upwards, they avoid attenuation by the small ice particle in cirrus clouds due to their relatively long wavelength. As a result, forecasters routinely use 89GHz imagery, which has a radar-like appearance, for situational awareness of the cloud structures like rainbands and eyewalls below the cirrus shield that so often limits the utility of geostationary infrared (IR) imagery. Despite the utility of such images, the current temporal and spatial coverage of 89GHz imagery is limited to just a few differing Low-Earth-observing (LEO) satellite sources, which have coverage gaps in the Tropics, refresh rates of 2 to 3 per day, and rather poor timeliness (2 to 3 hours).

To overcome the shortcomings of the current LEO observing system and to provide timely and frequent estimates of 89GHz imagery, several machine learning techniques have been used to train the full spectral content of GOES ABI imagery to estimate what the 89Ghz images would look like. This enables full disk estimates of 89Ghz imagery every 10 minutes from GOES and Himawari satellites covering all the NWS regions. This new capability was demonstrated in real-time during 2022, and an example from Hurricane Ian is shown in Figure 28.

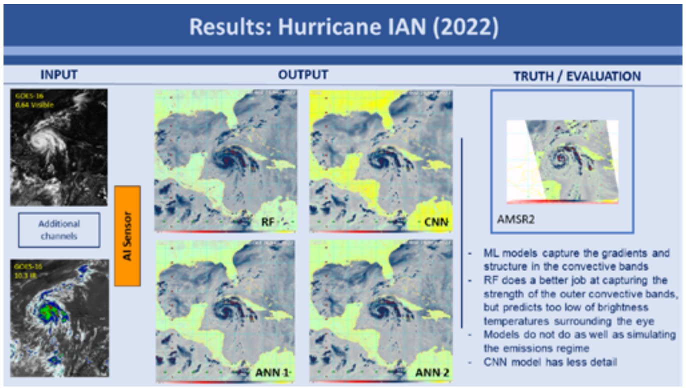


Figure 28. Full disk estimates of 89Ghz imagery of Hurricane Ian from GOES East.

WINDS

Wind, over both land and ocean surfaces, is a fundamental variable of weather and as an Essential Climate Variable (ECV). The heating of Earth's surface and atmosphere by the sun drives winds that move heat and moisture from one place to another, as well as heating and cooling by the ocean through air-sea interaction and exchanges of momentum and energy. Variations in large-scale wind circulation patterns are responsible for the daily weather we experience. Satellite-based wind data are among the most important information contributing to the accuracy of global weather prediction models.

NOAA/NCEI Blended Seawinds (NBS v2.0) from Multi-Satellite Observations

Improving forecasts of storms and hurricanes and their potential impacts is highly important to public safety, economic security, commerce, and community infrastructure. One key element of forecast improvement is more accurate and increased spatial–time coverage of observational data for model calibration, quality control and initialization, and/or data assimilation. NOAA has been producing a global gridded 0.25° and 6-hourly sea surface winds product that has wide applications in marine transportation, marine ecosystem and fisheries, offshore winds, weather and ocean forecasts, and other areas. The NOAA NCEI Blended Sea winds (NBS) v1.0 product (Zhang et al. 2016) was generated by blending observations from multiple sources (satellites), including scatterometers and microwave radiometers/imagers (Figure 29). However, these sensors do not provide accurate observations of intensive high-speed hurricane winds because their signals saturate in very high winds or degrade in the presence of rain. Recent advancements in satellite wind retrievals revealed that the L-band (1.42 GHz) instrument on the Soil Moisture Active Passive (SMAP) satellite and the AMSR2 All-Weather channel (~6.9 GHz) can provide accurate hurricane winds of up to 65 m/s (145 MPH) without being affected by rain; these data are incorporated in a new version of the Blended Seawinds, NBS v2.0 (Figure 30, Saha and Zhang, 2022), using a multi-sensor data fusion technique based on random errors, enabling it to resolve very high winds, especially along the eyewalls of tropical cyclones and hurricanes. NBS v2.0 provides both a long-term record of 30+ years retrospectively since July 1987 and a near-real-time mode with 1-day latency, as well as the 30-year (1991-2020) Climatology/Climate Normals for daily and monthly resolutions, separately. Comparisons among other products and IBTrACS showed that our NBS v2.0 is superior in terms of resolving high storm winds (Figure 30).

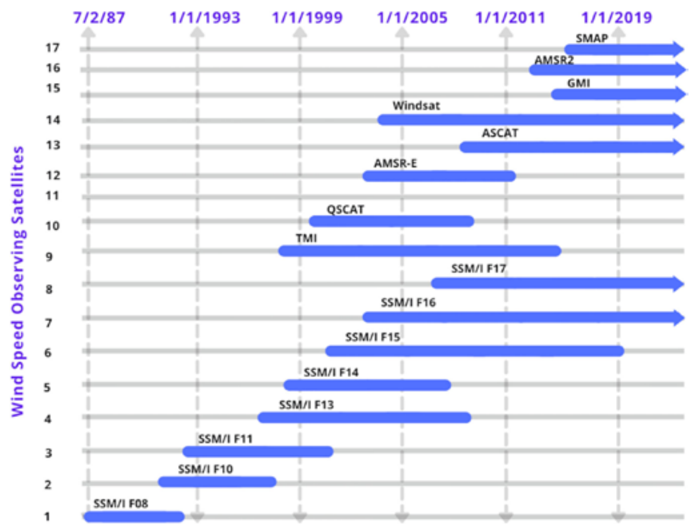


Figure 29. The primary U.S. wind speed observing satellites. Observations from these satellites are used to produce NBS products. The arrow represents data that are currently available into the future in near-real-time.

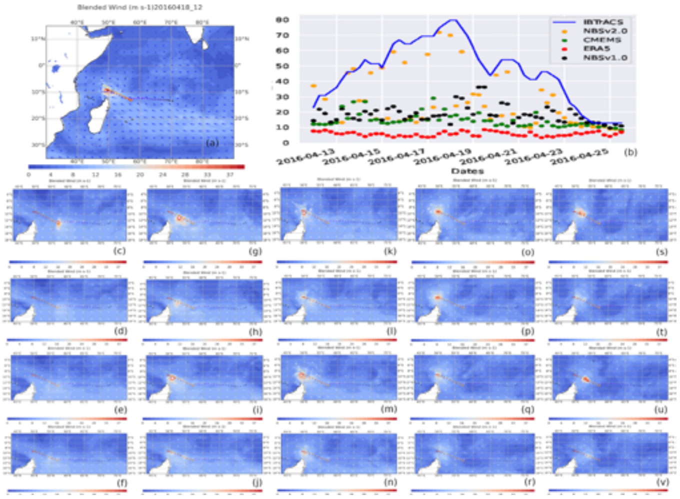


Figure 30. (a) Tropical cyclone Fantala's maximum wind speed with best track from IBTrACS data set. (b) Time series of maximum wind along the track of the Tropical Cyclone Fantala from several widely used products, showing that only NBS 2.0 can match the high storm winds observed from IBTrACS. (Saha and Zhang 2022)

Global Winds From Polar-Orbiting Satellite—VIIRS Tandem Winds

The operational single-satellite polar winds products provide wind speed, direction, and height wherever there is a suitable feature that can be tracked in a sequence of three orbits with a total time between the first and last of the triplet of approximately 200 minutes. Because the region of overlap in the three orbits is used for tracking, coverage is limited to an area poleward of approximately 65 latitude. With the launch of Suomi NPP and NOAA-20 (and now NOAA-21) in a similar orbit but delayed by ½ orbit in time, there is an opportunity to track clouds from the NOAA-20/ Suomi NPP tandem. This will reduce the time interval between images to approximately 50 minutes, which will result in reduced latency in product availability, potentially higher quality winds due to the shorter time interval for tracking, and global rather than only high-latitude coverage. A VIIRS "tandem" winds product has been developed and is being generated routinely at the Cooperative Institute for Meteorological Satellite Studies (CIMSS). An example from several orbits of alternating passes from Suomi NPP and NOAA-20 is shown in Figure 31.

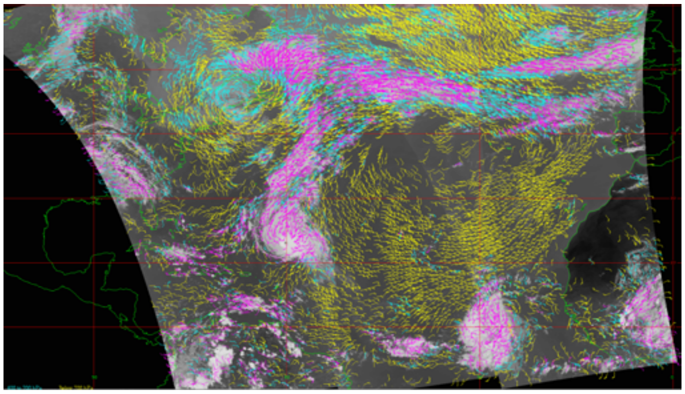


Figure 31. VIIRS tandem winds coverage using several orbits of alternating passes from Suomi NPP and NOAA-20, color-coded by height: Yellow (below 700 hPa), cyan (400 to 700 hPa), magenta (above 400 hPa).

Stereo Observing of Clouds to Derive Atmospheric Winds

Stereo observing of cloud features provides a means of retrieving atmospheric wind vectors while simultaneously retrieving their height in the atmosphere using a pair of Geostationary (GEO) satellites or a GEO and a Low-Earth Orbiting (LEO) satellite. Stereo imaging from two satellites is an old idea that has been given new life with the new generation of GEO and LEO satellites such as the Geostationary Operational Environmental Satellites R (GOES-R) and JPSS-series of satellites operated by NOAA, which offer imagery with much-improved image navigation and registration (INR). The new generation of GEO and LEO satellites from NOAA's international partners also enable the application of stereo imaging to these satellites as well.

A stereo winds height model has been successfully and seamlessly integrated with NOAA/NESDIS' enterprise winds algorithm and has been successfully applied to GEO-GEO combinations of ABI and AHI observations (from GOES-E, GOES-W, and Himawari satellites) and from GEO-LEO combinations of ABI, AHI, and VIIRS observations (from GOES-E, GOES-W, Himawari, Suomi NPP, NOAA-20, and soon NOAA-21). A composite of GEO-GEO stereo winds generated from pairings of ABI and AHI Band 14 11um infrared imagery between GOES-16/GOES-17 and GOES-17/Himawari-8 on April 6, 2020, 11:20 UTC is illustrated in Figure 32.

By its reliance on the principle of parallax, the stereo winds height model directly retrieves geometric cloud heights that lead to the assignment of more accurate heights to the derived winds, thereby improving their quality. This result is a significant accomplishment since height assignments have been demonstrated to be the largest source of error associated with today's operational satellite-derived wind observations.

NOAA/NESDIS is a leader in the development of this new stereo winds capability and plans are in place to begin transition into NESDIS operations. It is expected that the GEO-GEO and GEO-LEO stereo winds generated today will increase the utilization of NOAA's satellite winds in NOAA and international partner operational Numerical Weather Prediction (NWP) forecast systems with the potential for measurable improvements in the accuracy of global and regional weather forecasts. Through its application to increasing combinations of NOAA and International partner GEO and LEO satellites, the future vision is to produce a global stereo wind product that has the potential to bring further improvements to the accuracy of global and regional NWP model forecasts.

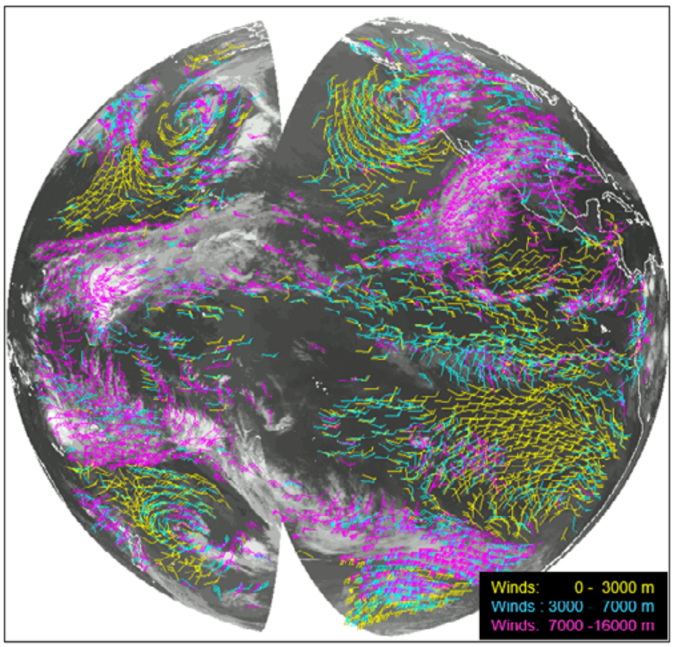


Figure 32. A composite of stereo winds generated from pairings of ABI and AHI Band 14 11um infrared imagery between GOES-16/GOES-17 and GOES-17/Himawari-8 on April 6, 2020 11:20 UTC.

Cryosphere

The cryosphere, which contains all the frozen water on Earth, is one of the few components of the Earth's climate system that holds many important clues of climate change. And yet it is one of the lesser-sampled components of the climate system due, in part, to being in some of the most inaccessible and inhospitable areas on Earth, which makes conventional monitoring logistically challenging and prohibitively expensive. Changes in the cryosphere have major impacts on health, water supply, agriculture, transportation, freshwater ecosystems, hydropower production, and cryosphere-related hazards such as floods, droughts, avalanches, and sea-level rise. NESDIS' remote sensing capabilities are essential for monitoring and observing the cryosphere and to help understand its dynamics and impacts on resources such as water. They also help to fill critical gaps in observations from airborne and ground-based instruments. Finally, NESDIS' scientific expertise in cryospheric research, observations and information contributes to the operational excellence of the U.S. National Ice Center.

LAKE AND SEA ICE

In polar regions, areas of sea ice—ice atop ocean waters— support the entire ecosystem and affect Earth's climate by reflecting most of the sunlight back into space, preventing absorption into the ocean. Lake ice controls the biological productivity of lake ecosystems and the migration of species that depend on ice or open water, as well as determines the extraction of winter water for human use (shallow lakes can freeze to the bottom). Lake ice is also a component of ice roads, providing winter road access to remote locations. Finally, lake ice influences weather patterns and, thus, weather forecasting and climate modeling.

NESDIS products provide information on various cryospheric variables including Ice Concentration, Ice Surface Temperature (IST), Ice Fraction, Ice Motion, Binary/ Fractional Snow Cover (FSC) and snow depth/ snow water equivalent (SWE), which are employed in a wide variety of applications.

New Research With CDRs Provides More Robust Information In Sea Ice Thickness and Volume

Research from NOAA's satellite climate data records has produced new information on dramatic, multi-decadal changes not only in Arctic sea ice area, but also sea ice thickness and volume. The work employs a new perspective based on ice longevity and provides a unique view of where the ice is persistent and where it is disappearing. This is crucial information as it is the presence and persistence of ice in an area that directly influences local weather and climate, marine transportation, and ecosystems.

Results show that the Arctic has become less ice-covered in all seasons, especially in summer and autumn, and that the loss of the perennial sea ice-covered area

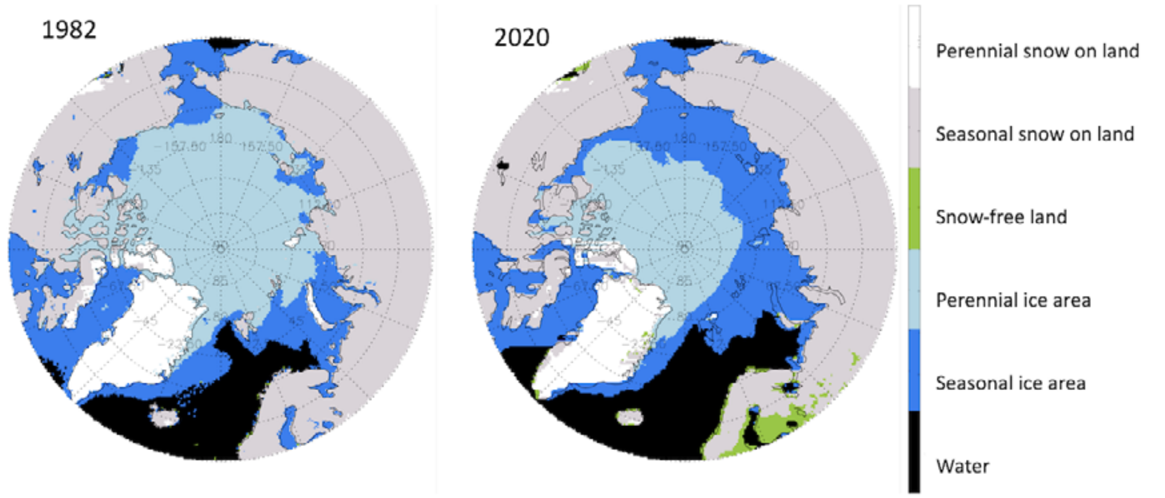


Figure 33. Spatial distribution of Arctic sea ice in 1982 (left) and 2020 (right) for perennial and seasonal sea ice and snow on land.

is the major factor in the total sea ice loss in all seasons. Arctic sea ice thickness has been decreasing, resulting in about 52% reduction from 1982 to 2020. Arctic sea ice volume has also been decreasing, with a 63% reduction over the same period. If the current rates of sea ice changes in extent, concentration, and thickness continue, the Arctic is expected to have ice-free summers by the early 2060s.

Satellite Data Reveals the Role of Dynamics in Arctic Sea Ice Thickness

Thermodynamic and dynamic sea ice thickness processes are affected by differing mechanisms in a changing climate. Passive microwave satellite data (AMSR2) has been used to develop the first long-term, sub-seasonal temporal resolution, basin-wide climatology of dynamically and thermodynamically driven sea ice thickness effects across the Arctic. Figure 34 shows the contribution of ice growth, advection, and deformation to changes in Arctic sea ice thickness from late 2010 through early 2021. Results show that Lagrangian dynamics account for almost half of the ice thickness growth, depending on the region. This new information is critical to the assessment of ice processes in couple models.

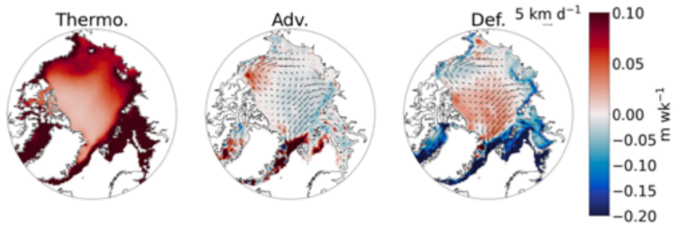


Figure 34. Wintertime mean sea ice thickness changes from late 2010 through early 2021 due to thermodynamic growth, advection, and deformation.

SNOW AND GLACIERS

Because snow is so reflective, it plays an important role in regulating climate: it reflects incoming sunlight back into space, cooling the planet. Snow also supports life. Melting of seasonal snow (as well as glaciers) provides water for drinking and irrigating crops in many parts of the world. Snowmelt moisturizes soil and reduces the risk of wildfire. Too much snow, however, can lead to springtime floods when the snowpack melts.

Increased Scientific Knowledge of Different Snowfall Regimes That Impact the Great Lakes

Winter weather in the Great Lakes Region is strongly influenced by the lakes, most notably through the production of lake-effect snow caused by cold air outbreaks with Arctic origins that interact with the lakes before substantial ice forms. NOAA-supported snowflake microphysics and profiling radar observations that are collected at the Marquette, MI NWS Weather Forecast Office (WFO) have contributed substantial knowledge about different snowfall regimes and their associated microscale snowflake properties in the Upper Great Lakes. The transition from higher to lower density (i.e., more "fluffy") snowflakes and markedly different snow particle size distributions have been thoroughly documented by these unique observations. See, for example, Figure 35, which shows a sample of the data collected from Marquette, MI NWS WFO observational suite during a 13–24 December 2017 snow event. This microphysical transition has been illustrated in numerous case studies of large-scale synoptically-driven snow events that are associated with deeper cloud structures evolving to lake-effect snow structures that are produced by shallow boundary layer convection initiated by air-lake interactions. Aggregate statistical studies generated from multiple years' worth of observations also quantify the regime-dependent snowflake density and size distribution properties of snowfall events, as well as the relative contribution to annual snowfall amounts from different snowfall regimes. The importance of atmospheric rivers in producing snowfall at this site has also been documented.

Besides shallow lake-effect snow events, these observations have shown the importance of combined lake and orographically induced processes that produce and/or enhance snowfall in this region. These observations have also demonstrated that lake-orographic processes play an important role in multi-day extreme snowfall events that can produce 1–3 feet of snowfall accumulation. These ground-based observations are directly translated into a new snowfall rate estimation product derived by combining GOES and Next Generation Weather Radar (NEXRAD) observations, helping to fill radar observational gaps and improve forecasting situational awareness in the Great Lakes region.

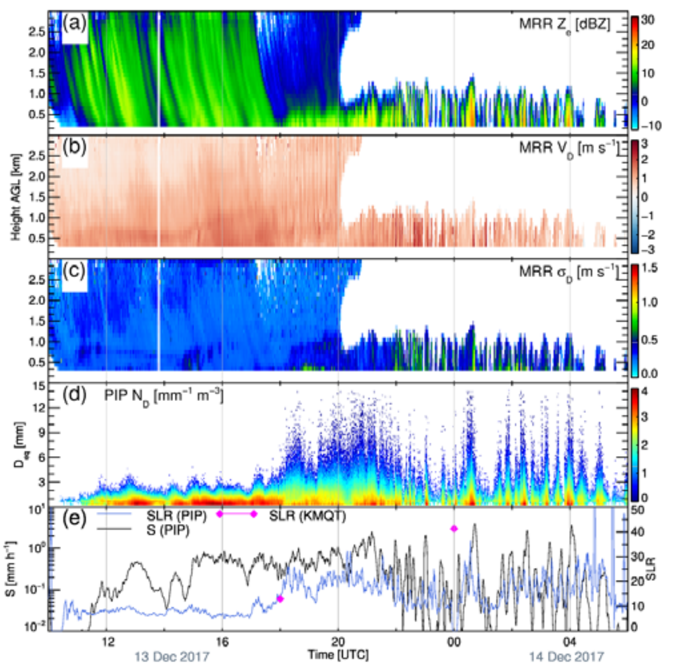


Figure 35. Micro Rain Radar (a) radar reflectivity [dBZ], (b) Doppler velocity [m s-1], and (c) Doppler spectrum width [m s-1] profiles for 13–24 December 2017 that illustrate three different snowfall regimes (synoptic or "system" snow, lake-enhanced system snow, and lake-effect snow) throughout the event duration. Precipitation Imaging Package one-minute (d) particle number concentration as a function of particle size (colored in logarithmic units) [mm-1 m-3], (e) liquid-equivalent snowfall rates (S) [mm h-1] (black), and snow-to-liquid ratio (SLR) (blue) are also shown. KMQT NWS six-hourly SLR measurements are also indicated (magenta diamonds).

Relationship Between Greenland Snow Extent and Sea Ice

The yearly minimum snow extent over Greenland, Iceland, and the Canadian Arctic Archipelago from 2014 to 2020 shows a strong correlation with the yearly minimum sea ice extent in the Arctic. Snow extent was determined from the NOAA VIIRS snow fraction product, while ice extent is calculated from a passive microwave product. As shown below in Figure 36, the correlation between the two variables is high, greater than 85%. This finding reinforces the importance of increasing temperatures as a major influence on changes in the Arctic cryosphere, though changes in sea ice dynamics and ocean currents certainly play a role in the decline of the sea ice cover.

