Over Thirty Years Reporting on NASA's Earth Science Program

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The Editor's Corner

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Autumn is now upon us, and the COVID-19 pandemic continues. NASA has made some progress toward returning to in-person work, with NASA's Johnson Space Center and Michoud Assembly Facility currently at Stage 2 on the agency's four-stage framework.[1] However, all other NASA facilities remain at Stage 3, where, with a few exceptions, only mission-essential personnel are allowed onsite. The vast majority of NASA's workforce is still teleworking.