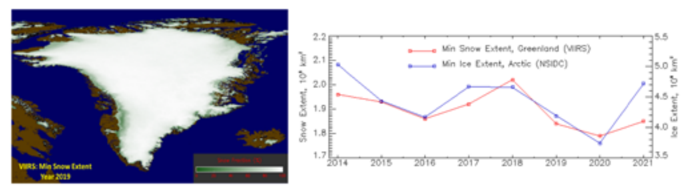


Figure 36. (Left) Yearly minimum snow cover fraction over Greenland and adjacent islands for year 2019 derived from VIIRS daily snow retrievals. (Right) Times series of yearly minimum snow extent in Greenland compared to corresponding changes of the yearly minimum ice extent in the Arctic for 2014–2021.

Land & Surface Hydrology

The land surface is the primary place of human social and economic activities. It is an important boundary of local, regional and global weather, water and climate systems. Land surface conditions directly impact societal and economic activities, which signifies a need for near real-time and historical observations of land surface conditions in relation to weather, water and climate on an array of scales from local, regional and global.

NESDIS land products include Active Fires, Land Surface Temperature (LST), Land Surface Emissivity, Soil Moisture (SM), and Normalized Difference Vegetation Index (NDVI). Land products can be applied to hydrological models to predict flooding events, as well as monitor drought or overall vegetative health. They are also used to detect and monitor fires and smoke, prescribed burns, deforestation, and other agricultural applications.

FIRES

Wildfires—whether natural or anthropogenic—occur across a wide range of ecosystems, including forests and grasslands. They can occur in remote and unpopulated areas, but also near or in densely populated areas, where they pose threats to human lives and property. Often, wildfire impacts depend on factors such as their proximity, size, speed, intensity, and whether the population is prepared. Wildfires also emit smoke aerosols that degrade air quality and impact human health and welfare, particularly at risk members of the population such as those with asthma, Chronic Obstructive Pulmonary Disease (COPD), or heart disease. Smoke aerosols also reduce visibility, which can lead to unsafe conditions for transportation, and have climate impacts.

Based on well-established evidence, scientists have concluded that wildfire events are becoming more frequent and severe. Given this, along with the increasing threats extreme wildfire and heavy smoke pollution episodes pose to life and property, it is important to detect, forecast, track, and monitor the location and intensity of wildfires and their smoke emissions, as well as assess their impacts on communities, the economy and the environment.

Satellites are the only observational tool capable of systematic monitoring of global wildland fire activity. NESDIS science seeks to transform satellite data into actionable insights and analysis-ready data for a variety of critical wildland fire applications, including fire detection, tracking, and monitoring. NESDIS fire products improve the timeliness of new fire detections, enable operational smoke forecasting, and alert NWS Incident Meteorologists and fire behavior analysts to rapid changes in fire spread and behavior. A product example is the Fire Temperature RGB, which is built using ABI bands 7, 6, and 5 (shortwave and near-infrared), which are used to detect hot spots. The active hot spots show up as red, yellow, and white as the fires grow increasingly hotter. When used in combination with geocolor imagery, RGB imagery is made partially transparent and placed over the geocolor, so both the fire's hot spots and smoke plume are visible, as shown in Figure 35.

Continued use-inspired exploitation of satellite and complementary data sources is expected to yield new and improved NESDIS fire products and services that address critical capability gaps and emerging needs.

Figure 37. GOES-18 GeoColor, Fire Temperature image of the Cedar Creek Fire in Oregon, captured at 17:01:15 UTC on September 9, 2022.

FLOODS

Floods are among the most common natural hazards in the United States. They can be deadly and cause billions of dollars in damages. According to the NCEI, billion-dollar inland—non-tropical—flood events have increased in the United States, and are likely to continue as the atmosphere holds more water vapor due to warmer temperatures.

To help predict and mitigate the risk of flooding, NESDIS develops a wide and varied range of products. These include flood maps, products that can monitor soil moisture and moisture advection (Ex. MIMIC-TWP), satellite-derived rainfall intensity measurements using algorithms such as CMORPH2, and products that utilize data from a number of NOAA and other satellites to monitor flood extent.

NOAA's Access to RadarSat Constellation Mission (RCM) Reached Another Milestone

The United States does not currently have any SAR satellites on orbit. SAR's all weather, high-resolution capacities provide valuable information for a variety of NOAA's missions including monitoring ice, floods, winds, tropical cyclones, waves, vessels, and oil spills. STAR applied and became a vetted international partner with the Canadian Space Agency (CSA) which allowed NESDIS to access approximately 400-600 images per day over North America and the Arctic at no cost beyond internal processing. NOAA STAR is working to ensure optimal production and delivery for RCM products and imagery, disseminated to other line offices by STAR during 2021-2022 seasons, ensuring product stability and refinement before operationalizing the production in NESDIS in 2023. RCM collections over flooding conditions near the US/Canadian borders have been important to monitoring floods by the

National Water Center and NWS RFOs in the Red River of the North, Dakotas, Alaska, and Washington State.

Housing market and sea-level rise

The rate of future global sea-level rise will likely increase due to elevated ocean temperatures and land-ice loss (Rodziewicz et al 2022). Coastal properties are expected to become more prone to coastal flooding in coming decades due to relative sea-level rise caused by both global and local factors. Translating sea-level rise projections into lost physical and economic value is critical for companies, governments, and regulators. A team of NCEI researchers and their collaborators, including CIRES, and the Federal Reserve Bank of Kansas City, MO, has been using probability distributions of local sea-level rise projections, NOAA coastal digital elevation models, and CoreLogic housing data to estimate the timing of future sea-level rise inundation and a range of housing market impairments in four U.S. coastal metros (Figure 38. Atlantic City, NJ; Miami, FL; Galveston, TX; and Newport-San Pedro, CA) for a series of climate scenarios. The team has implemented a novel methodology, which refines estimates for the timing for future inundation, considers both housing properties' elevation above the tidal datum (Mean Higher High Water-MHHW), and hydrologic connectivity to the ocean—a critical consideration where natural or human-built features alter the relationship between sea levels and inundation. Each of the four metros presented unique risk factors (housing market, topography, and local sea level), which helped illustrate how the team's methods are applicable across geographies and scales of observation. The results from this study provide an important perspective on the timing of future losses, the associated uncertainty, and highlight positive (high-skewed) asymmetry of risk from sea-level rise inundation. This information can aid planners, policymakers, and investors in cost-benefit decision-making related to mitigation, adaptation, and remediation at the local and national levels.

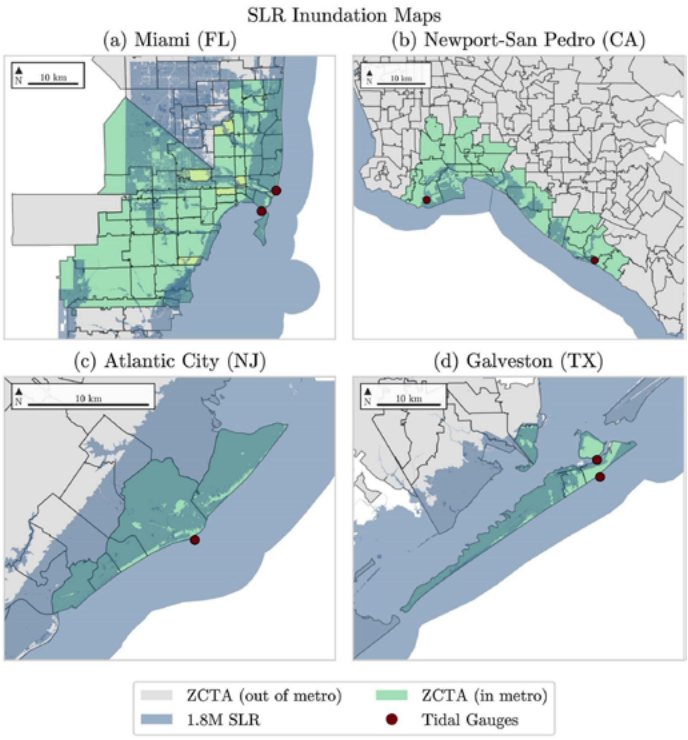


Figure 38. Four metro area maps; Metro areas are comprised of USPS Zip Code Tabulation Areas (ZCTA) and 1.8-meter sea level rise (SLR).

SURFACE MOISTURE

Surface moisture is represented by soil moisture and evapotranspiration. Both variables are among critical land surface states or flux rates between land surface and the atmosphere. Thus, observations of these variables are not only essential for the verification, calibration and data assimilation of the numerical water, weather and climate models, but also important for societal applications such as agricultural productivity forecasts, drought monitoring, and wildfire forecasts.

Soil Moisture

To provide satellite data products of soil moisture to the NWS for their NWP and water model research and operations, NESDIS has made the soil moisture operational product system (SMOPS) operational since 2016. As an innovative scientific research effort, scientists at NESDIS STAR have used machine learning approaches to refine and reprocess the satellite soil moisture data products for the NWS and other users. Figure 39 shows an example of the reprocessed SMOPS daily global soil moisture data product with significantly improved accuracy and spatial and temporal coverage compared to the currently operational SMOPS products (Yin et al, 2022). The operational SMOPS takes observations from several non-NOAA satellite sensors such as NASA's Soil Moisture Active Passive (SMAP), ESA's Soil

Moisture Ocean Salinity (SMOS), EUMETSAT Advanced Scatterometers (ASCAT), JAXA's GCOM-W Advanced Microwave Scanning Radiometer (AMSR-2) and NASA's Global Precipitation Mission Microwave Imager (GMI). Innovative Machine Learning algorithms are currently examined to further improve the quality, spatial and temporal coverage, and especially spatial resolution (for example downscaled to 1km) of SMOPS data products.

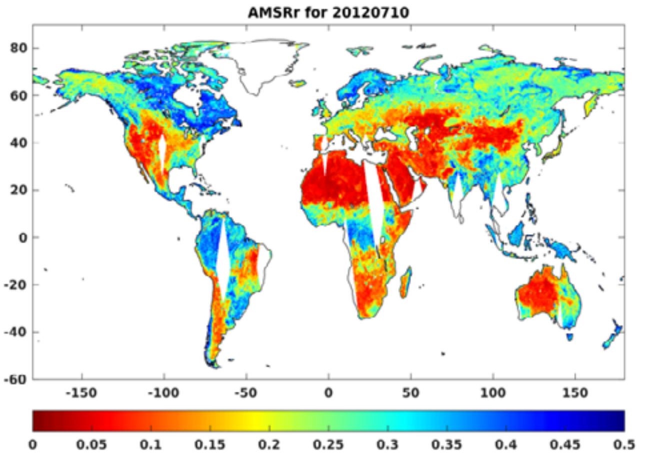


Figure 39. Reprocessed daily global soil moisture data product from SMOPS using machine learning algorithm for blending multi-satellite observations.

Evapotranspiration (ET) and Evaporative Stress Index (ESI)

ET data products are used to verify land surface latent heat flux simulations which are critical for numerical weather predictions because heat fluxes between land surface and the atmosphere are the main energy sources of the atmospheric weather systems. ET observations are also important for hydrological prediction models as it is one of the most important components of land surface water balance. The National Water Model requires ET observations for model verification, calibration and future data assimilation. Anomalies of the ratio of the actual ET and potential ET are computed as evaporative stress index (ESI) which is one of the most important and independent data layers used for drought monitoring. The National Integrated Drought Information System (NIDIS) uses ESI in their weekly publication of the U.S. Drought Monitor. NESDIS has developed the GOES ET and Drought (GET-D) product system to generate ET and ESI data products for the above-stated users. The GET-D product system was based on the thermal channel observations of the GOES ABIs. Since the thermal observations are available for clear sky or regions without cloud contamination, the daily ET maps would be patchy. To fill the data gaps caused by clouds, NESDIS STAR scientists have developed an approach to deriving land surface temperature for GET-D from the Ka-band microwave observations of the GCOM-W AMSR2 sensor using a machine learning algorithm. The improvements, as shown in Figure 40, are significant. More details can be found from Fang et al (2022).

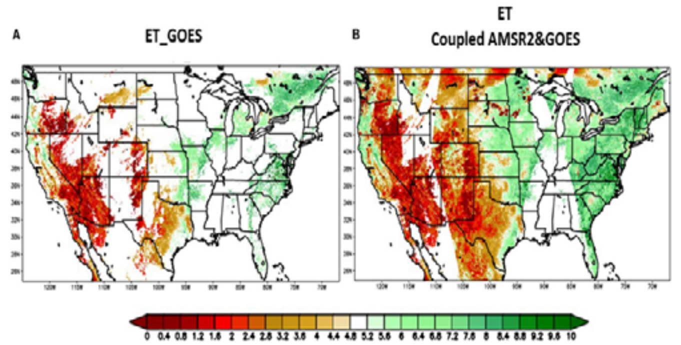


Figure 40. Daily ET map from NESDIS GET-D product system based on GOES only (A) or both GOES & AMSR2 (B) observations.

LAND SURFACE TEMPERATURE

Land Surface Temperature (LST) is defined as a measure of how hot or cold the surface of the Earth would feel to the touch. Surfaces over inland water and coastline were included in the LST domain. The knowledge of LST provides critical information on the temporal and spatial variations of the surface equilibrium state and is of fundamental importance in the weather and climate system controlling surface heat and water exchange between the land and the atmosphere. LST has been widely used in a variety of fields such as numerical weather prediction models and data assimilation systems, as well as urban heat island monitoring. It has been listed as one of the Essential Climate Variables (ECVs) by the Global Climate Observation System (GCOS) of the World Meteorological Organization (WMO).

LSTs from The JPSS

Operational LST data have been produced through JPSS satellites, including Suomi NPP since 2012, NOAA-20 since 2018; the most recent JPSS satellite, NOAA-21 will produce operational LST data from September 2023 onward. An enterprise LST algorithm has been applied for the LST production through thermal infrared band observations from the VIIRS onboard each JPSS satellite, which ensures consistency of the LST products from different satellites. Swath LST data of JPSS is generated right after the overpass of the satellite, at spatial resolution 750 meters; while a global composite LST product (see Figure 41) which contains a daytime LST dataset and a nighttime LST dataset, at spatial resolution 1 km, is generated daily. Considering that overpass of the JPSS satellites is at around 1:30 pm and 1:30 am local time, the global daytime and night-time data represent daily maximum and minimum LSTs, respectively.

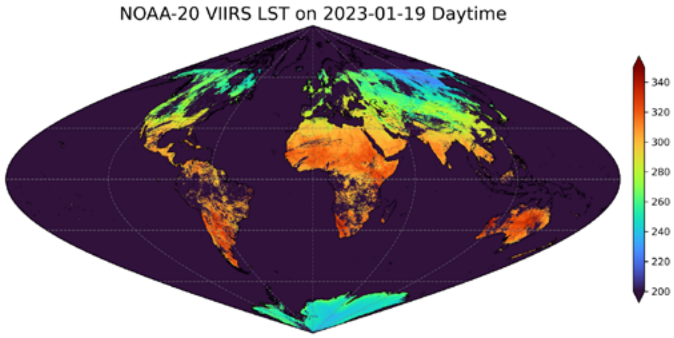


Figure 41. A daily composite global LST map (in degree K) derived from NOAA-20 VIIRS observation.

LSTs from The Geostationary Satellite R (GOES-R) series mission

The same enterprise LST algorithm has been applied for the GOES-R operational LST products through the thermal infrared band observations from an ABI sensor onboard each GOES-R satellite. The GOES-R LSTs are produced from three ABI scan modes: Full Disk mode, as shown in Figure 42, with temporal resolution of 5-15 minutes, Continental US/Pacific US mode with 5 minutes temporal resolution, and Mesoscale mode with 30-second temporal resolution. Spatial resolution of the GOES-R LST products are 2 km. GOES-R LST products have been operational since 2017, 2019, 2022, for GOES East (-16), GOES-17, and GOES West (-18), respectively.

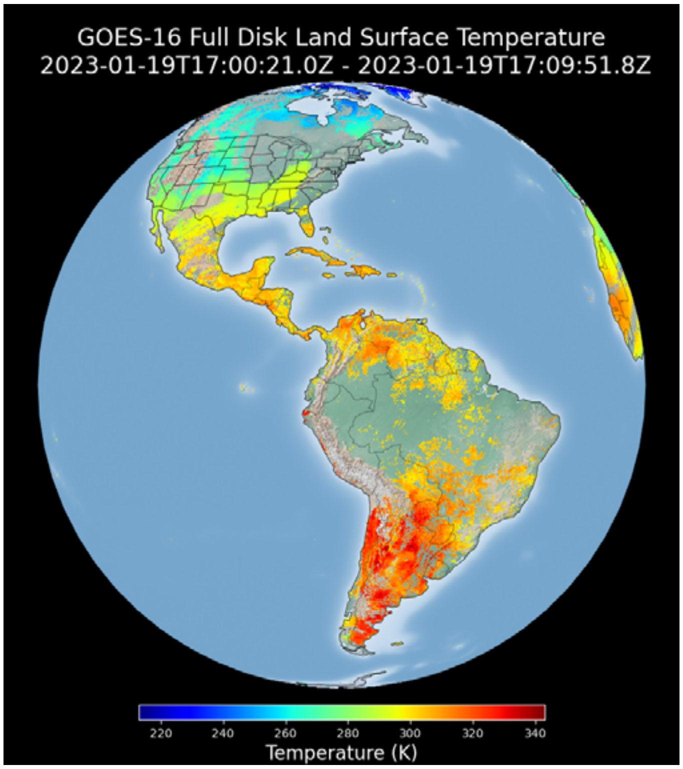


Figure 42. A full disk LST map derived from NOAA GOES East (-16) ABI observation.

Developed Routine Global Monitoring of the Land Surface Anomaly System

Over the past few decades, the frequency and intensity of extreme weather events have been rapidly increasing, posing serious threats to lives. In a study designed to address concerns from the public, scientists at NESDIS STAR developed a comprehensive system to monitor land surface temperature anomalies through satellite observations. In general, land surface temperature anomalies can be driven by a variety of factors from large-scale climate events (e.g., El Niño/La Niña) to local hazard impact (e.g., wildfire). These anomalies are often a response to the frequency and intensity of extreme weather events. A series of monthly summaries provide focus and help detection of corresponding strong weather anomalies and high-impact environmental events. Recent studies included multiple hazardous weather events, encompassing heatwaves, wildfires, winter storms, strong cold events, drought, and their potential impacts on the environment. The new land surface temperature anomaly monitoring system has improved understanding of weather anomaly status, raised people's awareness of increasing risks due to changes in climate, and helps decision making.

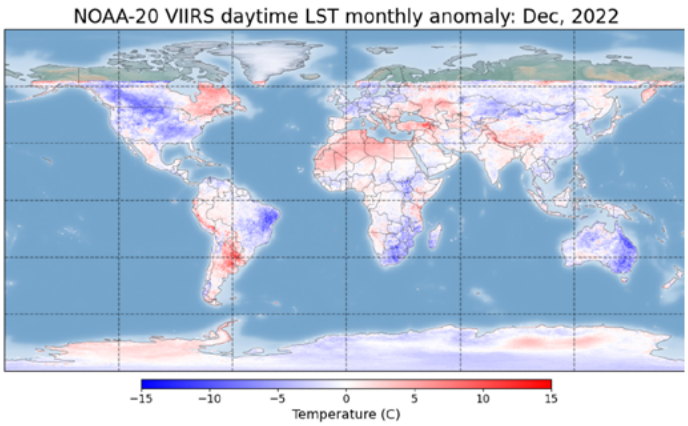


Figure 43. Example of the monthly global LST anomaly report.

Visit https://www.star.nesdis.noaa.gov/smcd/emb/land/index.php?product=LST to read more.

LAND SURFACE ALBEDO

The Land Surface Albedo (LSA) is a measure of how much of the Sun's energy is reflected back into space, which reflects the cooling effect of the earth. Annual albedo varies with the dynamics of the sea ice and snow and also changes due to deforestation or black carbon caused by the burning of wood or fossil fuels. The Albedo variation reflects the land-atmosphere boundary condition change under dynamic climate patterns or weather events is important to be closely monitored. Two related products, Bidirectional Reflectance Distribution Function (BRDF) and Nadir BRDF-Adjusted Reflectance (NBAR) are also provided to users according to requests from local efforts. The BRDF models the surface anisotropic features and can be inverted to predict reflectance in a given sensor/solar geometry, such as the nadir observation at a local solar zenith angle which is defined as the JPSS and GOES-R NBAR products. Albedo is one of the Essential Climate Variables (ECVs) by the Global Climate Observation System (GCOS) of the World Meteorological Organization (WMO) and also one fundamental satellite product series in National Aeronautics and Space Administration (NASA) and European operational satellite agency (EUMETSAT).

Land Surface Albedo from the JPSS

The current Enterprise VIIRS albedo product (SURFALB) (displayed in two views in Figure 44) provides shortwave daily mean blue-sky-albedo which contributes to radiation budget estimation, to provide real-time global blue-sky albedo defined under actual illumination over land and sea-ice surface. The Suomi NPP and NOAA-20 VIIRS L2 Enterprise Albedo products have been operationally generated in the NDE system since Sep 19, 2019. The Enterprise Albedo from NOAA-21 will be operational soon, and will join the SURFALB products family of the 750-m L2 swath albedo and 1-km L3 global albedo. VIIRS BRDF (Figure 45) and NBAR data have been evaluated in local user environments and are pending integration into operational systems.

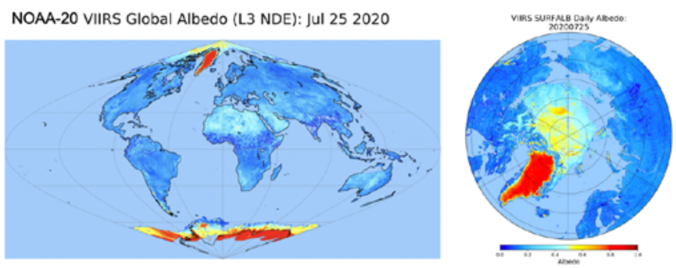


Figure 44. A daily composite of v2r2 SURFALB product from NOAA-20 in two views.

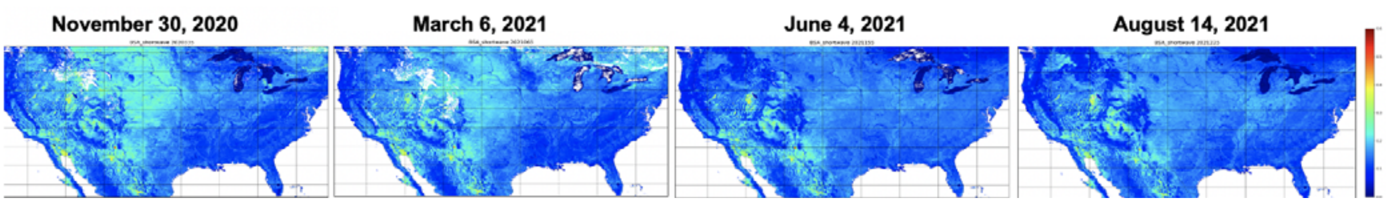


Figure 45. BRDF-derived shortwave albedo sample data derived from Suomi NPP and NOAA-20 VIIRS observation.

Land Surface Albedo from the GOES-R Mission

Albedo and surface reflectance (LSA/BRF) products from NOAA's GOES East and GOES West satellites (such as the full disk LSA maps shown in Figure 46) are operational and provide near-real-time information for users. Albedo and surface reflectance acquired by geostationary satellites have the advantages of offering both a long-term dataset and frequent retrievals to monitor the parameter change, which can be used for monitoring diurnal variation of surface albedo and reflectance. Following the launch of the Enterprise system in 2021, algorithms for the GOES-R LSA/BRF products were adjusted and the data have been available since April 2022, for GOES East, GOES-17, and January 2023, for GOES West.

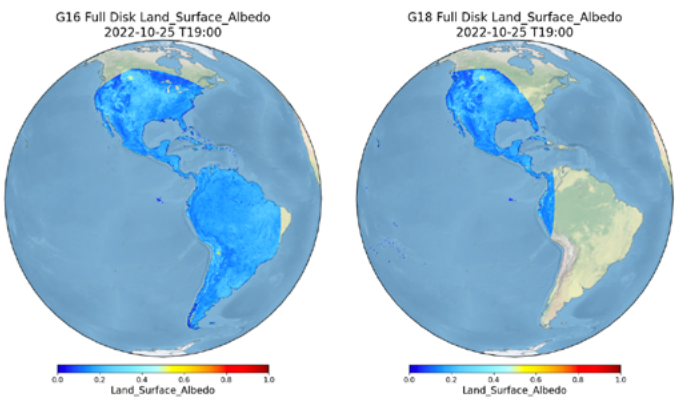


Figure 46. A full disk LSA map derived from NOAA GOES East (left) and GOES West (right) ABI observation.

Contributed to Routine Global Monitoring of The Land Surface Anomaly System

Scientists at NESDIS STAR monitor several key parameters linked to the hydrological cycle, the carbon cycle, and the energy balance for anomalies. These key parameters include precipitation, land surface temperature (LST), land surface albedo (LSA), vegetation index (VI) and Evapotranspiration (ET). Multi-variable anomaly analysis demonstrates the relationship among the variables and provides understanding of the surface response to climate patterns and extreme weather change. For example, see Figure 47, which shows the correlation between the Oceanic Niño Index (ONI), which is NOAA's primary index for tracking the ocean part of the El Niño-Southern Oscillation (ENSO) climate pattern, and snow-free albedo.

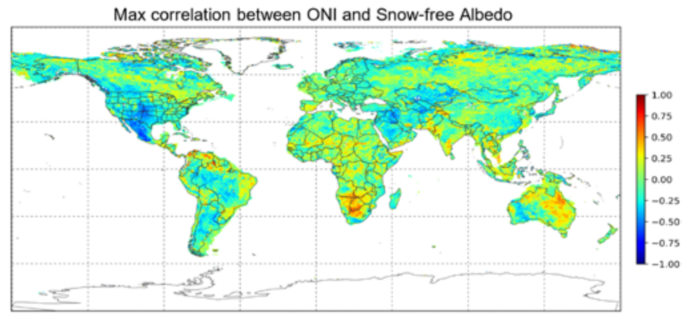


Figure 47. Correlation between Oceanic Niño Index (ONI) and snow-free albedo, which denotes the influence of El Niño-Southern Oscillation climate pattern (ENSO) on LSA. Red color denotes positive correlation and blue color corresponds to negative correlation.

Visit https://www.star.nesdis.noaa.gov/smcd/emb/land/index.php?product=LSA to read more.

VEGETATION

The Ocean covers about 70 percent of the Earth's surface. The remaining 30 percent is covered by land masses, of which vegetation covers a considerable portion. Satellite vegetation data are used in myriad ways including to classify land cover, forecast agricultural yields, estimate crop acreage, detect plant stress, monitor drought, and help understand the global carbon cycle. They are also used in numerical weather and seasonal climate prediction models at the NCEP. The following satellite vegetation data products have been generated at NESDIS for various users at the NCEP and elsewhere.

Vegetation Index

Satellite vegetation index (VI) products are commonly used in a wide variety of terrestrial science applications that aim to monitor and characterize the Earth's vegetation cover from space. VIs are optical measures of vegetation canopy "greenness", a composite property of leaf chlorophyll, leaf area, canopy cover, and canopy architecture. Although VIs are not intrinsic physical quantities, they are widely used as proxies in the assessment of many biophysical and biochemical variables, including canopy chlorophyll content, leaf area index (LAI), green vegetation fraction, gross primary productivity (GPP), and fraction of photosynthetically active radiation absorbed by the vegetation (FAPAR). Operational VI data have been produced through the JPSS satellites, as expansion of the EOS/MODIS VI products. Three VI products are made both globally and regionally over land regions: the Top of the Canopy (TOC) NDVI (Figure 48), the TOC Enhanced Vegetation Index (EVI) (Figure 49), and the Top of the Atmosphere

(TOA) Normalized Difference Vegetation Index (NDVI) (Figure 50). The products come with associated relevant quality flags (i.e., Land/water mask, cloud confidence, and aerosol loadings). These VI products are produced at temporal resolutions of daily, weekly (8-day) and bi-weekly (16-day) and spatial resolutions of 0.036° (4 km) at the global scale and 0.009° (1 km) at the regional scale.

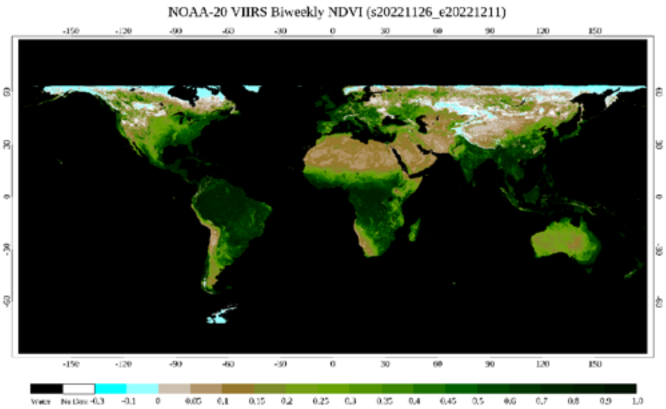


Figure 48. A biweekly composite (Nov 26–Dec 11, 2022) global TOC NDVI map derived from NOAA-20 VIIRS observation.

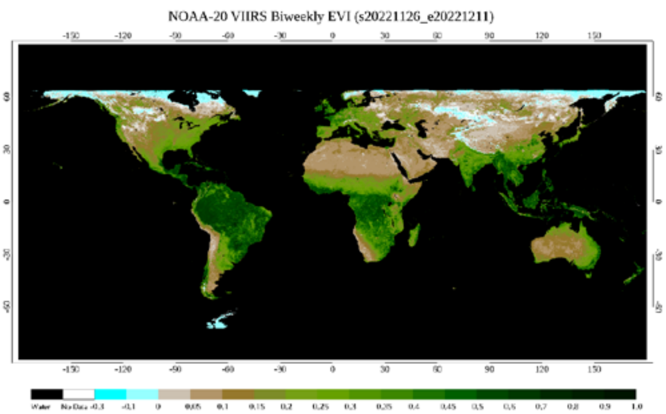


Figure 49. A biweekly composite (Nov 26–Dec 11, 2022) global TOC EDVI map derived from NOAA-20 VIIRS observation.

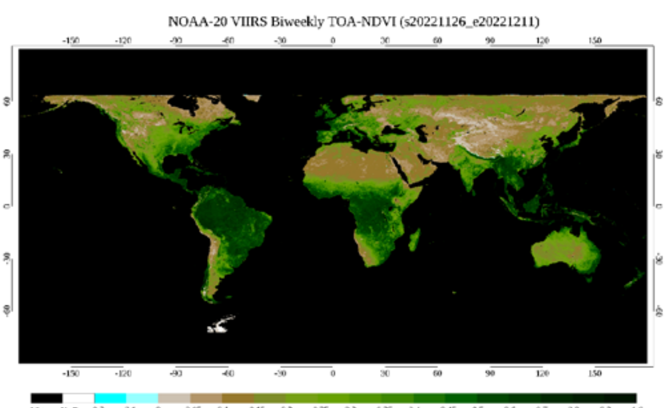


Figure 50. A biweekly composite (Nov 26–Dec 11, 2022) global TOA NDVI map derived from NOAA-20 VIIRS observation.

Green Vegetation Fraction

Green Vegetation fraction (GVF) is defined as the fraction of a pixel covered by green vegetation if it is viewed vertically. It quantifies the spatial extent of the green vegetation. It is used to separate vegetation and soil in energy balance processes, including temperature and evapotranspiration. Therefore, GVF is needed for land surface initialization in numerical weather prediction models and land surface monitoring. Operational GVF data have been produced through JPSS satellites, including Suomi NPP since 2012, NOAA-20 since 2019, for applications in numerical weather and seasonal climate prediction models at the NCEP.

The VIIRS GVF algorithm is a modified version of Gutman and Ignatov's (1998) GVF algorithm, which uses VIIRS red (I1), near-infrared (I2) and blue (M3) bands centered at 0.640 µm, 0.865 µm and 0.490 µm, respectively, to calculate the Enhanced Vegetation Index (EVI) and derive GVF from EVI. The initial inputs to the GVF algorithm are reflectances that have already been gridded within the Vegetation Index (VI) algorithm. To meet the data needs of NCEP and other potential users, GVF is produced as a daily rolling weekly composite at 0.036° (4 km) resolution (global scale), as shown in Figure 51, and 0.009° (1 km) resolution (regional scale), as shown in Figure 52. The most recent JPSS satellite, NOAA-21 will produce operational GVF data from September 2023.

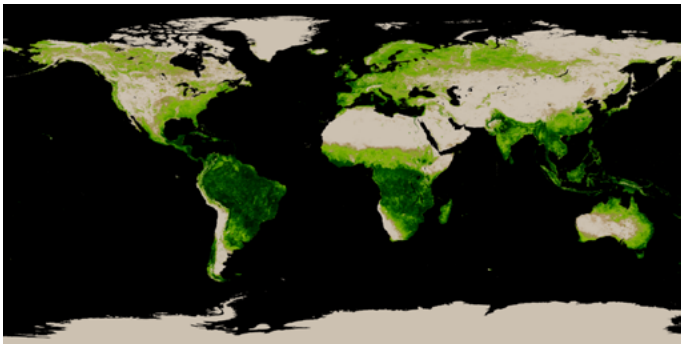


Figure 51. A weekly composite (Jan 13–19, 2023) global GVF map derived from NOAA-20 VIIRS observations.

Figure 52. A weekly composite (Jan 13–19, 2023) regional GVF map derived from NOAA-20 VIIRS observations.

To read more, visit:
https://www.star.nesdis.noaa.gov/smcd/emb/land/index.php?product=GVF
https://www.star.nesdis.noaa.gov/smcd/emb/land/index.php?product=VI

Surface Type

Numerical water, weather, and climate models require information of vegetation and other surface types to set up their model parameters (e.g. roughness). NESDIS STAR scientists have been generating an annual surface type from Suomi NPP and NOAA-20 VIIRS observations as a requirement from the JPSS program. To improve the accuracy of surface type representations, the VIIRS surface type team has integrated observations of VIIRS and the GEDI-Lidar of NASA for retrieving forest structure parameters such as vegetation canopy height, percent canopy cover, plant area index and foliage height diversity using an innovative machine learning approach. These parameters are retrieved for each grid/pixel of a region. Current NCEP models use only one surface type label to assign those parameter values looked up from the surface type label while different grids/pixels with the same surface type label may have different values of these parameters. Therefore, the new approach may improve NCEP models in the future when those parameter satellite retrievals will be made operationally available. Details of the new approach are presented in Huang et al (2022).

Vegetation Health Indices

Vegetation health indices provide information on current vegetation health or stress status for vegetation monitoring, especially crop health status. NESDIS STAR scientists have been generating and delivering global and regional vegetation condition index (VCI), temperature condition index (TCI) and Vegetation Health Index (VHI) with VHI being a combination of VCI and TCI from observations of Suomi NPP and NOAA-20 VIIRS. A time series of almost 40 years of these indices up to the current week have been posted at a NESDIS STAR website and widely used in the monitoring and forecast applications of global and regional crop productivity by the U.S. Department of Agriculture (USDA) and several other national or international agencies/organizations (e.g. the CPC, FEMA, NIDIS, USDA's World Agricultural Outlook Board, etc). Figure 53 shows the NESDIS-generated VHI, displayed in GIS (ARCMap).

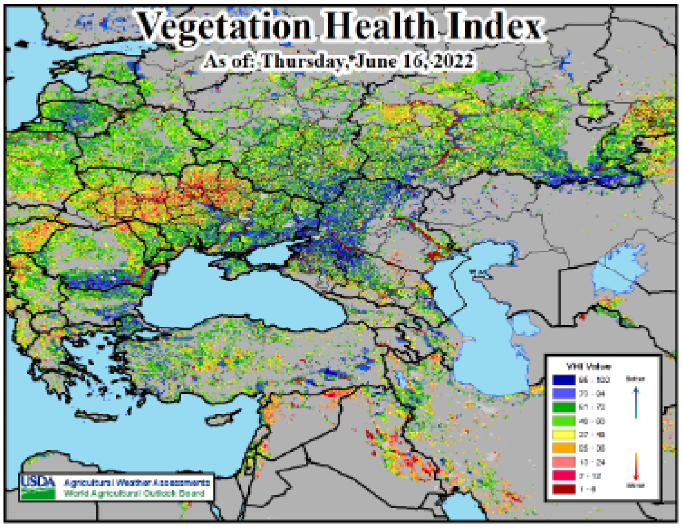


Figure 53. NESDIS generated VHI shows the impact of extreme weather on wheat and corn productivity in Ukraine. Areas shown in red signify stress conditions, while areas shown in blue indicate very favorable conditions.

In addition to the weekly production and delivery of legacy vegetation health data products, the NESDIS STAR vegetation health product team is exploring other potential satellite observations to enhance the VHI performance in crop production monitoring and forecasts for some crops in some regions of the world. A Radiation Condition Index (RCI) based on satellite observations of daily incoming solar radiation was added as an additional term in the VHI algorithm and was found to improve the correlation with wheat yield in India for the years from 2000-2019.

Oceans, Freshwater & Coasts

The Ocean, which holds roughly 97 percent of the water on Earth, is by far the planet's largest reservoir. In addition, the Ocean covers more than 70 percent of the surface of our planet, yet it is one of the most sparsely observed areas of the globe. Global sampling of the surface ocean is feasible only from earth-observation satellites. They provide more data over oceans than would be possible to obtain solely from conventional sources. It is worthwhile to note that satellites, in turn, require calibration and validation can only derive from in-water measurements.

The Ocean also contributes approximately 50% of the world's oxygen and absorbs 50 times more carbon dioxide than our atmosphere.

NESDIS is an active participant in NOAA's ocean efforts. NESDIS not only maintains the World Ocean

Database (WOD), and develops new data products, but its data also enables the blue economy. Ocean products include Sea Surface Temperature (SST), Sea Surface Height (SSH), Sea Surface Salinity (SSS), Ocean Color, Ocean Surface Wind Vector (OSWV), and Sea Surface Emissivity. Ocean products have a variety of applications, from navigation to monitoring ENSO events, to detecting algae blooms or coral bleaching. The 2022 NOAA CoastWatch Annual Meeting convened at the NOAA Center for Weather and Climate Prediction (NCWCP) in College Park, Maryland. The meeting offered a rich assortment of talks on NESDIS' satellite observations, including their use in combination with surface buoy measurements to track the surface temperature conditions of the Great Lakes. That knowledge can help, for example, better predict the duration of ice cover and when harmful algal blooms will form.

Prolonged Marine Heatwaves in the Arctic

Events of extremely warm waters in the oceans are known as marine heatwaves (MHWs). Studies have indicated that marine heatwaves (MHWs) have had severe impacts on the marine ecosystem in the tropical Pacific, tropical Atlantic, and Indian Oceans, but there have been few studies focused on MHWs in the Arctic and high-latitude oceans. A recent study based on NOAA Daily Optimum Interpolation Sea Surface Temperature (DOISST) version 2.1(Huang et al. 2021) showed (a) MHWs do exist in the Arctic coastal regions, (b) MHWs in the Arctic strengthens with time in the past decades, (c) MHWs are as strong as or stronger in the Arctic than in the other oceans. The MHW metrics of annual intensity, frequency, duration, and areal coverage in the Arctic regions have increased significantly in recent decades. The increase of the annual duration is mainly owing to the postponed end time, thus the prolonged periods, of the MHW seasons. The increasing trends of the annual intensity, frequency, duration, and areal coverage in the Arctic are closely associated with the increasing surface air temperature and decreasing sea-ice concentration under the global warming environment. These features are robust across three different sea surface temperature (SST) products and use different MHW criteria.

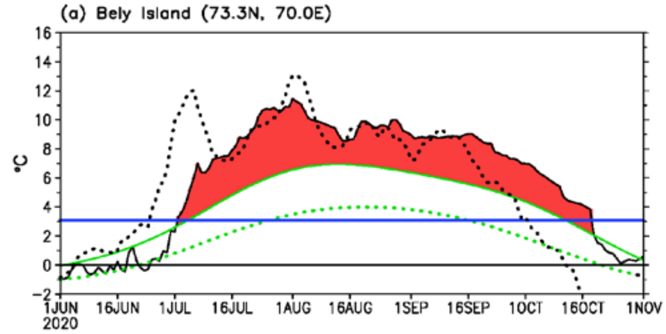


Figure 54. An example of marine heatwaves (MHWs, red shaded) surrounding (within 2.5°×2.5° box) Global Historical Climatology Network stations at Bely Island (73.3°N, 70.0°E) in 2020 indicated by sea surface temperature (SST, solid black), climatological SST (SSTc, dotted green), MHW SST criterion (95th percentile SST, solid green), long-term mean summer temperature (LMST, solid blue), and surface air temperature (SAT, dotted black). A 7-day running filter is applied to SAT.

Multi-Satellite Blended Seawinds in Support of Blue Economy and Offshore Wind Energy

The NOAA NCEI Blended Sea-winds (NBS) product is an important element in NOAA's Blue Economy Strategic Plan, supporting offshore renewable energy, marine transportation, marine ecosystem and fisheries, and other vital economic drivers. NBS provides long-term (1987 onward) satellite-based sea-winds over the global ocean to show climatology patterns (e.g. max. winds), and seasonal and annual variations. The NBS V2.0 blends multiple satellite and reanalysis data to generate sea surface (10m) vector winds on a global 0.25degree grid at time resolutions of 6-hourly, daily and monthly, and a climatology. NBS V2.0 also captures hurricane scale winds using modern-day observations and techniques. In support of Offshore Wind Energy, a suite of wind products (see Figure 55 for an example) is being developed over the USA coastal regions, including wind roses, wind speed maps and occurrences (in % of time) of effective wind speed (between 5-25 m/s), and >3MW/5MW wind energy occurrences (in %).

These resources help stakeholders in their decision-making related to renewable energy development. The NBS 10m winds can be converted to wind-turbine heights; an early study by a renewable consulting firm showed that the adjusted 10m NBS winds to mast anemometer heights have correlations of ~94% for monthly means and 98% for yearly means. Using the National Renewable Energy Laboratory (NREL) Wind Integration National Dataset (WIND) toolkit, the output Power (for 6MW turbine) can be simulated from NBS.

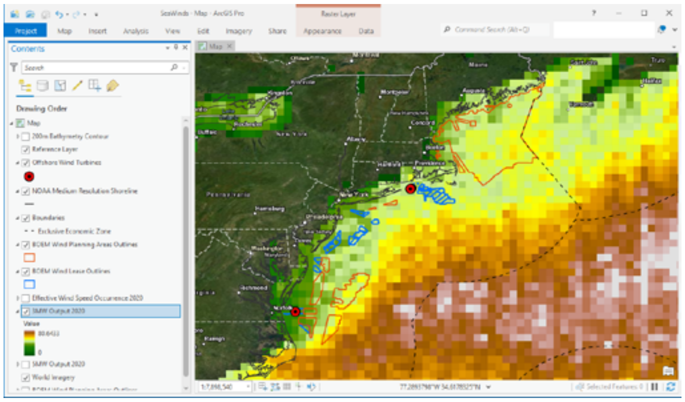


Figure 55. "Wind-Energy": Left—Interactive Wind-Roses along US coastal regions; Right—>3MW wind energy occurrences (in %) in 2020 for selected regions.

TOPOGRAPHY AND BATHYMETRY

Advancing the New Blue Economy is one of NOAA's top priorities as stated in NOAA's strategic plan. NCEI plays a key role in supporting NOAA mission requirements to collect and apply data and information about the seafloor. Data collected in support of ongoing national and international seafloor mapping campaigns are used to develop foundational and mission-critical products that support ocean navigation and coastal resilience.

Within NCEI, this includes hosting the world's most authoritative global database of bathymetric data. This database provides the foundational data for several user-driven products such as the NCEI-produced digital elevation models and the ETOPO Global Relief Model.

The NCEI Bathymetry Database and Archive are a fundamental component of many NOAA office initiatives. NOS Office of Coast Survey relies on NCEI to conduct their bi-annual U.S. Bathymetry Gap Analysis and also underpins their National Bathymetry Source Project and BlueTopo Product. OAR Ocean Exploration depends on NCEI data holdings to help guide and execute their data exploration plans and to aid in their seafloor characterization studies. In addition, these data are important to the private sector for a variety of applications, from global base maps (ESRI Ocean Basemap, Google Earth) to natural resource extraction to telecommunications.

New Global Relief Model

NOAA NCEI, through its collaboration with the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder, developed a new global relief model, ETOPO 2022. Its predecessor, ETOPO1, has been an important modeling tool for the tsunami and coastal hazards community since its generation more than a decade ago. The ETOPO 2022 spatial resolution is 15 arc-second (~0.5 km), which is four times higher than ETOPO1. ETOPO 2022 was generated with a combination of numerous airborne lidar, satellite-derived topography, and shipborne bathymetry datasets from U.S. national and global sources. ETOPO 2022 uses bare-earth topographic data from NASA's Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) to independently validate both the input datasets and the final ETOPO 2022 model.

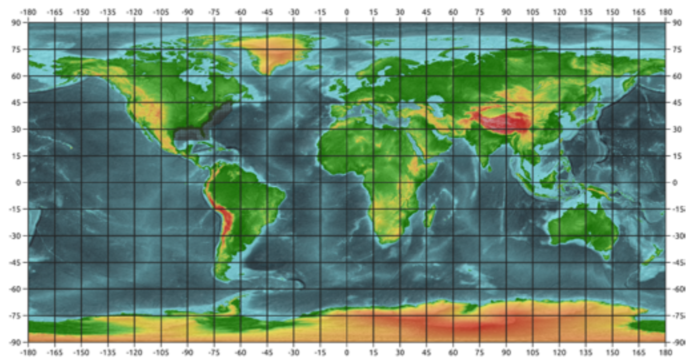


Figure 56. ETOPO 2022 with 15° tile boundaries.

ETOPO 2022 is available to download as "Ice Surface" (top of Antarctic and Greenland ice sheets) and "Bedrock" (base of the ice sheets) versions from:

- ETOPO Product Website
- THREDDS Catalog
- Grid Extract Tool
- Bathymetric Data Viewer Grid Extract Tool
- Metadata Landing Page

Seabed 2030

Focus on seafloor mapping is increasing from all levels including NOAA, Congress, the White House, and the international community. Many of these initiatives name NCEI as the steward for data collected to support these initiatives. Most recently (June 2022), NOAA signed an MOU with the Nippon Foundation GEBCO Seabed 2030 Project committing NOAA support for this ocean mapping effort. That MOU explicitly states that the NCEI-hosted Data Center for Digital Bathymetry will serve as the steward for bathymetry data collected as part of this effort.

SURFACE HEIGHT

Since 1992 a series of active radar satellites have been taking detailed satellite measurements of the surface of the ocean for weather, climate, and undersea mapping applications (Figure 57). The most recent in this series, Sentinel-6 Michael Freilich (S6MF) is a NOAA-partnered mission with EUMETSAT, NASA, and ESA, launched on 21 November 2020, and is today's most advanced satellite radar altimeter tasked with measuring ocean height, waves, and winds. Measuring these allows oceanographers and climatologists to detect patterns of global sea level rise, hurricane intensity, El Niño and La Niña, eddies, surface currents, ecosystem ecology and other applications. When water warms, it expands and raises the surface of the ocean, so measuring the ocean surface height allows scientists to understand how much heat is stored in the oceans, which is critical to tropical cyclone intensity forecasting at the National Hurricane Center. In addition, measurements of wave heights and wind speeds are provided to the NWS within hours, which helps forecasters determine if a specific weather system is behaving as models have predicted.

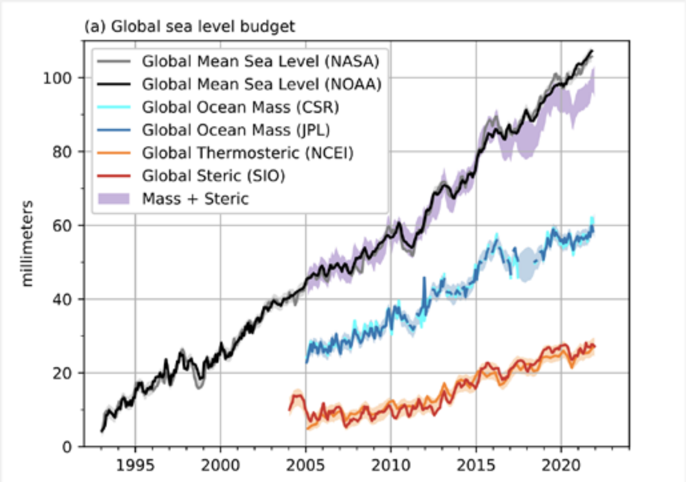


Figure 57. Closure of the sea level budget using the ocean observing system. (a) Monthly averaged global mean sea level (mm) observed by satellite altimeters (1993–21) from the NOAA Laboratory for Satellite Altimetry (black) and NASA Sea Level Change Program (gray). Monthly global ocean mass (2005–21) from GRACE and GRACE-FO calculated from mascons produced by NASA JPL (blue) and University of Texas Center for Space Research (CSR, cyan). Monthly global mean steric sea level (2004–21) from SIO Argo data (red). Monthly global mean thermosteric sea level from NCEI Argo and hydrographic data (orange). Monthly global ocean mass plus steric (purple). Shading around all data sources represents a 95% confidence range. (From the 2021 State of the Climate Report.)

Extreme Wave Heights in the Bering Sea

On 17 September 2022 the remnants of Typhoon Merbok (Figure 58a) caused flooding that devastated Coastal Alaska. Storm surge flooded communities along 1,000 miles (1,609 km) of Alaska's west coast, damaging homes, submerging roads, and triggering evacuations. Sentinel-6 Michael Freilich recorded 17 observations of significant wave height exceeding 14 m (46 feet) on 16-17 September 2022 (Figure 58b, dark red dots). Such a sea state is defined as "phenomenal" by the World Meteorological Organization (WMO). During those 48 hours, five percent of all satellite radar altimeter observations in the Bering Sea exceeded nine meters (30 ft), defined as "very high" seas by the WMO (Figure 58c), and 19% of observations exceeded six meters (20 ft), WMO "high" seas. S6MF recorded the largest individual observation of significant wave height at 15.3 m (50.2 ft), equivalent in height to a five-story building. Although the Bering Sea is considered one of the most treacherous seas in the world, such very high and phenomenal sea states are unusual for September. NESDIS supports an investigation of long-term changes in the Bering Sea over the past two decades, which has found that the roughest seas are most commonly observed in the winter months between November and February. The analysis of satellite radar altimeter observations of significant wave height in the Bering Sea shows median wave heights in September typically span 1.5 to 2.4 m. Over 20 years between 2002 and 2021, only five percent of observations show significant wave height > 4 m (Figure 58c, solid black curve). Conditions in September 2022 were quite different from this when between 16–17 September, five percent of all observations showed waves > 9 m tall (Figure 58c, gray bars).

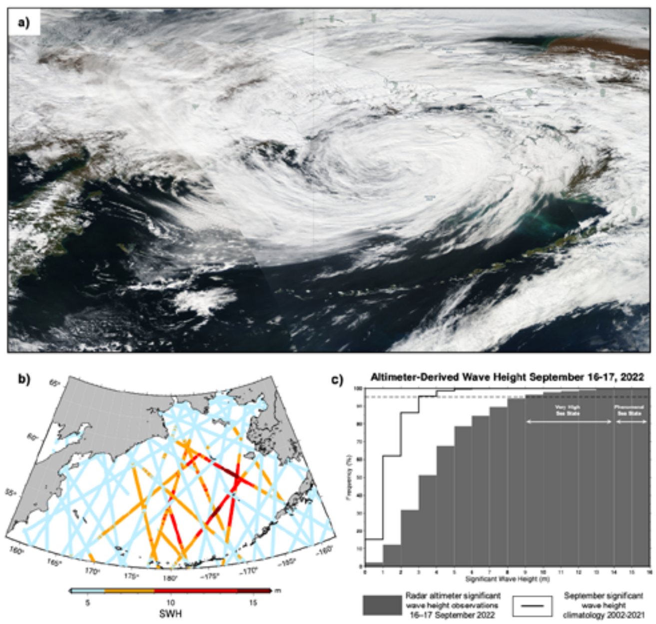


Figure 58. Remnants of Typhoon Merbok moving across the Bering Sea (a).

WATER TEMPERATURE AND SALINITY

Processes that took place throughout Earth's history, such as the weathering of rocks, evaporation of ocean water, and the formation of sea ice, have made the ocean salty. Those are still at work today and are counterbalanced by processes that decrease the salt in the ocean, like freshwater input from rivers, precipitation, and the melting of ice. The result is an ocean surface where the salinity—the concentration of salt—changes. These changes, small as they may be, have large-scale effects on Earth's water cycle and ocean circulation. Sea surface salinity (SSS) plays a key role in ocean circulation and the regulation of Earth's climate. Deciphering the dominant processes that affect SSS—evaporation and precipitation—will improve our ability to monitor, understand, and model those factors that ultimately govern ocean motion and climate variation. NESDIS/NCEI supplies gridded SSS monthly data for the Blended Analysis of Surface Salinity (available from NCEP through ftp.cpc.ncep.noaa.gov/precip/BASS). Analysis of BASS results are included in monthly NCEP reports.

On longer time scales, U.S. climate anomalies are linked to slow variations of sea surface temperature. Improving long-term consistent in situ and satellite monitoring, understanding and modeling of these ocean dynamics and atmospheric interactions will help improve near-term forecasts and longer-term projections of weather and climate changes affecting every segment of society.

Science and information regarding the subsurface essential ocean variables (EOV; temperature and salinity, as well as dissolved oxygen, carbon/acidification variables, nutrients, primary productivity, etc.) are dependent on NESDIS/NCEI foundational data sets. The WOD is an aggregation and dissemination point for subsurface ocean profile data. The WOD is an international project under the International Oceanographic Data Exchange (IODE) managed within NESDIS/NCEI which pulls together all available historical and recent ocean profile data from the Global Ocean Observing System as well as national research and monitoring programs for utilization in global EOV monitoring and input to reanalysis models.

A paper in the Bulletin of the American Meteorological Society detailing the effects of the pandemic on ocean observing led by NESDIS/NCEI scientists shows the state of ocean observing in the years 2019-2021 by quantifying the change in ocean coverage for many EOVs in that time period. The calculation of ocean heat content and sea surface temperature time series at NCEI were found to be unaffected. For these variables, independent (as opposed to ship-based) observing platforms such as Argo floats sustained observations through the pandemic but the lack of ship time for deployment and replenishment of the Argo array will lead to geographic 'holes' in the observing system, such as we see for 2022 in the northwest Indian Ocean (Figure 59).

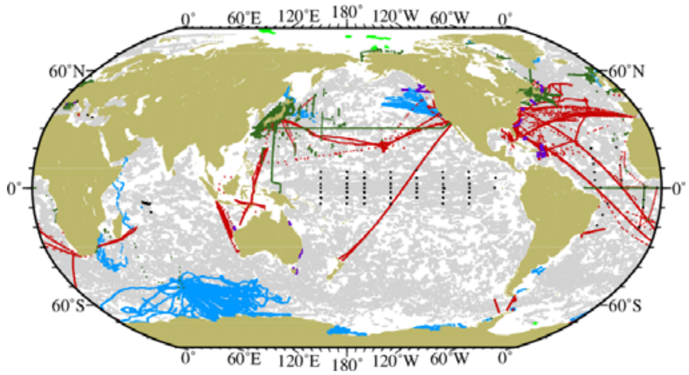


Figure 59. Data for 2022 in the World Ocean Database: Grey: Argo floats; Red: Ship of Opportunity Program Expendable Bathythermographs; Blue: instrumented pinnipeds from AniBos and other programs; Black: Moored Buoys from the tropical moored buoy array and OceanSites, Purple: gliders from U.S. IOOS National Glider Data Assembly Center, Australian and European sources, Dark Green: Conductivity-Temperature-Depth (CTD) casts from various sources, mainly through the Global Temperature and Salinity Profile Program (GTSPP); Light Green: Ice Tethered Profilers from Woods Hole Oceanographic Institute.

From the historical ocean profile data, NESDIS/NCEI produces long-term climatological mean fields of subsurface oceanographic variables, the World Ocean Atlas series. These mean fields are used as input to ocean and climate models, as baselines for investigating environmental change, quality controlling oceanographic data, and many other uses. In 2022, NESDIS/NCEI released the first set of World Ocean Atlas 2023 series, 30-year climate normals 1991–2020 for temperature and salinity. These are further discussed in the Analytical/Climate section of this report. A regional set of long-term climatologies for the Northwest Atlantic Ocean were also released in 2022. The regional climatology has a higher geographic resolution than the global climatology, allowing for more detailed information in coastal regions and better representation of regional features. A full set of revised temperature and salinity global climatologies are scheduled for 2023. A north Pacific regional climatology is also planned, which is intended to provide a tool for helping to understand the changes in Snow Crab and other fisheries in the region.

Temperature and salinity data from WOD and baseline means from the WOA are used to calculate ocean heat content, salt content, and steric sea level time series on a quarterly basis.

The time series were updated four times in 2022 (Figure 60). The information from the ocean heat content time series informs a number of publications, including Cheng et al. (2022) which was one of the top 10 climate papers for news and social media attention according to Carbon Brief. The ocean heat content time series was also included in the World Meteorological Office State of the Climate 2021 and the Bulletin of the American Meteorological Society State of the Climate 2021 in the Oceans chapter/ocean heat content section (led by Greg Johnson, OAR/PMEL) as well as the NOAA Annual Climate Report 2021. The ocean absorbs about 90% of the Earth's Energy Imbalance (EEI)—difference between incoming solar radiation and outgoing longwave and reflected solar radiation at the top of the atmosphere.

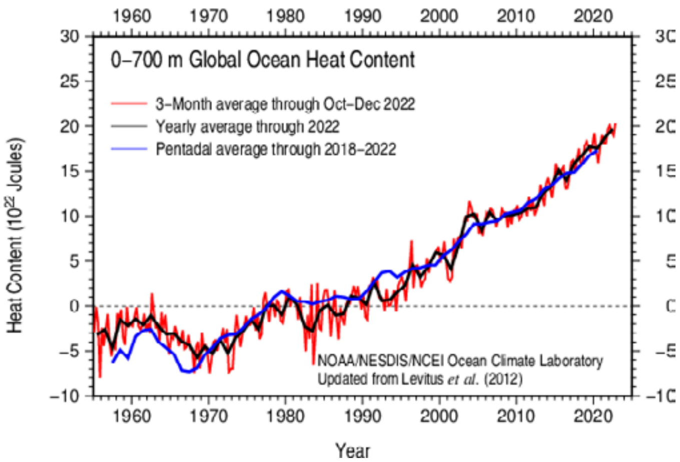


Figure 60. Ocean heat content time series 1955–2022.

The ocean provides a good quantification of EEI, essential for monitoring changes to the Earth's environment. All of the above reports note an increase in ocean heat content 2022 over 2021 despite the presence of a La Nina throughout the year. On a regional scale, Wang et al. (2023) the Gulf of Mexico ocean heat content was found to increase between 1950–2020 mainly through advection as opposed to direct surface warming. This work can be a basis for regional monitoring of Gulf of Mexico ocean heat content, an important component in hurricane intensification. Work on understanding the uncertainty in ocean heat content calculations continued with NESDIS representation at an International Space Studies Institute workshop on Challenges in Understanding the Global Water Energy Cycle and its Changes in Response to Greenhouse Gas Emissions. As part of this effort, and crucial to the possible extension of NCEI updates of ocean heat content to a monthly time frame, an international workshop is planned, the results of which will inform intended improvements in the NCEI time series calculation.

The NCEI time series of salinity anomalies are used in the State of the Climate report, and were also published in the Oceans chapter, subsurface salinity section led by Jim Reagan (NESDIS/NCEI). Changes in subsurface salinity are indicative of intensifying evaporation/precipitation patterns and other environmental changes. Figure 61 illustrates the zonally averaged salinity trends from 2005-2021 in each major ocean basin from Reagan et al. (2022). The Atlantic (Figure 61a) is primarily dominated by salinification with freshening localized to the Northern North Atlantic (>40°N), and the Pacific (Figure 61b) is primarily dominated by freshening in the near-surface (<50m). This may be indicative of an amplifying hydrological cycle.

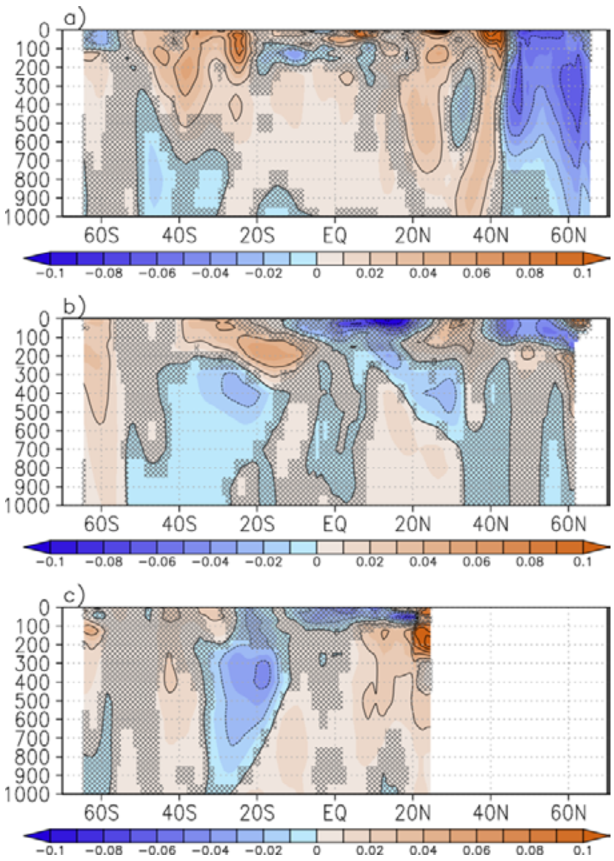


Figure 61. The linear trend of zonally-averaged salinity from 2005–2021 over the upper 1000m for the a) Atlantic, b) Pacific, and c) Indian basins. The salinity trend is per decade and computed using least squares regression. Areas that are stippled in dark gray are not significant at the 95% confidence interval (from Reagan et al. (2022)).

Steric sea level time series are utilized as a comparison with altimeter measurements to directly monitor sea level component changes, as long-term sea level change is affected by temperature change (thermosteric expansion) and salinity change (halosteric contraction).

The International Comprehensive Ocean Atmosphere Data Set

NOAA/NESDIS is the lead for the world collaboration project "The International Comprehensive Ocean Atmosphere Data Set" (ICOADS), which offers surface marine data spanning 1662-present. It contains observations from many different observing systems encompassing the evolution of measurement technology over hundreds of years. From historical ship observations to present-day autonomous systems, ICOADS is the most complete and heterogeneous collection of surface marine data worldwide. A new version of ICOADS, R3.0.2 (Liu et al., 2022), was released in 2022, for the first time combining data collections transmitted by the World Meteorological Organization (WMO) Global Telecommunication Systems (GTS) in both the Traditional Alphanumeric Codes (TAC) format and the Binary Universal Form for Representation of Meteorological Data (BUFR) format. The number of observations in R3.0.2 increased by nearly 1 million reports per month, and the coverage of buoy and ship sea surface temperatures (SSTs) on monthly 2° × 2° grids increased by 20%. The number of reported ECVs also increased in R3.0.2 (Figure 62). For example, observations of SST and sea level pressure (SLP) increased by around 30% and 20%, respectively, as compared to R3.0.1, and salinity is a new addition to the ICOADS NRT product in R3.0.2.

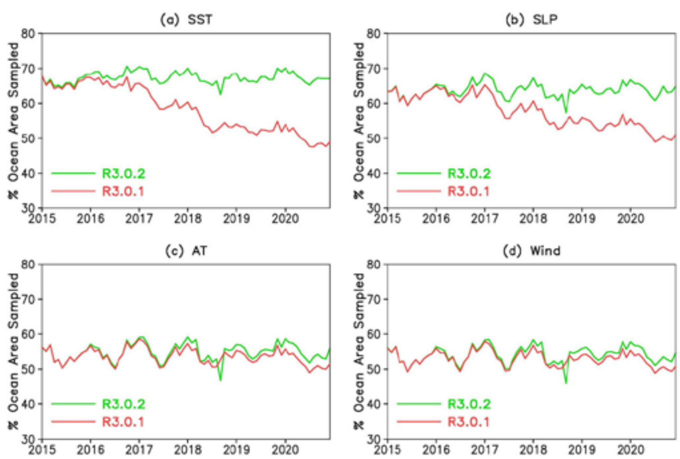


Figure 62. Monthly percentage of the ECV coverage from January 2015 to December 2020 for 2° ocean boxes. (a) Sea surface temperature, (b) sea level pressure, (c) air temperature, and (d) wind speed. R3.0.1 is the red line, and R3.0.2 is the green line.

ICOADS serves as a foundational dataset for NOAA higher level climate products, such as the centennial scale (1854–present) monthly Extended Reconstructed Sea Surface Temperature (ERSST), the in-situ and satellite observation blended Daily Optimum Interpolation

Sea Surface Temperature (dOISST), and the land and ocean surface combined NOAA Global Surface Temperature (NOAAGlobalTemp). In turn, these products have been used as input to the climate monitoring and assessment in NOAA, the Nation and worldwide.

BIOLOGY AND BIOGEOCHEMISTRY

NESDIS National Centers of Environmental Information (NCEI) archives a vast volume of global ocean biogeochemical measured open access data which has been collected over many decades, by many countries, institutions, and instruments. The oceanographic biochemical data include multiple organic and inorganic compounds, transient tracers, isotopes, plankton, gases, and other variables including Essential Ocean Variables (EOV). The data are acquired from multiple sources including the World Ocean Data Service for Oceanography hosted at NCEI and the global networks of National Oceanographic Data Centers under the International Oceanographic Data and Information Exchange (IODE) of the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

The World Ocean Database

The NESDIS NCEI WOD integrates and quality controls the archived historical and modern physical and biochemical global ocean data and makes it research-ready and FAIR-compliant for multiple purposes including climate variability. WOD biochemical variables with global coverage are objectively analyzed into gridded global surface to bottom ocean climatologies of known science quality for dissolved inorganic nutrients (phosphate, nitrate+nitrate, silicate) and dissolved oxygen as part of World Ocean Atlas (WOA) products (for example Figure 63). In addition, WOD biochemical data are objectively analyzed for global and regional decadal-scale trends in ocean deoxygenation and short-term coastal hypoxia regions. In addition, WOD includes world ocean plankton data useful for abundance studies.

NCEI's Ocean Carbon and Acidification Data System (OCADS) project identifies and archives ocean carbon and acidification-related data sets from the national and international oceanographic projects such as Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), Global OA Observing Network Data Explorer (GOA-ON), Ships of Opportunity Program (SOOP), Global Time-Series and Moorings Project and Coastal Carbon Data Project. OCADS has been involved in the creation of data synthesis products including Global Ocean Data Analysis Project (GLODAP), Surface Ocean Carbon Atlas (SOCAT) and Coastal Ocean Data Analysis Product in North America (CODAP-NA).

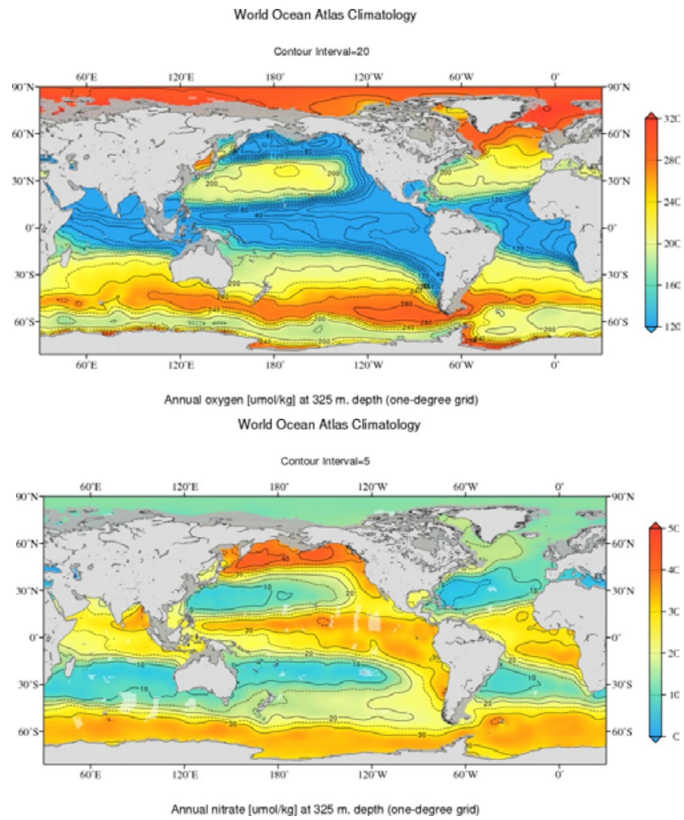


Figure 63. Top panel shows climatological mean dissolved oxygen distribution at 325m depth. Bottom panel shows climatological mean nitrate+nitrite distribution at 325m depth based on the WOA18.

Satellite Ocean Color

Satellite ocean color data are critical in ocean environment monitoring and ocean ecological and biological research. With multi-sensor merged and global gap-free ocean color data, NESDIS will continue to improve the surveillance and forecast of harmful algal blooms, water quality, and ocean biological productivity. Ocean color data derived from satellite measurements have been widely used for ocean environment monitoring of global oceans and inland lakes, as well as research and applications of ocean ecological, biological, and biogeochemical processes. Satellite ocean color products including normalized water-leaving radiance spectra (i.e., ocean color), chlorophyll-a (Chl-a) concentration, diffuse attenuation coefficient at 490 nm (Kd(490)), and suspended particulate matter (SPM) concentration. Satellite-derived Chl-a data provide global continuous measurements of the ocean phytoplankton (or biomass) concentration and are used for monitoring harmful algal blooms (HABs), ocean/water biological productivity, and other ocean/inland water environment processes. Kd(490) data have been used for monitoring ocean water quality and studying ocean processes such as thermal dynamics and phytoplankton photosynthesis. SPM data are useful to quantify water clarity over the world ocean and inland lakes, and have been used for modeling sediment transportation, tracing ocean circulation, and studying land-ocean flux and global carbon cycle.

Global Multi-sensor Merged Ocean Color Products

In NOAA STAR, global Level-3 ocean color products are being routinely produced from several satellite missions, including the VIIRS instruments onboard the Suomi NPP and NOAA-20, and the Ocean and Land Colour Instrument (OLCI) on the Sentinel-3A and Sentinel-3B satellites. In general, however, there are about 70% of missing pixels in a daily global image derived from VIIRS, and about 80% of missing pixels in a daily global OLCI image. Merging daily ocean color data from different sensors can significantly reduce the number of missing pixels. Currently, we routinely produce daily merged Chl-a, Kd(490), and SPM data from two sensors (VIIRS), three sensors (two VIIRS and one OLCI), and four sensors (two VIIRS's and two OLCI's). It is estimated that a two-sensor merged daily image has ~38% more valid pixels than a single VIIRS sensor, a three-sensor merged image has ~12% more valid pixels than a two-sensor image, and a four-sensor merged image has ~8% more valid pixels than a three-sensor image.

Global Daily Gap-free Ocean Color Products

To completely fill the gaps of missing pixels, the Data Interpolating Empirical Orthogonal Function (DINEOF) method has been used to reconstruct missing pixels in the multi-sensor merged images. Currently, global daily gap-free Chl-a, Kd(490), and SPM data are being generated in near-real-time based on two-sensor and three-sensor merged ocean color images, and these products are freely distributed through CoastWatch. The global gap-free data are in both 2-km (as shown in Figure 64) and 9-km spatial resolutions, and the large- and mesoscale ocean features like equatorial current, Gulf Stream, and mesoscale eddies can be revealed. Furthermore, using global 2-km gap-free ocean color products, some fine ocean features such as coastal eddies and filaments along the coastal region can be well resolved. It is also found that adding more data from additional satellite sensors to the merged images not only significantly increases the number of valid pixels, but also improves the quality of the derived global gap-free images. In particular, the coastal features are significantly enhanced in the three- or four-sensor-derived gap-free ocean color product images.

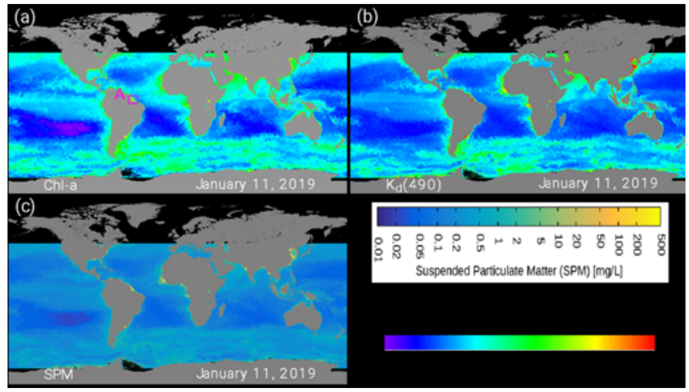


Figure 64. Global gap-free (a) Chl-a, (b) Kd(490), and (c) SPM images of 2-km spatial resolution on January 11, 2019.

Images and Data Links:
https://www.star.nesdis.noaa.gov/socd/mecb/color/index.php
https://coastwatch.noaa.gov/cwn/products/noaa-msl12-multi-sensor-dineof-global-gap-filled-products-chlorophyll-diffuse-attenuation.html

WATER POLLUTION

Marine debris is a persistent pollution problem that reaches throughout the entire ocean and Great Lakes. Our ocean and waterways are polluted with a wide variety of marine debris, ranging from tiny microplastics, smaller than 5 mm, to derelict fishing gear and abandoned vessels. Worldwide, hundreds of marine species have been negatively impacted by marine debris, which can harm or kill an animal when it is ingested or they become entangled and can threaten the habitats they depend on. Marine debris can also interfere with navigation safety and potentially pose a threat to human health.

Satellite data by its very nature can observe larger areas of the world, including the most remote parts of our oceans, often and repeatedly. This is a capacity not afforded by other methods on the same scale. NCEI has been working with the Marine Debris Program for the Marine Debris Clearinghouse, to collate, archive and provide a one-stop repository for info needed for marine debris study and has established itself as the primary location for data management.

Global Marine Microplastics Database And Map Portal

Marine microplastics have been found from the sea surface to the sediment covering the ocean floor. The increase in microplastics pollution is a growing concern, affecting coastal communities, marine ecosystems, marine life, human health, and the economy. NESDIS has initiated and now maintains a global marine microplastics database and map portal providing access to global surface marine microplastic data. The microplastics database aggregates datasets that have been archived with NCEI. The map portal allows scientists and managers to access and explore the concentrations of microplastics collected by other researchers around the world.

Space Weather

Space Weather refers to variable conditions on the Sun and in the space environment that can influence the performance and reliability of space-based and ground-based technological systems, as well as endanger life or health. Space Weather is characterized not by rain or snow, but by plasma winds and magnetic waves that move through space and impact the volume of space that surrounds planets in the form of a geomagnetic storm and accompanying radiation field. These storms can impact Earth's upper atmosphere and magnetic field affecting various technological systems including satellite-based positioning and navigation, satellite operations, high-frequency radio communications, and the electric power grid. Additionally, bursts of high energy radiation from our Sun can also temporarily modify Earth's upper atmosphere affecting communications and high-altitude radiation environments.

SUN, SOLAR WIND, HELIOSPHERE

The Sun is a major source of space weather events. It continually emits plasma from its outermost atmosphere, the corona. Our planet's atmosphere and magnetic field help protect us from the persistently present but ever-changing stream of radiation and charged particles emitted from the Sun, known as the solar wind. The solar wind permeates the region around the Sun, called the heliosphere, which defines the extent of the influence of the Sun. Eruptions of radiation and plasma from our dynamic Sun can disrupt our power grids and communications systems, as well as impact satellite operations and GPS navigation capabilities. Furthermore, astronauts and civilian space tourists operating outside our planet's protective atmosphere have to be very careful of exposure to extra radiation, which can cause a variety of health problems.

NESDIS develops and operates satellites and supporting infrastructure to collect information about solar phenomena before they reach Earth and cause detrimental effects on the Nation's critical technological systems. The raw data collected from NOAA satellites are turned into actionable information via calibrated data products that are used by NOAA's Space Weather Prediction Center (SWPC) which uses real-time data to generate space weather forecasts, alerts, and warnings to the public. Customers in the US and around the globe use this information to protect critical systems and reduce risks to personnel. These data are also used by the space weather research community across the globe to improve our fundamental understanding of space weather and advance our knowledge of the underlying science of the phenomena that cause space weather. The primary solar products developed at NESDIS today are derived from observations taken by the GOES-R SUVI extreme ultraviolet (EUV) imager, the GOES-R EXIS X-ray and EUV irradiance monitor. The launch of GOES-U will add a solar coronagraph to monitor the large rarified outer atmosphere of the Sun and image coronal mass ejections (CMEs).

SUVI Images the Extended Solar Corona to Trace Coronal Eruptions

The Large Angle and Spectrometric Coronagraph Experiment (LASCO) instrument on the joint NASA/European Space Agency (ESA) research mission—Solar and Heliospheric Observatory (SOHO)—is the only currently operating coronagraph and was launched in 1995. NOAA is currently exploring gap mitigation options if the LASCO instrument fails before the GOES-U coronagraph is operational. Coronagraph imagery is extremely important to space weather forecasting activities as it shows the speed and direction of eruptions, which allows forecasters to predict whether they will hit the Earth, and how much energy they contain. The gap mitigation studies involve Extended Coronal Imaging (ECI) campaigns with GOES-17 and GOES West where the normally sun-centered SUVI imager takes an ongoing series of images to extend the field of view of the imager. Figure 65 is an example image taken with GOES West SUVI in September 2022 before the satellite was declared operational. The clear signal in the two side panels shows how the Sun's corona extends well beyond the SUVI field of view. Work continues to be ongoing, but researchers at NCEI can use these image series to track and characterize solar eruptions away from the solar disk and compare them to similar measurements made by LASCO. The successful series of GOES ECI campaigns proves the ability to execute the concept, but the conclusion of the research will result in a clear understanding of whether ECI-like operation of one of the SUVI instruments would be a sufficient gap mitigation effort in the event that LASCO becomes unusable before the NOAA coronagraphs are operational.

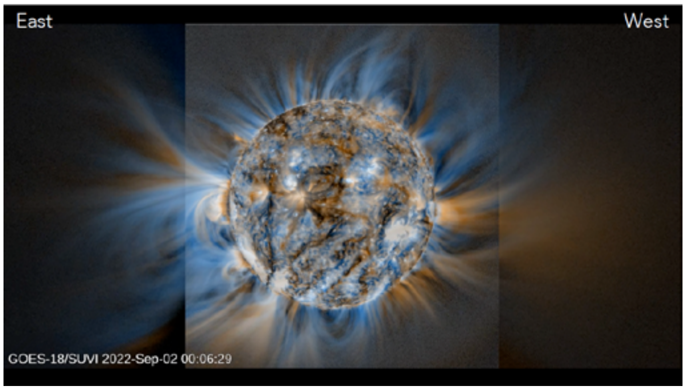


Figure 65. SUVI ECI image mosaic from GOES West. The central panel is the nominal SUVI pointing with additional side panels from two off points towards the east and west solar limbs. The image is a combination of the 171 Å channel in gold and the slightly hotter 195 Å channel in blue.

Recalibration of the XRS Irradiance Data Back to GOES-8

Some variation of the GOES X-Ray Sensor (XRS) has continuously observed solar X-ray irradiance for nearly 50 years. It is currently part of the EXIS instrument on the GOES-R series. The XRS measurements provide crucial solar and space weather information, including the standard X-ray intensity classification of solar flares. NCEI has been carefully reprocessing and recalibrating science-quality XRS datasets to create an authoritative data record going back to GOES-8 (1994). The new dataset corrects a long-standing scaling error to bring nearly three decades of data into balance. This detailed scientific analysis involved close coordination with X-ray irradiance communities across the globe and results in a significant difference to this climatological space weather record. The new data have implications in many fields including the long-standing solar coronal heating problem (which relies on flare statistics) and understanding of space weather impacts on our planet that are driven by solar X-ray radiation.

HELIOSPHERE

The Heliosphere is the volume of space dominated by plasma that originates from our Sun. This dynamic environment contains plasma and magnetic fields flowing outward from the sun as solar wind, and transient events like CMEs. Satellites in the heliosphere monitor this environment for potential earth impacts. The Lagrange-1 orbit is about 1.5 million kilometers away from the Earth towards the Sun, 'upstream' from us in the solar wind. NOAAs current Deep Space Climate Observatory (DSCOVR) satellite and future SWFO-L1 satellite are both in a Lagrange-1 orbit.

Compact Coronagraph Development

The Space Weather Follow On (SWFO) program continued development of two Compact Coronagraphs (CCORs); accommodating one CCOR instrument (called CCOR-1) on the GOES-U satellite and the other (designated as CCOR-2) on the SWFO L1 spacecraft. Integrating CCOR instruments on both the GOES-U platform in geostationary orbit and on a satellite at the Earth-Sun Lagrange Point 1 (L1) adds robustness resiliency—at a relatively low cost—for providing the most critical space weather data for forecasting CMEs, providing to deliver 1–4-day warnings of geomagnetic storm conditions. CME imagery is currently only available through the ESA/NASA SOHO research satellite, which was launched in 1995 and is projected to lose power in 2025.

Upstream solar wind measurements, which provide 15–60-minute notice for geomagnetic storm conditions, are provided by NOAA's Deep Space Climate Observatory (DSCOVR) satellite with NASA's Advanced Composition Explorer (ACE) satellite serving as a backup. DSCOVR, which was launched in 2015, and operating past its design life, is expected to operate until the mid-2020s. ACE, which was launched in 1997 and also operating well beyond its design life, is expected to run out of fuel in 2029.

In 2022, CCOR-1 was delivered to the GOES-R program for integration on the satellite after passing its Pre-Ship Review on January 21, 2022. As part of NOAA's SWFO program, CCOR-1 was developed at the U.S. Naval Research Laboratory in Washington, DC, and will reside on GOES-U's Solar Pointing Platform along with other space weather monitoring sensors. These include the SUVI and EXIS.

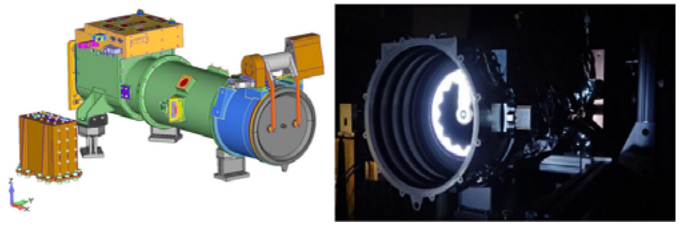


Figure 66. CCOR-1 design for the GOES U satellite (left); GOES-U CCOR-1 in optical test (right).

The CCOR-1 will monitor the outer layer of the sun's atmosphere, known as the solar corona, and will help detect and characterize CMEs. The critical space weather information collected by CCOR-1 on GOES-U (Figure 66) will ensure continuity of critical CME imagery to enable the NWS Space Weather Prediction Center to issue warnings 1–4 days prior to damaging geomagnetic storm conditions.

Modulation of Galactic Cosmic Rays in the Heliosphere

Galactic Cosmic Rays (GCRs) are charged particles with high energies. They originate from supernovae remnants within or outside of our galaxy. A better understanding of the modulation of the GCRs in the heliosphere is crucial as past variations of solar activity levels, including historical solar eruptions, are directly dependent upon GCR flux at Earth. The modulation of the GCRs in the heliosphere has four main physical mechanisms; (i) convection of particles caused by out-blowing solar wind from the Sun, (ii) drift of the GCR particles via curvatures and gradients in the heliospheric magnetic field (HMF), (iii) diffusion of the GCRs due to the fluctuations in the HMF, and (iv) adiabatic cooling in the expanding SW. Even though these mechanisms on the GCR modulation are well understood, their relative importance through solar cycles is still an ongoing research. In a study by Inceoglu et al 2022, aiming to demonstrate the value of using AI methods to investigate non-linear physical processes in Space Physics in the era of big data, NCEI space weather scientists utilized an AI method, the so-called Light Gradient Boosting Machines, to disentangle this nonlinear time-dependent problem using various data sets extending from the Sun to the Earth. Based on the study's results, the team concluded that the relative importance of these main drivers are very dynamic in time and in different timescales, and they are not static as was previously suggested.

Validation of DSCOVR Data Compared to Wind and ACE

NCEI and NWS scientists conducted a validation study of the NOAA DSCOVR space weather data archive against Wind and ACE satellite data (Loto'aniu et al 2022). All three of these satellites live about 1.5 million km from the Earth, facing towards the Sun and orbiting around a location known as the 1st L1. Solar wind observations at L1 are critical to NOAA space weather operations and the science community and DSCOVR was NOAA's first operational satellite launched to L1. Currently, this study is the only published statistical study of the NOAA DSCOVR space weather archive. An important result from the paper showed that correlation between the satellites is dependent on spacecraft separation, which has implications for space weather forecasting since single point L1 measurements, instead of orbits around L1, are used in forecasts and forecasting/nowcasting models.

Solar Sail Concept Work

NCEI, SWO, NASA, and NWS-SWPC scientists wrote a white paper submitted to the National Academy of Sciences Heliospheric Decadal Survey that describes a solar sail mission concept that could observe the solar wind along the Sun-Earth line closer to the Sun than the L1. Solar wind observations along the Sun-Earth line are critical to NOAA space weather operations, and better proximity to the Sun provides more lead time for space weather forecasting. However, satellites are restricted by the laws of physics to orbiting an object and therefore cannot maintain continuous measurements along the Sun-Earth line unless they use propulsion, or unless they take advantage of special gravitationally stable locations in space known as Lagrange points. However, solar sails can transform the energy from sunlight into propulsion to maintain their location for an extended period. This paper shows that solar sail technology could be used with a science payload of in-situ plasma and magnetic field sensors. This solar sail satellite could be located closer to the Sun than L1 and provide increased lead time for forecasting space weather that is moving towards Earth.

THERMOSPHERE

The thermosphere is the region of Earth's atmosphere that lies between ~90 and ~1000 km altitude. It is characterized by extremely high temperatures that reach up to 2800 degrees Fahrenheit (1810 Kelvin) during the day. The high temperatures are caused by the absorption of ultraviolet radiation from the Sun, which heats the upper atmosphere. Thermosphere is the region where a majority of LEO satellites operate, making them susceptible to changes in thermospheric density via variations in drag that cause them to lose altitude and reenter the atmosphere.

The Impact of Neutral Density Coverage from Satellite Accelerometers on an Assimilation System: An Observing System Simulation Experiment (OSSE)
The SWO team conducted OSSEs to examine the optimal set of observation parameters, such as measurement types, ranges, and locations, for thermospheric numerical modeling and situational awareness. The study relied on advanced data assimilation methods that have been developed in the last 25 years by the thermospheric-ionospheric research community and recently applied to the T-I coupled system. This OSSE evaluated the thermospheric density range and sensor locations in altitude, local time, and inclination that will produce the greatest increase in the specification accuracy of the density.

In this study, the team used Iterative Driver Estimation & Assimilation (IDEA), a technique known to work well when assimilating accelerometer-derived neutral mass densities into a physics-based model of the ionosphere-thermosphere system [see Sutton, 2018]. Using this technique, multiple DA scenarios can be simulated to examine the sensitivity of the DA technique to the coverage of the synthetic data sets. Each scenario will assimilate a distinct subset of the full constellation of Observing Satellites. Figure 67 shows the overall OSSE setup described above, while the following subsections provide additional detail on the individual components.

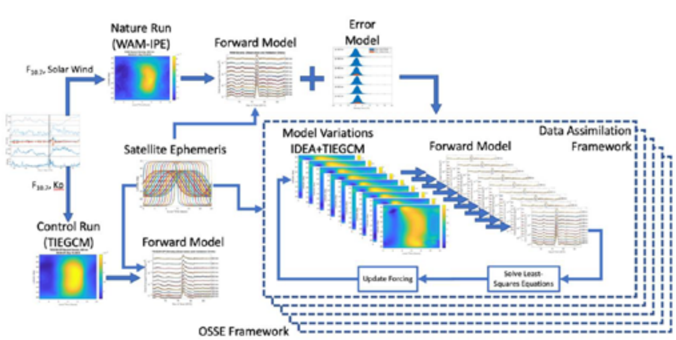


Figure 67. Flowchart of the OSSE framework. See text for a description of the OSSE process.

One of the key findings of this study was that it is important to have observations at altitudes near where highest fidelity in thermospheric density is needed. It would be important to target the altitudes of interest when designing an observing system. Assimilating data at 400 km skews the results towards the lower regime while assimilating observations at 550 km skews towards the upper regimes. For the purposes of monitoring satellite constellations such as Starlink, with operational altitudes around 550 km, this OSSE suggests that it could be important to have a sensor—or multiple sensors—near those altitudes. By the same token, it could also be valuable to determine the altitude regimes most critical for collision avoidance operations and place the appropriate instruments at those altitudes.

IONOSPHERE

The Ionosphere is part of Earth's upper atmosphere, between 80 and about 600 km where Extreme UltraViolet (EUV) and x-ray solar radiation ionizes the atoms and molecules thus creating a layer of electrons. The ionosphere is important because it reflects and modifies radio waves used for communication and navigation. Other phenomena such as energetic charged particles and cosmic rays also have an ionizing effect and can contribute to the ionosphere.

OSSE Probe of Ionospheric Electron Density Data From Future Radio Occultation Constellations
An OSSE study was recently conducted to evaluate the impact of ionospheric electron density (EDP) measurements from future radio occultation (RO) constellations, including their orbital parameters, on ionospheric specification accuracy compared to the accuracy achieved by the present observing system. The objective of this study is to determine the optimal set of observing system parameters, such as RO platform orbital parameters, sensor types, measurement types, spatiotemporal distributions, and measurement accuracy and precision, for ionospheric specification and nowcasting. The team used the Ensemble Adjustment Kalman Filter (EAKF) implemented by the Data Assimilation Research Testbed (DART) with the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) running as the background model. The EAKF uses data assimilation cycling, containing alternating forecasting steps and analysis steps. In forecast steps, states are propagated through TIEGCM dynamics to produce prior states. In analysis steps,

states are optimally updated with Bayesian statistics to produce posterior states. Nature run simulations were executed by the Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics (WAM-IPE) model [Akmaev, 2011, Maruyama et al., 2016] using the empirical magnetospheric and solar forcing specification driven with 1-minute solar wind and daily F10.7 values. Synthetic radio occultation observations were generated using the WAM-IPE nature-run simulations.

The OSSE study found that assimilation of EDP observations decreases the large model biases between WAM-IPE and TIEGCM near the equatorial ionization anomaly regions. There is consistent improvement seen for NmF2 RMSE at low- and high-latitudes for the quiet and storm periods as the constellation size is increased. The study also revealed that one source of poor analysis updates is the error in Abel inversion. Using the Abel inversion algorithm to derive the electron density profiles allows for better representation of the true errors and biases present in real observations. Where the assimilated EDP is biased from the true WAM-IPE electron density, these errors can manifest in poor analysis updates. The analysis step improves the TIEGCM posterior to better match the assimilated observation, however since the observed EDP is biased from the truth, the OSSE error increases. These errors are mainly due to breakdowns in the spherical-symmetry assumption. The team concluded that it is important to consider ionospheric asymmetry when retrieving EDPs from RO measurements prior to data assimilation.

COSMIC-2 Space Weather Product Cal/Val

In 2022, calibration and validation of the COSMIC-2 Tri-GNSS Radio Occultation System (TGRS) space weather products concluded. Products derived from high-rate scintillation data collected by the TGRS sensors onboard the six COSMIC-2 satellites were validated, the results briefed to stakeholders at the Department of Defense and NOAA SWPC, and distribution of the products for transition into operations commenced. Two algorithms for geolocating the ionospheric irregularity that caused the scintillation along the line of sight path of the GNSS shown in Figure 68(a), were developed independently by Boston College (BC) and the University Corporation for Atmospheric Research (UCAR). Both were validated against ionospheric bubble imagery from NASA's GOLD instrument and transitioned into the data processing chain at UCAR for distribution to users. The geolocated scintillation is used by a BC algorithm to identify the location of ionospheric depletions to generate TGRS bubble maps, shown in Figure 68(c). Additionally, the All-Clear product (Figure 68(c)) which identifies regions that are free of ionospheric irregularities based on the lack of high-rate scintillation data was distributed to the DoD and SWPC for use in their operations. The irregularities that cause fluctuations in the phase and amplitude of radio signals like the GNSS signals tracked by COSMIC-2 TGRS impact positioning, timing and navigation (PNT) systems and communications systems used extensively by aviation, agriculture, and multitude of other users. COSMIC-2 scintillation products provide valuable information about the locations of those potential impacts, or locations where performance is not expected to be impacted by the ionosphere as in the case of All-Clear, in the low latitudes where those irregularities are most likely to occur.

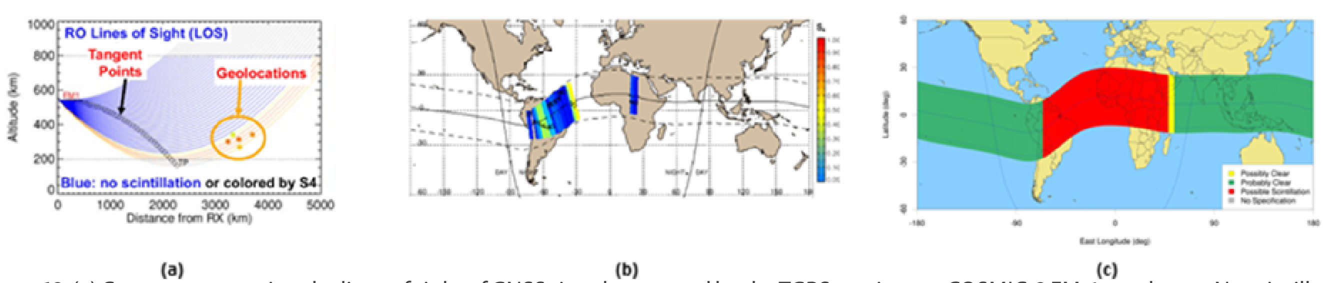


Figure 68. (a) Curves representing the lines of sight of GNSS signals captured by the TGRS receiver on COSMIC-2 FM-1 are shown. No scintillation was detected along the blue LOS curves, while those in yellow show the location of the irregularity that caused the scintillation. (b) A Bubble Map generated from TGRS data. The colored lines depict locations and extent of ionospheric bubbles identified by the algorithm. The colors correspond to the magnitude of the S4 index for the geolocated scintillation. (c) A map of the TGRS All-Clear product. The green regions represent locations where observed performance degradation are not likely to be caused by the ionosphere.

MAGNETOSPHERE

Earth's magnetosphere shields our planet from solar and cosmic radiation, like a giant force field. The shape of the magnetosphere changes according to the amount of solar wind bombarding it on the side facing the sun (Figure 69). If the magnetosphere were not in place, Earth would likely be uninhabitable. As the shield is hit by space weather, it deforms and transfers energy from the cosmic environment to regions inside it. This plays a key role in determining the effects of space weather—including geomagnetic storms that can damage power grids, impact GPS, and create communications challenges for airlines, mobile telephones, and more.

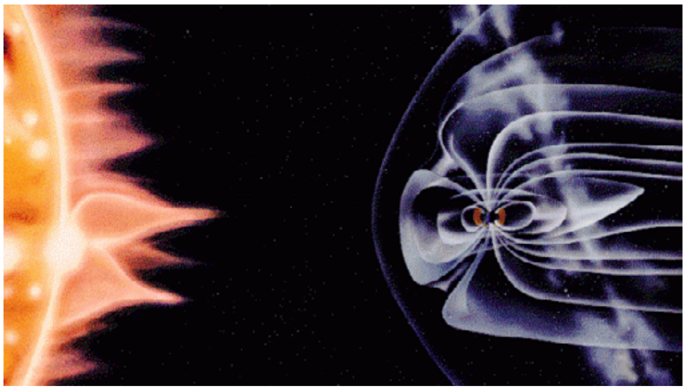


Figure 69. Illustration of solar wind impact on the shape and size of Earth's magnetic field.

Since 1975, each of NOAA's GOES satellites, located in Earth's geographic equatorial plane, approximately 6.6 Earth radii from the center of Earth, have carried magnetometers to monitor the geomagnetic field and its variations. The geomagnetic field measurements are important for interpreting GOES energetic particle measurements and for providing alerts to many customers, specifically for indicating the onset of a geomagnetic storm (known as a sudden storm commencement). GOES magnetometer data are also important in research, being among the most widely used spacecraft data by the national and international solar and space weather research community (see e.g. NASA Coordinated Data Analysis Web (CDAWeb) usage statistics). The data have often been used to support launch decisions for research-sounding rockets. The measurements can also be used to validate large-scale space environment models.

40 Years of Magnetospheric Proton Measurements are Correlated With Solar EUV Irradiation

Solar cycle prediction provides an approximation of the frequency of space weather storms of all types, from radio blackouts to geomagnetic storms and solar radiation storms. In Bregou et al 2022, NCEI scientists examined the inner zone proton radiation belt consisting of 10's to >100 MeV protons trapped in the Earth's magnetic field from 1980 to mid-2021 using measurements from four NOAA POES satellites. The study included plotting the maximum flux in the South Atlantic Anomaly[9] (SAA) for >70 MeV protons found using a Gaussian (independent of L-value) fit to the maximum flux (Figure 70). They found a long-term increase in measured proton flux over four ~11 years cycles of solar activity. This increase correlates with the current one-hundred-year minimum in solar activity known as the Gleissberg cycle. Inner zone proton flux is correlated with decreasing solar irradiance maxima at a wavelength of 10.7 cm, serving as a proxy for EUV input to Earth's atmosphere. The study also found that current peak proton flux, occurring at a longitude and latitude where the Earth's magnetic field is weaker, is at the highest levels seen since the beginning of observations in 1980. A model calculation of the inner zone proton flux is found to generally confirm the long-term trend. The scientists concluded that this trend observed over ~40 years accompanies an average decrease in solar EUV in comparison with previous solar maxima when EUV irradiation was higher as parametrized by F10.7. The reduced EUV at solar maximum reduces proton loss to the atmosphere, thus explaining the observed long-term increase in inner zone proton flux.

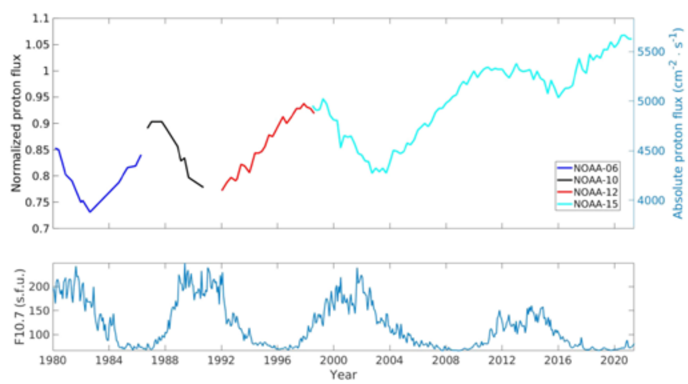


Figure 70. 3-month averaged peak flux for >70 MeV protons in the South Atlantic Anomaly is normalized to flux (= 1) at the beginning of 2010 (top) and plotted against 10.7 cm solar flux (F10.7, bottom) from 1980 to June 2021 to extend Figure 3 in Qin et al. (2014) which covered 1980 through 2009. Different colors are used to represent different POES satellites. Prior to the NOAA-15 data beginning in 1999, satellites measured >80 MeV proton flux. Qin et al. (2014) found good agreement between the >80 MeV and >70 MeV proton flux data and determined that no correction factor was necessary. (F10.7 flux in s.f.u. = 10–22W m–2 Hz –1).

9 A region where the inner zone proton flux is observed to increase at low altitude.

Modeling Earth's Magnetic Field Using Iridium Communications Satellites

Models of Earth's large-scale magnetic field are used to study dynamics in the planet's core, space weather, and local anomalies in Earth's crust, and are key components of ubiquitously used navigation and reference systems. For example, the World Magnetic Model (WMM) is a standard model used by the U.S. and U.K. governments as well as other international organizations. The WMM is used for navigation, altitude, and heading referencing systems, and is installed on practically every smartphone. Current state-of-the-art geomagnetic models are constructed from high-quality measurements made by dedicated research satellite missions. As the current generation of dedicated magnetic satellite missions approaches end-of-life, researchers from NCEI/NOAA investigated the possibility of using instrumentation on the Iridium satellite constellation to construct geomagnetic field models for navigation purposes (Califf et al 2022). The 66-satellite Iridium constellation is designed for communications; however, each satellite carries a vector fluxgate magnetometer for attitude determination and control. The NCEI researchers, working in collaboration with Iridium and Johns Hopkins Applied Physics Lab, processed Iridium data, constructed geomagnetic field models, and demonstrated that the resulting models were of sufficient quality to meet the error specifications of the WMM.

MagNet competition for forecasting geomagnetic variations from solar-wind data

Absolute directional information provided by the Earth's magnetic field is of primary importance for navigation and the pointing of technical devices such as antennas, satellites and smartphones. The NCEI/CIRES Geomagnetism team develops and distributes magnetic-field models of the Earth for the nation's civilian and defense navigational systems. To improve precision magnetic navigation information during times of heightened space weather, NCEI Innovates funded a competition to improve a machine learning (ML) model to predict a key Space Weather index using NOAA DSCOVR satellite solar-wind data, mitigating impacts on magnetic navigation. In partnership with the NASA Tournament Lab, the Geomagnetism team conducted a crowdsourcing challenge, "MagNet: Model the Geomagnetic Field". The challenge, implemented by DrivenData and HeroX, called on the global community of problem solvers and data scientists to develop better models to forecast changes in Earth's magnetic field disturbances. Specifically, the solvers are asked to forecast the disturbance-storm-time index (Dst) using the solar-wind measurements by NOAA's DSCOVR satellite and/or NASA's ACE satellite. The event garnered nearly 600 participants from 64 countries and 1200 model submissions. The top four prize-winners vastly outperformed the previously set benchmark model. An ensemble of top four models performs best of all. The top two models are currently being run in a real-time environment for transitioning into NCEI's High-Definition Geomagnetic Model—Real Time (HDGM-RT), which will significantly improve the ability to accurately predict Earth's Magnetic field during space weather events. This model is used by oil and drilling industries, the US government, and researchers. Additionally, the two top models were converted into online tutorials with the help of NOAA's Center for Artificial Intelligence (NCAI) for the benefit of the NOAA AI community. The lessons learned were captured in Learning Journeys and used to educate students at the 2022 Trustworthy Artificial Intelligence for Environmental Science Summer School (TAI4ES trust-a-thon).

Analytical

Analytical products synthesize geophysical infomation into highly processed datasets such as fused and blended analysis datasets, multi-mission time series, climate data records, written reports, and human interpretive analyses and assessments. Beyond numerical represetations of data, analytical products help us to monitor the environment for global changes and significant weather events. These products support national and international users responsible for environmental monitoring and weather forecasts.

The following are analytical themed areas organized according to product categories of the NESDIS portfolio for science data and information products and services.

Climate

"Earth's climate is now changing faster than at any point in the history of modern civilization, primarily as a result of human activities. The impacts of global climate change are already being felt in the United States and are projected to intensify in the future-but the severity of future impacts will depend largely on actions taken to reduce greenhouse gas emissions and to adapt to the changes that will occur." NCA4, 2018 NOAA satellites collect information about the land, oceans, and atmosphere that help us understand the Earth's long-term climate. They monitor weather patterns, greenhouse gases, vegetation health, the extent of sea and polar ice, flooding, ocean acidification, coral reef bleaching, desertification, wildlife migratory patterns, and many other environmental indicators. Improvements to satellite sensors, computing speed, and storage capacity have revolutionized the study of climate and are paving the way to learn even more for the future.

NCEI hosts and provides access to one of the most significant archives on earth, with comprehensive oceanic, atmospheric, and geophysical data. From the depths of the ocean to the surface of the sun and from million-year-old tree rings to near-real-time satellite images, NCEI is the nation's leading authority for environmental information.

NCEI's Climate Data Records (CDRs)—developed by applying modern data analysis methods to historical global satellite data—are robust, sustainable, and scientifically sound climate records that provide trustworthy information on how, where, and to what extent the land, oceans, atmosphere and ice sheets are changing. These datasets are thoroughly vetted time series measurements with the longevity, consistency, and continuity to assess and measure climate variability and change. CDRs can be used to manage natural resources and agriculture, measure environmental impacts on human health and community preparedness, and inform policy development and decision-making for other sectors and interest groups.

Artificial Neural Network Method Improves The NOAAGlobalTemp Product

NOAAGlobalTemp is NOAA's operational global surface temperature product, which consists of land surface air temperature (LSAT) and sea surface temperature (SST) and has been widely used in the Earth's climate assessment and monitoring. However, the reliability of spatial distributions of NOAAGlobalTemp was limited due to sparse observations in the remote areas like Antarctic, Arctic, and the Southern Ocean in the early time before the 1950s. To improve the spatial interpolation of monthly land surface air temperatures (LSATs) in NOAAGlobalTemp, a three-layer artificial neural network (ANN) system was developed (Huang et al. 2022). The ANN system was trained and validated by the LSATs from ERA5 (1950–2019). Independent validations show clear improvements of ANN over the original empirical orthogonal teleconnection (EOT) method: The global spatial correlation coefficient (SCC) increases by 16% and the global root-mean-square-difference (RMSD) decreases by 0.42°C during 1850–2020 (Figure 71). The improvements of SCCs and RMSDs are larger in the Southern Hemisphere (SH) than in the Northern Hemisphere (NH), and are larger before the 1950s and where observations are sparse.

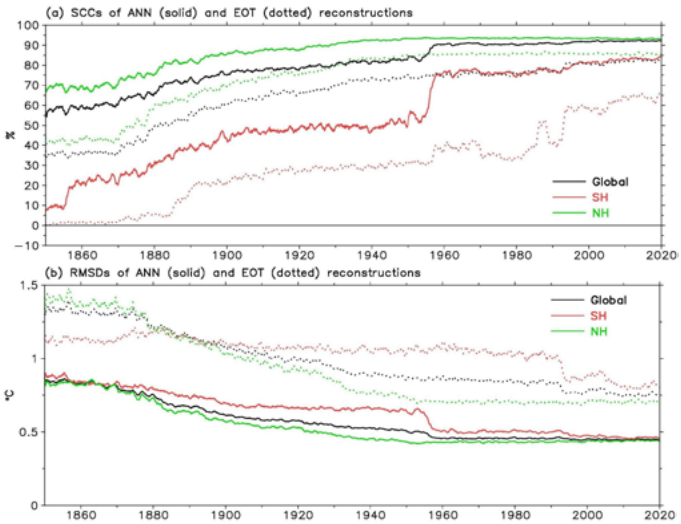


Figure 71. (a) SCCs and (b) RMSDs (ºC) of ANN (solid lines) and EOT (dotted lines) reconstructions against independent ERA5 20-member ensemble LSATs over the land surface in global (black), SH (red) and NH (green).

New Products For The Contiguous U.S. Added to the NOAA Monthly U.S. Climate Gridded Dataset

NCEI's new NOAA Monthly U.S. Climate Gridded Dataset nClimGrid-Daily product contains 5-km gridded fields with area averages of daily temperature and precipitation amounts for the contiguous United States—with data from January 1, 1951, to the present. In addition to the daily gridded data, NCEI is now producing climate normals of key variables, based on the same underlying 5-km grid.

Gridded datasets include several variables that can be used to understand the weather conditions on any given day, such as daily maximum and minimum temperatures, daily average temperatures, daily precipitation totals, month-to-date precipitation totals, and year-to-date precipitation totals.

To provide an indication of observation density, NCEI is also rolling out a supplemental product called nClimGrid-Daily-Auxiliary. This product provides daily gridded fields of the numbers of maximum temperature, minimum temperature, and precipitation observations within 30 miles of each grid point.

These all-new datasets will help place regional- to national-scale meteorological events into a long-term historical context in near-real-time (Figure 72).

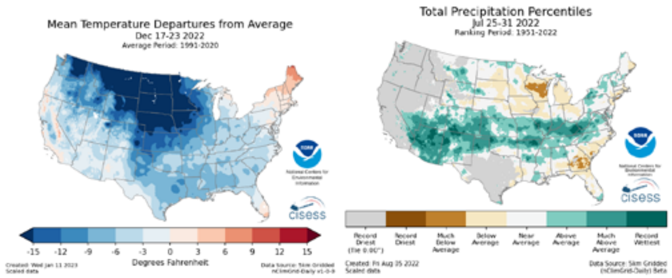


Figure 72. Temperatures for the week Dec 17–23, 2022, shown as departures (in degrees Fahrenheit) from the 1991–2020 average (left), July 25–31, 2022 U.S. Total Precipitation Percentiles map (right).

Updated World Ocean Atlas Climate Normals

A major update has begun for the World Ocean Atlas (WOA)—its initial release introduces temperature and salinity in 1991–2020 climate normals. This is a new standard for the widely used resource of ocean observations and compliments other recently released 1991–2020 global and U.S. Climate Normals. In the first stages of the update, NCEI, which produces the WOA, released new temperature and salinity normals (Figure 73).

The 1991–2020 temperature and salinity climate normals were derived from in situ ocean observations within NCEI's WOD. The new climate normals can be utilized in a variety of ways. Some of these include providing initial/boundary conditions for numerical models, a validation tool for satellite measurements, and for assessing changes in the ocean. This subset is part of a full update, from WOA18 to WOA23 to be released in late 2023.

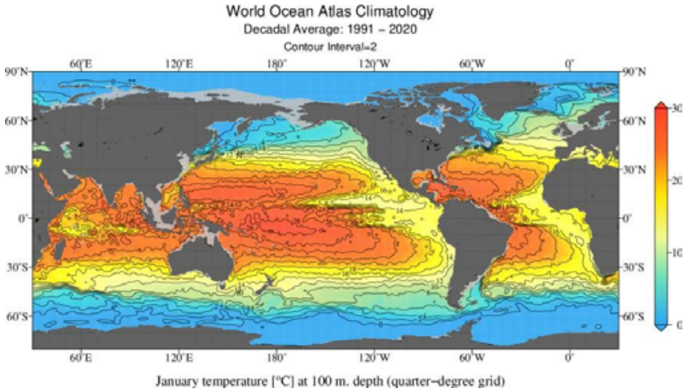


Figure 73. The WOA23 1991–2020 climate normal of January temperatures at 100m depth on a ¼-degree grid.

BAMS State of the Climate Report

The 32nd annual *State of the Climate* report (Figure 74), led by NCEI and published by the American Meteorological Society (AMS), provides a detailed update on global climate indicators, notable weather events, and some emerging impacts of change. It is informed by tens of thousands of measurements from datasets collected on land, water, ice, and in space. Analysis is provided for well over three dozen Essential Climate Variables, as defined by the Global Climate Observing System (GCOS). The report was authored this year by more than 530 scientists from 67 countries, including about 90 NOAA civil servants or affiliates from NESDIS, OAR, NWS, and NOS. This year's edition was the largest and most international authorship of the series. This report informs and is part of the data-gathering fabric that supports and supplements broader, less frequent efforts, like the National Climate Assessment and the Intergovernmental Panel on Climate Change (IPCC).

Broadly, in 2021 the climate system continued to undergo changes in recent years. Atmospheric concentrations of the dominant greenhouse gases carbon dioxide, methane, and nitrous oxide, along with global mean sea level and ocean heat content, all reached new annual highs, as has become typical. A La Niña event kept global average temperatures cooler than recent peaks, although still much higher than the average of the past 30 years. In fact, the last seven years (2015–21) were the seven warmest years on record. Drought coverage reached a new record extent in August, at 32% of the planet's land area.

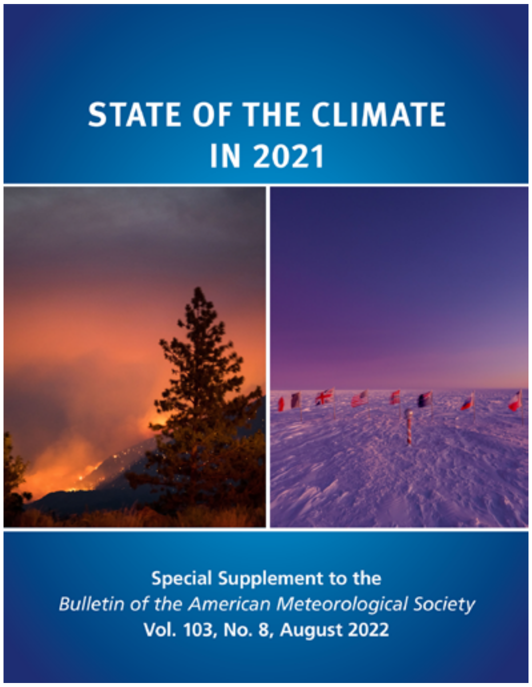


Figure 74. Cover of the 32nd issuance of the State of the Climate Report.

Applications of Climate Data Records (CDRs)

Operational long-term satellite CDRs (https://www.ncei.noaa.gov/products/climate-data-records) of NOAA/NESDIS for essential climate variables (ECVs) have been used for the studies of climate and environmental changes. For example, the Gridded Satellite (GridSat) B1 CDR has been used to inform food security decisions to manage global famine and aerosol CDR has been used to determine air quality changes associated with extremely hazardous scenarios, such as heavy smoke from wildfires and COVID-19 lockdowns. These CDRs have also been used to provide CEOS/CGMS CDR use cases (Use Cases for Climate Monitoring from Space—Climate Monitoring from Space—Joint CEOS/CGMS Working Group). The aerosol and cloud CDRs have been used to study the aerosol-cloud interaction for deep convective clouds from a climatological perspective (https://www.mdpi.com/2225-1154/10/11/167). Aerosol, cloud, SST, and precipitation CDRs have been used together to study the aerosol effect on Asian summer monsoon.

Weather

Each year, the United States averages some 10,000 thunderstorms, 5,000 floods, 1,300 tornadoes and 2 Atlantic hurricanes, as well as widespread droughts and wildfires. Weather, water and climate events cause an average of approximately 650 deaths and $15 billion in damage per year and are responsible for some 90 percent of all presidentially-declared disasters. About one-third of the U.S. economy—some $3 trillion—is sensitive to weather and climate.

NOAA satellites don't just help us monitor severe weather but also help us analyze weather patterns to predict when and where severe weather will strike. The NWS analyzes information from station-based, radar-based, and satellite-based observation systems in numerical weather models to predict the location and intensity of high-pressure and low-pressure systems, cold and warm fronts, and tropical weather systems like tropical storms and hurricanes. NCEI takes the data from these observation systems and compares it to historical databases in web-based State of the Climate monthly reports to put current weather and climate anomalies into historical perspective.

The weather in the U.S. and around the world during 2022 ran the gamut from normal temperature and precipitation patterns to extreme heat and cold, droughts and floods, and devastating tornadoes and hurricanes. Some of the extreme weather events entered the record books. The year began with extreme to exceptional drought in the West and southern Plains, and nearly half (46.3%) of the country (50 states and Puerto Rico) experiencing moderate to exceptional drought, according to the U.S. Drought Monitor (USDM). A heat wave in the southern Plains, that began in April and lasted well into the summer, led to the warmest April-July period in Texas since 1895. Texas also ranked fourth driest for April-July. Prior to this, the same dry conditions which plagued the southern Plains since the beginning of the year gave Texas the second driest January-July in the 128-year record. Unusually hot conditions extended into the Pacific Northwest during July, beginning with a heat wave that lasted through October. Idaho, Montana, Oregon, and Washington each had the warmest July-October on record. Dry conditions also occurred in the Pacific Northwest during this period, giving Washington the second driest July-September. Rain returned to the Four Corners states in June as the 2022 Southwest Monsoon kicked in. The eighth wettest June-October in Arizona and New Mexico shrank their drought areas from 98.5% to 46.8% over the period in Arizona and from 100% to 46.1% in New Mexico. A stalled frontal system brought historic rainfall to parts of central and eastern Missouri and eastern Kentucky in late July. Major flooding caused disruptions throughout the region, including loss of life. While much of the Pacific Northwest, Great Plains, and Mississippi Valley were parched in September, powerful cyclonic systems struck at the extreme ends of the country. Hurricane Fiona brought massive flooding to Puerto Rico, and Hurricane Ian made landfall in Florida as a strong Category 4 hurricane, resulting in major flooding, damage, and fatalities. Up north, the powerful remnants of Typhoon Merbok—the strongest storm to enter the Bering Sea during September in 70 years—produced widespread damage along Alaska's western coast after becoming entangled in a frontal system. Flash drought caused by the heat and dryness during the summer in America's breadbasket significantly impacted agricultural production. At the end of October, 35% of the nation's winter wheat crop and 48% of the nation's pasture and rangeland were in poor to very poor condition, and 64% of the nation's topsoil and 66% of the subsoil were short or very short of moisture (dry or very dry). According to the U.S. Department of Agriculture, the overall U.S. winter wheat condition was the worst it has been in the last 20 years for this early in the season. By October, months-long drought in the Arkansas-White-Red River basin and Missouri River basin had developed or expanded in the Ohio, Tennessee, and Upper Mississippi basins. These are all within or are tributaries of the broader Mississippi River basin. This convergence of drought resulted in the lowest water levels in a decade of the Mississippi River near Memphis, Tennessee and Vicksburg, Mississippi, closing off a vital channel to barge traffic at a crucial time of the year for the transport of crops from the nation's heartland. The first landfalling U.S. hurricane in November in nearly 40 years—Hurricane Nicole, struck Florida, flooded its eastern coast and knocked out power to thousands, some of which is still recovering from Ian's destruction. In late December, a historic cold wave swept across the Great Plains to the Eastern and Gulf of Mexico coasts, breaking hundreds of temperature records and straining the nation's heating systems. This weather system, and another in November, slammed parts of the Great Lakes region with several feet of snow, especially in favored lake effect areas. New York was especially hard hit. California had the driest January-October on record, due to sparse winter storms in the West, which left the mountains without much-needed snowpack; and a dry summer season. The dryness was compounded by record heat, with California having the warmest June-October and March-October in the 1895–2022 record. Precipitation in November and December reduced drought conditions in California, but fell short of eliminating several years of deficits, with November 2019-October 2022 ranking as the driest and third warmest such 36-month period on record for the state. The multi-year dryness extended across much of the West, with many reservoirs reaching record or near-record low lake levels at some point during 2022. Such was the case for Lake Powell and Lake Mead, which reached historically low levels and risked falling to "dead pool" status, where water level in the dams was so low it could no longer flow downstream and power the hydroelectric power stations. On September 1, the Great Salt Lake, the largest saltwater lake in the Americas and eighth largest in the world, recorded its lowest water level since records began in 1847. More than 66,000 wildfires burned over 7.5 million acres in the U.S. during 2022—these statistics are greater than the 10-year average and include the largest April wildfire in Alaska's history. By June 18, Alaska had exceeded the 1 million acres burned wildfire threshold—the earliest such occurrence in a year than any time in the last 32 years. By July and continuing into August, the state had experienced the seventh-largest wildfire season since 1950. An outbreak of numerous large wildfires in August and September accompanied the heat wave and drought in the Pacific Northwest.

NOAA and NASA satellites monitor drought across all of the continents of the world. The global precipitation, evapotranspiration, soil moisture, groundwater, and vegetative health tools created from this satellite data are presented in the Global Drought Information System's (GDIS) Global Drought Monitor housed at NCEI. The year began drier than normal across parts of southern Europe, with the Iberian Peninsula in the midst of a prolonged dry spell that had lasted for much of 2021. Drier-than-normal conditions developed across most of Europe during March 2022 and recurred across parts throughout the summer and fall. Temperatures were above normal across most to all of the continent in January and February, but extreme evapotranspiration, brought on by excessive heat from May to August, exacerbated the dry conditions. Above-normal temperatures returned in October and November. The combination of below-normal precipitation and hot conditions dried out soils, lowered streamflow and groundwater, and desiccated crops and other vegetation. Europe had the warmest February-August, June-November, and October-November, with January-November 2022 ranking as the second warmest such 11-month period in NCEI's 113-year global temperature record. In Australia, 2022 began with dry soils in the west. Drier- and warmer-than-normal conditions in austral fall (March-May) dried out soils in northern areas, but above-normal conditions during austral spring (September-November) reduced precipitation deficits and improved soil moisture conditions across most of the continent. By the end of 2022, Australia was the only continent not experiencing areas of severe drought. Drier- and warmer-than-normal conditions occurred in various parts of Asia at varying times during the year, but two regions stood out in terms of drought impact. Parts of Southwest Asia were dry during most months in 2022, with dry conditions during much of the last three years lowering groundwater levels and ravaging crops. In August, dry conditions in the southwestern parts of China prompted the country's first national drought alert of the year amid struggles with forest fires, and crops damaged by high temperatures and evapotranspiration. Drought shifted east during September, lowering soil moisture and groundwater levels in southeastern China where high evapotranspiration rates damaged crops; these conditions persisted through the fall. For the last three to four years, the Sahel region and much of East Africa were dry. The persistent dryness and high temperatures/evapotranspiration in 2022 depleted soil moisture, lowered groundwater, and desiccated vegetation. In East Africa, there were four consecutive failed rainy seasons, a climatic event not seen in at least 40 years, which left more than 23 million people in Ethiopia, Somalia, and Kenya facing severe hunger/famine. In South America, drought stretched from Peru and central and southern Brazil to the agricultural lands of Argentina, with 2022 marking the second year of dry conditions in many of these areas. Satellite-based data revealed low groundwater, dry soils, and poor vegetative health. Rain fell across some on the drought areas during some months of 2022, but fell short on erasing deficits that built up over 12 to 24 months. Temperatures were frequently above normal, enhancing evapotranspiration that added to the stress on crops in Argentina and Uruguay. North America endured its warmest July-October in NCEI's 1910-2022 historical record. The excessive heat increased evapotranspiration that ravaged crops in drought-stricken western and central areas of the U.S., the Prairies of Canada, and parts of Mexico. Areas of the U.S., including portions of the southern Prairies and much of the western U.S., have been in drought since the summer of 2020, but excessively dry conditions during July-October 2022 expanded drought across much of western Canada. And some areas, such as parts of the southwestern U.S. (the Four Corners states), have had drought since 2017. A very dry start to the 2022 wet season in Mexico expanded drought across the central and northern areas during the spring and early summer, before late summer and fall rain prompted contraction.

Helpful NOAA/NESDIS/NCEI Resources:
NCEI State of the Climate Monthly Web Reports
NCEI Climate At A Glance Tool
GDIS Global Drought Monitor

Global Drought Information System Enhancements
The Global Drought Information System (GDIS) displays current drought conditions globally utilizing high-resolution low-latency daily satellite-based and in situ-based products for drought monitoring. The GDIS was developed and is maintained leveraging resources from NOAA and partners utilizing the latest technology. The GDIS website contains an interactive map hosted within the NOAA GeoPlatform (ArcGIS Online) displaying data from Google Cloud Storage provided by the NOAA Open Data Dissemination program. Continental drought monitor products provided by North American (North American Drought Monitor) and European (European Drought Observatory's European Combined Drought Indicator) partners are incorporated into a Global Drought Monitor. In addition, there are currently 45 drought indices derived from precipitation, evapotranspiration, soil moisture and vegetation data presented at time scales ranging from one month to 72 months that show the current status of drought worldwide, along with a gridded population layer that is utilized to show how drought is impacting population centers. In 2022, the drought layers were reorganized into data type categories to enhance drought index utility, a global drought narrative feature was developed (to be updated monthly), and an agricultural layer was added to show how drought is affecting crop production worldwide.

A New Study Uses The U.S. Drought Monitor To Put Drought Into Historical Context
In a new groundbreaking study, NCEI scientists used the weekly U.S. Drought Monitor (USDM), one of the most holistic drought descriptors, to characterize drought in the U.S. Many other drought indices, though they are beneficial in specific circumstances, tell an incomplete story of drought. The USDM integrates these drought indices, as well as drought impacts, to provide a complete description of drought and is the de facto official drought monitoring product for the country. The study analyzes all drought events through 2019 in the 23-year record of the USDM and is one of the most complete of its kind, as well as being one of the first to analyze drought characteristics in Alaska, Hawaii, and Puerto Rico.

The results of the study show significant geographical differences in drought across the United States. Over the past twenty years, the western U.S. has seen fewer but longer-duration droughts than the eastern U.S., where droughts generally did not last as long but were more frequent. Drought also developed more slowly in the West, while "flash drought," or drought that develops or intensifies quickly due to both a lack of precipitation and high temperatures, was much more common in the South.

The study also notes that the most severe drought in the 20-year record analyzed was the 2012 drought, when more than 21% of the U.S. experienced its largest number of weeks at or above Extreme Drought (D3) conditions (Figure 75). The western U.S. has also not only spent more time in drought than the eastern U.S. but has also spent more time in Extreme Drought (D3) or greater.

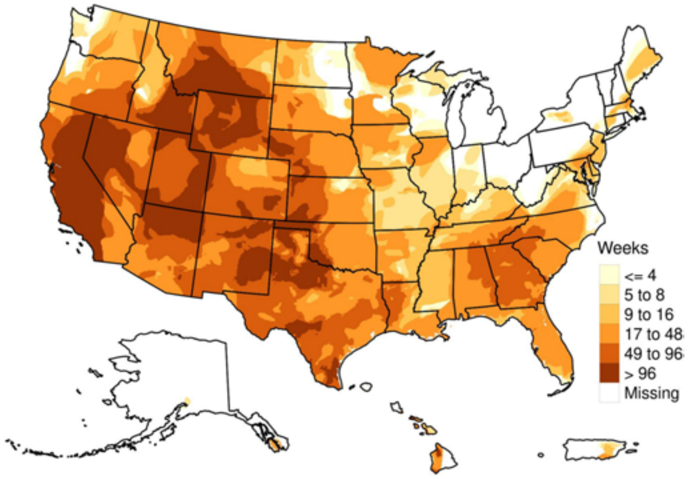


Figure 75. Map of U.S. showing the total number of drought weeks at or exceeding the Extreme Drought (D3) status from 2000 to 2019. Areas having no drought weeks exceeding D3 status were set to missing.

Monitoring Fire and Smoke Across North America
NOAA's Hazard Mapping System (HMS) uses satellite near real-time data to generate daily active fire and smoke mapping information for all North America, Hawaii, and the Caribbean (https://www.ospo.noaa.gov/Products/land/hms.html). The HMS system combines the power of automated satellite data processing algorithms with human analyst expertise to create unique fire and smoke datasets and help advance the development of fire emissions modeling applications and improve fire detection capabilities in the U.S. and among international partners. The HMS data routinely serves both fire management and scientific communities, while keeping the general public informed about potential hazards associated with major wildfires as well as prescribed burning and other seasonal fire activity. Thanks to its continuously expanding historical record, HMS provides a unique view of smoke occurrence over the Conterminous U.S. and Alaska (Figure 76), fostering numerous studies on air quality impacts across the region.

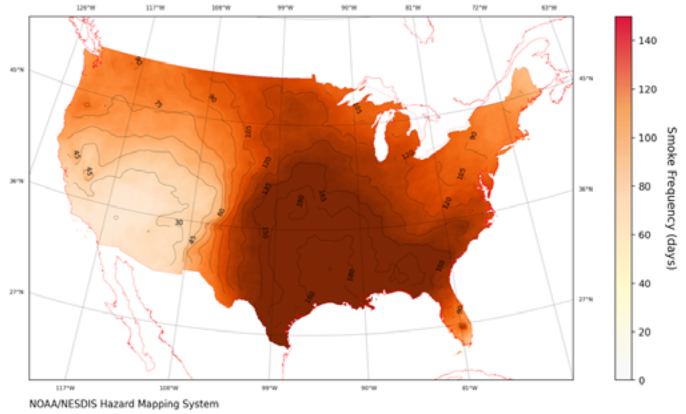


Figure 76. Annual map of the total number of days with smoke observed across the Conterminous U.S. using NOAA's Hazard Mapping System (HMS) data from 2022.

The Billion-Dollar Disaster and Risk Mapping Tools Now Include U.S. Census Tract Data
Expanding on FEMA's National Risk Index to provide an integrated view of U.S. hazard risk, exposure, and vulnerability across more than 100 combinations of weather and climate hazards, the NCEI enhanced their interactive Billion-Dollar Disaster and Risk Mapping tools by utilizing over 72,000 U.S. Census tracts—small subdivisions of counties that average about 4,000 inhabitants—data. Users can now visualize combined physical exposure, socioeconomic vulnerability, and markers of resilience to natural hazards on a finer scale than ever before.

View the interactive enhanced state and county-level maps on NOAA's Billion-Dollar Disasters website.

Oceans, Freshwater & Coasts

The ocean and large inland lakes play an integral role in many of the Earth's systems, including climate and weather. More than 50% of all species on Earth are found under the ocean and the ocean helps sustain human life above the water by providing 20% of the animal protein and 5% of the total protein in the human diet. In the United States alone, there are over 95,000 miles of shoreline with more than half of the U.S. population living within 50 miles of the coast.

To monitor it all, NOAA satellites are gathering data that can, among other things, monitor gases, temperature, and the biological components of the oceans. Different branches of NESDIS work with the Ocean Service to conduct research using satellite and in-situ observations to infer various oceanic, coastal, climatic, and marine weather processes.

Marine Scientific Research Data Collected by International Scientists in U.S. Waters: NCEI Dedicates a Data Portal

As the designated repository for all data collected under the Marine Scientific Research program (MSR), NCEI released the Marine Scientific Research Data website. This site allows public discovery and access to data collected by international partners authorized by the U.S. Department of State to conduct MSR in waters subject to U.S. jurisdiction. This data includes oceanographic measurements, visual observations of marine wildlife, chemical measurements, and marine geophysical data, among others.

NOAA, The U.S. Navy, and Partners Launched the Sanctuary Soundscape Monitoring Project Portal to Listen and Learn About Underwater Sounds

To better understand underwater sound within National Marine Sanctuaries, NOAA and the U.S. Navy co-led the Sanctuary Soundscape Monitoring Project, SanctSound. SanctSound assesses sounds produced by marine animals, physical processes like wind and waves, and human activities. This information helps NOAA and the Navy measure sound levels and baseline acoustic conditions in sanctuaries.

From fall 2018 through spring 2022, the agencies worked with numerous scientific partners to study sound within seven National Marine Sanctuaries and one Marine National Monument, in waters off Hawaii and the East and West coasts of the continental United States.

SanctSound has collected close to 300 terabytes of data. The new data gathered by SanctSound will join information gained by listening to the other types of observations made in the National Marine Sanctuary System, including satellites, scuba and visual surveys, and research expeditions. A primary goal of SanctSound is to allow people to easily explore and access much of that data and to showcase the types of information that sound can provide to help us understand and protect our ocean and its inhabitants.

The project's data can be discovered, filtered, and accessed through the NCEI Passive Acoustic Data Archive web-based map viewer and immediately downloaded from Google Cloud Platform thanks to the NOAA Big Data Program. Additionally, the new interactive data portal introduces the project to users from a wide variety of backgrounds through guided questions like why and how did we listen, where and when did we listen, what did we measure, what did we hear, what did we learn, and who we are.

Monitoring for Oil Spills in US Waters

The Satellite Analysis Branch uses a broad variety of public and commercial satellite imagery and many ancillary datasets to monitor US waters for oil spills 24 x 7. In 2022, 296 reports (see, for example, Figure 77) were issued to the public, National Ocean Service, Coast Guard, Dept of the Interior and Dept of Defense personnel, state responding agencies, and many others and these can be found at: https://www.ospo.noaa.gov/Products/ocean/marinepollution/

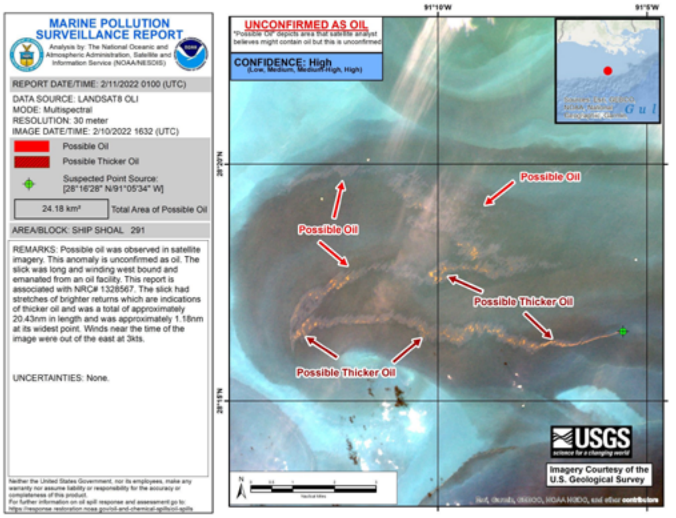


Figure 77. The image above is a report notifying responders of an oil leak from an abandoned oil well in the Gulf of Mexico.

Newest Version Of The Surface Ocean Carbon Atlas Released

The newest version of the Surface Ocean Carbon Atlas database, known as SOCATv2022, is now available from NCEI. This updates a synthesis activity for quality-controlled, surface ocean CO_2 observations by the international marine carbon research community which provides key information for the quantification of the ocean carbon sink and ocean acidification as well as for the evaluation of ocean biogeochemical models. SOCATv2022 has quality-controlled in situ surface ocean fugacity of CO2 measurements made on ships, moorings, autonomous and drifting surface platforms. Fugacity of CO2 (fCO2) is a type of quality control that corrects the observations for pressure differentials due to temperature.

SOCAT is used for quantification of ocean CO2 uptake and is the cornerstone of the Global Carbon Budget 2021. It is also used for evaluation of climate models and sensor data. NCEI provides access to the SOCATv2022 database through the NCEI Ocean Carbon Data System (OCADS). The OCADS collection is an ocean carbon data repository created to support regional to global ocean carbon cycling and ocean acidification research.

Free, Open and Easy Access to Suite of Products and Services

“Increasing access to scientific data and research findings generated by Federal agencies or resulting from Federally funded research is a U.S. policy priority.” OSTP, Executive Summary, 2016

A key goal of NESDIS science is to improve the use of our data products and information. We utilize several methods to reach this goal, including user engagement activities; making our outputs shareable (e.g. through repositories, archives, testbeds); and open knowledge via free, open and easy access to the NOAA suite of products and services.

The following are some examples:

CoastWatch
NOAA CoastWatch (https://coastwatch.noaa.gov/cwn/index.html) is a program to help people find, choose, access, and use observations from satellites for ocean, coastal and inland water applications that inform and benefit society. Initially serving customers Sea Surface Temperature (SST) data for the East Coast from POES/AVHRR instruments, CoastWatch has now expanded to providing users moderate assurance service of a variety of environmental data (i.e. SST, ocean color, winds, etc.) and value-added products and services from many NOAA and non-NOAA satellite platforms covering the globe, including the entire U.S. EEZ coastal waters, including Hawaii and Alaska, global ocean and polar (high latitude) products. Figure 78 is a screenshot of the CoastWatch Data Portal.

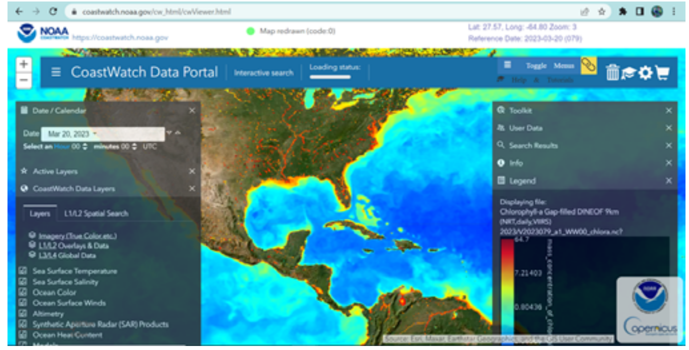


Figure 78. Screenshot of CoastWatch Data Portal.

PolarWatch
PolarWatch (https://polarwatch.noaa.gov/about/) is an extension of the CoastWatch program that enables data discovery, easy access, and broader usage of high-latitude satellite data products.

NOAA One Stop
An NCEI web portal (https://data.noaa.gov/onestop/) that was designed to broaden access to NOAA’s environmental data.

Looking Forward

Today's investments in NOAA's next-generation satellites and systems, data infrastructure, and services will allow us to make the observations needed to monitor global climate change and its impacts throughout our atmosphere, land, oceans, and coasts, and more completely deliver the NOAA mission.

GOES-U is scheduled to launch in 2024 as the final satellite in the GOES-R series, and GeoXO—the follow-on geostationary program—will launch its first satellite in the early 2030s. GOES-R satellites provide data every five minutes for hurricane, severe storm, and wildfire applications, providing timely and critical data for NOAA's weather forecasters.

NESDIS recently released a Request for Proposal for its second purchase of space-based commercial radio occultation data for use in NOAA's operational weather forecasts and awarded three Commercial Weather Data Pilot space weather contracts. We have also awarded Phase A study contracts for the GeoXO Imager, Hyperspectral Sounder, GLM, and Ocean Color instruments. At the time of writing this report, NASA, on behalf of NOAA, selected L3Harris Technologies Inc. of Fort Wayne, Indiana, to develop the imager.

Acquisition for NOAA's Polar Weather Satellites continues as well. The JPSS provides global observations that serve as the backbone of both short- and long-term forecasts, including those that help predict and prepare for severe weather events. The five-satellite fleet includes the currently-flying NOAA/NASA Suomi NPP satellite, NOAA-20, NOAA-21, and the scheduled JPSS-3 and JPSS-4 missions, which are planned to launch in 2028 and 2032 respectively.

Space weather initiatives remain a key priority. NESDIS has worked to ensure that the Space Weather Follow-On development schedule is timed to take advantage of a launch via rideshare on a NASA Interstellar Mapping and Acceleration Probe mission in 2025. On behalf of NOAA, NASA released a Sources Sought notice for spacecraft, instruments, and services for the Space Weather Next Lagrange 1 Series. These space weather observations will continue to provide critical data to the NWS SWPC, helping to protect grid infrastructure, communications and navigation, and national security.

INNOVATION

The NESDIS mission requires that the demands of providing better information to the world about our changing climate are met. Doing so requires listening to private sector, academia and agency partners as well as the communities NESDIS wants to help, to best identify the science and service innovations that will address their needs. That is why NESDIS is refocusing its requirements management processes to include active User Engagement, and why NOAA's Earth Systems Integration Board has endorsed a Service Delivery model that embraces customer engagement as a core competency. NESDIS will also ensure to align innovation priorities and plans to the societal challenges and outcomes as identified in NOAA's FY 2023–2027 Weather, Water, and Climate Strategy.

Science innovation extends both NESDIS baseline capabilities and user capabilities beyond original requirements and additionally focuses on fundamentally new capabilities. It encompasses "out-of-the-box" ideas and concepts not yet fully developed or demonstrated. Innovation projects influence future NOAA operations, including better understanding the utility of satellite data for emerging needs. The NESDIS Satellite Proving Ground (SPG), established in 2022 and one of twelve NOAA Testbeds and Proving Grounds, supports user demonstration by stimulating interactions between technical experts and key users and stakeholders. NESDIS is currently working to plan the inaugural FY 2024 SPG Call for Proposals, which is to be conducted based on the rolling Five-Year Science Innovation/User Readiness Roadmap, where peer-reviewed projects are selected, and funded projects will lead to innovative applications and identification of new capabilities.

NEXT GENERATION—GEOXO

The GOES-R Series (GOES East [-16], -17, West [-18] and U) is expected to last through 2036, with the launch of the final satellite in the series scheduled in 2024. Starting in the early 2030s, NESDIS plans to debut its next-generation Geostationary Extended Observations (GeoXO) satellite system to expand observations of Earth that the GOES-R Series currently provides from geostationary orbit. The information GeoXO supplies will address emerging environmental issues and challenges regarding weather, the ocean, and the climate that threaten the security and well-being of everyone in the Western Hemisphere.

New technology and scientific advancements will improve observations for weather forecasting and provide new ocean and atmospheric measurements, and data from GeoXO will contribute to weather forecast models and drive short-term weather forecasts and severe weather warnings. GeoXO will also detect and monitor environmental hazards like wildfires, smoke, dust, volcanic ash, drought, and flooding, and provide advanced warning to decision-makers.

NOAA currently flies sounders on polar-orbiting satellites. Notwithstanding that polar-orbiting satellites view most locations on Earth twice a day; once in daylight and once at night—except for the poles which receive frequent coverage, they cannot provide the nearly constant eye of geostationary spacecraft. GeoXO will feature new and enhanced technologies including a hyperspectral infrared sounding instrument, or GeoXO Sounder (GXS); a single-channel, near-infrared optical detector, the GeoXO Lightning Mapper (LMX), which will continue the critical observations provided by the GOES-R Series GLM and potentially improve its resolution; an Atmospheric Composition instrument (ACX); a hyperspectral, ultraviolet through near-infrared passive imaging radiometer that analyzes ocean data, which will be known as GeoXO Ocean Color (OCX) instrument; and a multi-channel passive imaging radiometer called GeoXO Imager (GXI). These instruments will enable nearly continuous observations of features such as wildfires, smoke, and dust. These advanced capabilities will help address our changing planet and the evolving needs of NOAA's data users.

To learn more about GeoXO, visit NESDIS.NOAA.gov/next-generation/GeoXO

NEXT GENERATION—NEON

NOAA has a history of successfully operating environmental satellites in low-Earth orbit (LEO) for more than 50 years. Low and medium Earth observations are critical for weather forecasting, environmental observation, climate monitoring and public safety, with satellites from NOAA, NASA and international partners contributing to more than a half-century of unbroken climate data records. LEO satellites are the backbone of global long-range weather forecasting models, supplying more than 80 percent of the numerical weather prediction model data used for 3 to 7-day forecasts, as well as detecting and monitoring hazards such as fires, droughts, floods, poor air quality, coral bleaching events, unhealthy coastal waters and others.

NOAA's Near Earth Orbit Network (NEON) Program will supplement and eventually replace the Joint Polar Satellite System (JPSS), ushering in a new paradigm for NOAA to continue to provide for these environmental measurements to support a wide variety of atmospheric, terrestrial, marine and polar observations. JPSS will continue to operate its series of polar orbiting satellites through the late 2030s. NEON will lay the groundwork for the next generation of LEO satellites long before the final JPSS launch takes place, providing a new approach to developing the next generation global environmental satellite system by launching small to medium-sized satellites with Earth-observing instruments more frequently.

To learn more about NEON, visit NESDIS.NOAA.gov/next-generation/NEON

SPACE WEATHER MONITORING WILL BE CRUCIAL IN THE COMING YEARS

NESDIS not only provides critical weather and environmental information to the nation, the agency also helps other space-based organizations. In a few years, the sun will be at its most active during the current 11-year solar cycle. When it reaches this "solar maximum," solar eruptions, CMEs, and geomagnetic storms will be more frequent and more powerful. These manifestations of space weather will put some satellites at increased risk.

NESDIS partners at NASA and the European Space Agency are developing additional new capabilities which the NOAA SWPC will use to provide additional and more accurate space weather forecasts. NOAA's Space Weather Follow-On (SWFO) L1 mission development schedule is timed to take advantage of a launch via rideshare on a NASA Interstellar Mapping and

Acceleration Probe mission in 2025 and services for the Space Weather Next Lagrange 1 Series. In addition, GOES-U (planned to launch in April 2024) will include the Compact Coronagraph to provide improved observations.

Some of the impacts of space weather were observed in February 2022 when a SpaceX Falcon 9 rocket launched 49 of its Starlink satellites to low Earth orbit from the Kennedy Space Center, just a short distance from where the GOES-T satellite launched. While the satellites maneuvered to raise their orbit after separation from the Falcon 9, the Earth was experiencing the effects of a fairly routine geomagnetic storm. Charged particles from the solar storm heated the earth's atmosphere, increasing its density of the atmosphere and the atmospheric drag on the satellites, and disrupting the critical early orbit checkout and orbit raising operations. Ultimately most of the fleet burned up in the atmosphere, which resulted in costly hardware losses.

Multiple NOAA and partner satellites had detected a coronal mass ejection from the sun and its progress through the solar system to the Earth, and the SWPC expected the storm to affect the Earth's atmosphere on Feb. 3–4. In fact, many observations the SWPC used for this space weather event came from instruments onboard NOAA's GOES-R satellites, GOES East (-16) and GOES-17: the SUVI and EXIS. Still, a lot remains to be learned about the precise, hour-by-hour response of the Earth's atmosphere to solar storms of this type.

The SpaceX Starlink incident demonstrates the value of the agency's existing ability to measure space weather, but it also demonstrates the need for enhanced measurements. GOES-18 (-West), launched in March 2022, will continue these observations.

DIGITAL TWIN

NESDIS is exploring leveraging Digital Twin (DT) technology and the underlying AI/ML techniques, to explore how this could benefit the agency's ground processing of satellite data in the future. Three projects have been initiated with private sector companies (Lockheed/Martin and NVIDIA, STC and Orion), to pursue a DT demonstration. More specifically, this DT approach is envisioned to be a pathfinder for the agency's next-generation ground architecture, and enable enhancements in processing, monitoring, quality-control, consolidating, fusing, and assimilating environment observations and streamlining the satellite data ground processing and dissemination to users and applications. The Earth Observations Digital Twin (EO-DT) system sought in NESDIS is an integrated Earth system replica of the Earth environment with multiscale, multi-variables features, integrating a large set of observing systems and environment analysis systems. It dynamically integrates Earth system data and observations (especially satellite data and ground-based data) and relies on trustworthy and responsible artificial intelligence tools, both Machine Learning (ML) and Computer Vision (CV).

NOAA CENTER FOR ARTIFICIAL INTELLIGENCE (NCAI)

Artificial intelligence is one of six key Science & Technology (S&T) Focus Areas that will advance NOAA's mission success. Cloud computing and data are two additional focus areas. The strategies for each focus area are designed to more fully accelerate advances and serve as force multipliers to solve tough problems and set the course to strengthen NOAA's S&T path for the coming decades. NCAI will serve as a central repository for AI-ready data, software, and interactive training materials. NCAI facilitates the development of collaborations and partnerships on AI efforts of importance to NOAA through its Community of Practice, annual workshops and seminars. NCAI will enable NOAA communication activities with interagency, academic, and industry partnerships to increase awareness of NOAA R&D to utilize AI applications to improve organizational and operational efficiencies. These activities are crucial to realizing improvements to the utility, quality, and timeliness of actionable information products and services for societal benefits.

References

Anheuser, J., Y. Liu, and J.R. Key. (2022). A simple model for daily basin-wide thermodynamic sea ice thickness growth retrieval, The Cryosphere, 16, 4403–4421. https://doi.org/10.5194/tc-16-4403-2022.

Anheuser, J., Y. Liu, and J.R. Key. (2023). A climatology of thermodynamic vs. dynamic Arctic wintertime sea ice thickness effects during the CryoSat-2 era, The Cryosphere, [preprint], in review. https://doi.org/10.5194/tc-2022-218.

Bates, J. J., J. L. Privette, E. J. Kearns, W. Glance, and X.-P. T. Zhao. (2016). Sustained production of multi-decadal climate records—Lessons from the NOAA Climate Data Record Program. *Bulletin of the American Meteorological Society,* 9. https://doi.org/10.1175/BAMS-D-15-00015.1.

Bratburd, J., P. Gupta, S. Kondragunta, H. Zhang, B. H. Henderson, P. Dickerson, A. Sayeed, Y. Liu, J. Mao, D. Pruthi, K. Gudipudi, J. E. White, R. Wyatt, A. J. Soja, R. Levy, R. V. Martin, S. A. Christopher, and N. R. Pavlovic, Incorporating Satellite Data Updates into AirNow, *EM Plus,* June 2022.

Bregou, E. J., Hudson, M. K., Kress, B. T., Qin, M., & Selesnick, R. S., Gleissberg Cycle Dependence of Inner Zone Proton Flux. (2022). Volume 20, Issue 7, *Space Weather.* https://doi.org/10.1029/2022SW003072.

Califf, S., Alken, P., Chulliat, A., Anderson, B., Rock, K., Vines, S., Barnes, R. and Liou, K. (2022). Investigation of geomagnetic reference models based on the Iridium constellation. *Earth, Planets and Space,* 74(1), pp.1–21. https://doi.org/10.1186/s40623-022-01574-w.

Carr, J., D. Wu, J. Daniels, M. Friberg, W. Bresky, and H. Madani. (2020). GEO-GEO Stereo-Tracking of Atmospheric Motion Vectors (AMVs) from the Geostationary Ring. *Remote Sensing,* 12, 3779. https://doi.org/10.3390/rs12223779.

Carr, J.L.; Daniels, J.; Wu, D.L.; Bresky, W.; Tan, B. (2022). A Demonstration of Three-Satellite Stereo Winds. Remote Sensing, 2022, 14, 5290. https://doi.org/10.3390/rs14215290.

Cintineo, J. L., Pavolonis, M. J., & Sieglaff, J. M. (2022). ProbSevere LightningCast: A Deep-Learning Model for Satellite-Based Lightning Nowcasting, *Weather and Forecasting,* 37(7), 1239–1257. https://doi.org/10.1175/WAF-D-22-0019.1.

Fang L, Zhan X, Kalluri S, Yu P, Hain C, Anderson M, Laszlo I. Application of a Machine Learning Algorithm in Generating an Evapotranspiration Data Product From Coupled Thermal Infrared and Microwave Satellite Observations. (2022). *Front Big Data.* 5:768676. https://doi.org/10.3389/fdata.2022.768676.

G. Gutman and A. Ignatov. (1998). The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models, *International Journal of Remote Sensing,* 19:8, 1533–1543. https://doi.org/10.1080/014311698215333.

Huang, B., X. Yin, M. J. Menne, R. Vose, and H. Zhang. (2022). Improvements to the Land Surface Air Temperature Reconstruction in NOAAGlobalTemp: An Artificial Neural Network Approach. *Artif. Intell. Earth Syst.,* 1, e220032, https://doi.org/10.1175/AIES-D-22-0032.1.

Huang, B., Z. Wang, X. Yin, A. Arguez, G. Graham, C. Liu, T. Smith, H.-M. Zhang. (2021). Prolonged Marine Heatwaves in the Arctic: 1982–2020. Geophys. Res. Lett., 48, e2021GL095590, https://doi.org/10.1029/2021GL095590.

Inceoglu, F., Pacini, A.A. & Loto'aniu, P.T.M. (2022). Utilizing AI to unveil the nonlinear interplay of convection, drift, and diffusion on galactic cosmic ray modulation in the inner heliosphere. *Sci Rep* 12, 20712. https://doi.org/10.1038/s41598-022-25277-0.

James, K. A., Stensrud, D. J., and Yussouf, N. (2009). Value of Real-Time Vegetation Fraction to Forecasts of Severe Convection in High-Resolution Models. Wea. *Forecasting,* 24, 187–210, https://doi.org/10.1175/2008WAF2007097.1.

Jia, A. L., Wang, D. D., Liang, S. L., Peng, J.J., & Yu, Y. Y. (2023). Improved cloudy-sky snow albedo estimates using passive microwave and VIIRS data. *ISPRS Journal of Photogrammetry and Remote Sensing,* 196, 340–355. https://doi.org/10.1016/j.isprsjprs.2023.01.004.

Jia, A. L., Wang, D. D., Liang, S. L., Peng, J.J., & Yu, Y. Y. (2022). Global daily actual and snow-free blue-sky land surface albedo climatology from 20-year MODIS products. *Journal of Geophysical Research: Atmospheres, 127,* (8). https://doi.org/10.1029/2021JD035987.

Jiang, Z., M. Vargas and I. Csiszar. (2016). New oprational real-time daily rolling weekly Green Vegetation fraction product derived from suomi NPP VIIRS reflectance data, *IEEE International Geoscience and Remote Sensing Symposium (IGARSS),* Beijing, China, 2016, pp. 3524–3527, https://doi.org/10.1109/IGARSS.2016.7729911.

Kulie, M. S., C. Pettersen, A.J. Merrelli, T.J. Wagner, N.B. Wood, M. Dutter, D. Beachler, T. Kluber, R. Turner, M. Mateling, J. Lenters, P. Blanken, M. Maahn, C. Spence, S. Kneifel, P. Kucera, A. Tokay, L. Bliven, D. Wolff, and W. Petersen. (2021). Snowfall in the Northern Great Lakes: Lessons Learned from a Multisensor Observatory. Bull. *Amer. Meteor. Soc.,* 102(7), E1317–E1339. https://doi.org/10.1175/BAMS-D-19-0128.1.

Leeper, R., D., Bilotta, R., Petersen, B., Stiles, C. J., Heim, R., Fuchs, B., Prat, O. P., Palecki, M., & Ansari, S. (2022). Characterizing U.S. drought over the past 20 years using the U.S. drought monitor. *International Journal of Climatology,* 1–15. https://doi.org/10.1002/joc.7653.

Li, F., X. Zhang, S. Kondragunta, X. Liu, I. Csiszar, C. Schmidt. (2022). Hourly biomass burning emissions product from blended geostationary and polar-orbiting satellites for air quality forecasting applications, *Remote Sensing of Environment,* 281, 113237, https://doi.org/10.1016/j.rse.2022.113237.

Liu, C., E. Freeman, E. C. Kent, D. I. Berry, S. J. Worley, S. R. Smith, B. Huang, H.-M. Zhang, T. Cram, Z. Ji. (2022). Blending TAC and BUFR Marine in Situ Data for ICOADS Near-Real-Time Release 3.0.2. *Journal of Atmospheric and Oceanic Technology,* 39, 1943–1959. https://doi.org/10.1175/JTECH-D-21-0182.1.

Liu, X. and M. Wang. (2022). Global daily gap-free ocean color products from multi-satellite measurements, *Int. J. Appl. Earth Obs. Geoinf.,* 108, 102714. https://doi.org/10.1016/j.jag.2022.102714.

Liu, Y., Y. Yu, P. Yu, H. Wang, and Y. Rao. (2019). Enterprise LST Algorithm Development and Its Evaluation with NOAA 20 Data. *Remote Sensing,* 11(17), 2003. https://doi.org/10.3390/rs11172003.

Liu, Y., P. Yu, H. Wang, J. Peng, and Y. Yu. (2022). Ten Years of VIIRS Land Surface Temperature Product Validation. *Remote Sens.* 14, 2863. https://doi.org/10.3390/rs14122863.

Loto'aniu, P. T. M., Romich, K., Rowland, W., Codrescu, S., Biesecker, D., Johnson, J., et al. (2022). Validation of the DSCOVR spacecraft mission space weather solar wind products. *Space Weather,* 20, e2022SW003085. https://doi.org/10.1029/2022SW003085.

Loto'aniu, P. T. M., P. Mulligan, L. Johnson, D. Biesecker, R. Steenburgh, V. Pizzo, F. Inceoglu, J.V. Rodriguez. (2022). Solar Sail Missions for Sub-L1 Sampling of the Interplanetary Magnetic Field and Plasma on the Sun-Earth Line. National Academy of Sciences Heliospheric Decadal Survey White Paper.

Mateling, M.E., C. Pettersen, M.S. Kulie, K.S. Mattingly, S.A Henderson, and T.S. L'Ecuyer. (2021). The influence of atmospheric rivers on cold-season precipitation in the Upper Great Lakes region. J. Geophys. Res., 126(13), e2021JD034754. https://doi.org/10.1029/2021JD034754.

Meng, H., C. Kongoli, and R.R. Ferraro. (2020). A 1DVAR-Based Snowfall Rate Algorithm for Passive Microwave Radiometers. In: Levizzani, V., Kidd, C., Kirschbaum, D.B., Kummerow, C.D., Nakamura, K., Turk, F.J. (eds) Satellite Precipitation Measurement. Advances in Global Change Research, vol 67. Springer, Cham. https://doi.org/10.1007/978-3-030-24568-9_17.

NOAA Research Council. (2020). NOAA Research and Development Vision Areas: 2020–2026, https://repository.library.noaa.gov/view/noaa/24933.

Noh, Y. J., J. M. Haynes, S. D. Miller, C. J. Seaman, A. K. Heidinger, J. Weinrich, M. S. Kulie, M. Niznik, and B. J. Daub. (2022). A Framework for Satellite-based 3D Cloud Data: An Overview of VIIRS Cloud Base Height Retrieval and User Engagement for Aviation Applications. *Remote Sens.*, 14(21), 5524, Special Issue "VIIRS 2011–2021: Ten Years of Success in Earth Observations." https://doi.org/10.3390/rs14215524.

O'Dell, K., D. Goldberg, G. H. Kerr, Z. Wei, H. Zhang, B. Henderson, S. Kondragunta, and S. C. Anenberg. (2022). Exploring the value of future geostationary satellite-based atmospheric composition data for improving health and air pollution injustice, manuscript in preparation.

Peng, J. J., Y.Y. Yu, P. Yu, & S.L. Liang. (2018). The VIIRS Sea-Ice Albedo Product Generation and Preliminary Validation. *Remote Sensing,* 10(11). https://doi.org/10.3390/rs10111826.

Pinker, R. T., Ma, Y., Chen, W., Laszlo, I., Liu, H., Kim, H.-Y., and Daniels, J. (2022). Top-of-the-atmosphere reflected shortwave radiative fluxes from GOES-R. *Atmospheric Measurement Techniques.* 15. 5077–5094. https://doi.org/10.5194/amt-15-5077-2022.

Reagan, J., T. Boyer, C. Schmid, and R. Locarnini. (2022). Subsurface salinity [subsection in "State of the Climate in 2021"]. *Bull. Amer. Meteor. Soc.,* 103 (8), S160–S162, https://doi.org/10.1175/BAMS-D-22-0072.1.

Rishmawi, K., Huang, C., Schleeweis K., and Zhan, X. (2022). Integration of VIIRS observations with GEDI-Lidar measurements to monitor forest structure dynamics from 2013 to 2020 across the conterminous United States. *Remote Sensing,* 14, 2320. https://doi.org/10.3390/rs14102320.

Rodziewicz, D., Amante, C.J., Dice, J. *et al.* (2022). Housing market impairment from future sea-level rise inundation. *Environment Systems and Decisions,* 42, 637–656. https://doi.org/10.1007/s10669-022-09842-6.

Rudlosky, S. D., and co-authors. (2020). Geostationary Lightning Mapper value assessment. NOAA Tech. Rep. NESDIS 153, 46 pp. https://doi.org/10.25923/2616-3v73.

Saha, K. and H.-M. Zhang. (2022). Hurricane and Typhoon Storm Wind Resolving NOAA NCEI Blended Sea Surface Wind (NBS) Product. *Frontiers in Marine Sciences—Ocean Observation 9,* 1–12. https://doi.org/10.3389/fmars.2022.935549.

Sutton, E. K. (2018). A New Method of Physics-Based Data Assimilation for the Quiet and Disturbed Thermosphere. *Space Weather,* 16(6), 736–753. https://doi.org/10.1002/2017SW001785.

Vargas, M., Miura, T., Shabanov, N., and Kato, A. (2013). An initial assessment of Suomi NPP VIIRS vegetation index EDR. *Journal of Geophysical Research: Atmosphere,* 118, 12,301–12,316. https://doi.org/10.1002/2013JD020439.

Wang, D., S. Liang, T. He, & Y. Yu. (2013). Direct Estimation of Land Surface Albedo from VIIRS Data: Algorithm Improvement and Preliminary Validation. *Journal of Geophysical Research-Atmospheres,* 118(22), 12577–12586. https://doi.org/10.1002/2013JD020417.

Wang, D., S. Liang, Y. Zhou, T. He and Y. Yu. (2017). A New Method for Retrieving Daily Land Surface Albedo from VIIRS Data. *IEEE Transactions on Geoscience and Remote Sensing,* 55(3), 1765–1775. https://doi.org/10.1109/TGRS.2016.2632624.

Wang, X., Liu, Y., Key, J. R., & Dworak, R. (2022). A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations. *Remote Sensing,* 14(8). https://doi.org/10.3390/rs14081846.

Yang, W., V. O. John, X.-P. T. Zhao, H. Lu, and K. R. Knapp. (2016). Satellite climate data records: development, applications, and societal benefits, *Remote Sensing,* 8 (331). https://doi.org/10.3390/rs8040331.

Yin, J., X. Zhan, J. Liu, and R.R. Ferraro. (2022). A New Method for Generating the SMOPS Blended Satellite Soil Moisture Data Product without Relying on a Model Climatology. *Remote Sens.* 14, 1700. https://doi.org/10.3390/rs14071700.

Yu, Y. and P. Yu. (2019). Land Surface Temperature Product from the GOES-R Series, The GOES-R Series, *A new Generation of Geostationary Environmental Satellites,* pp. 133–144. https://doi.org/10.1016/B978-0-12-814327-8.00012-3.

Yu, Y., Y. Liu, and P. Yu. (2017). Land Surface Temperature Product Development for JPSS and GOES-R Missions. *Comprehensive Remote Sensing.* Shunlin Liang, ed., Elsevier, 5, 284–303, http://dx.doi.org/10.1016/B978-0-12-409548-9.10522-6.

Zhang, H., Z. Wei, B. H. Henderson, S. C. Anenberg, K. O'Dell, and S. Kondragunta. (2022). Nowcasting Applications of Geostationary Satellite Hourly Surface PM2.5 Data, *Weather and Forecasting,* 37, 2313–2329, https://doi.org/10.1175/WAF-D-22-0114.1.

Zhao, X.-P., and M. J. Foster. (2022). Analyzing Sensitive Aerosol Regimes and Active Geolocations of Aerosol Effects on Deep Convective Clouds over the Global Oceans by Using Long-Term Operational Satellite Observations, *Climate,* 10(11), 167. https://doi.org/10.3390/cli10110167.

Zhou L, B. Yan, N. Sun, J. Huang, Q. Liu, C. Grassotti, Y-K. Lee, W. Straka III, J. Niu, A. Huff, S. Kalluri, and M. Goldberg. 2023. Observed Atmospheric Features for the 2022 Hunga Tonga Volcanic Eruption from Joint Polar Satellite System Science Data Products. *Atmosphere,* 14, 263. https://doi.org/10.3390/atmos14020263.

Zhou, Y., Wang, D., Liang, S., Yu, Y., & He, T. (2016). Assessment of the Suomi NPP VIIRS Land Surface Albedo Data Using Station Measurements and High-Resolution Albedo Maps. *Remote Sensing,* 8(2), 137. https://doi.org/10.3390/rs8020137.

National Environmental Satellite, Data, and Information Service
1335 East-West Highway
Silver Spring, MD 20910

www.nesdis.noaa.gov

DOI: 10.25923/ekdr-km08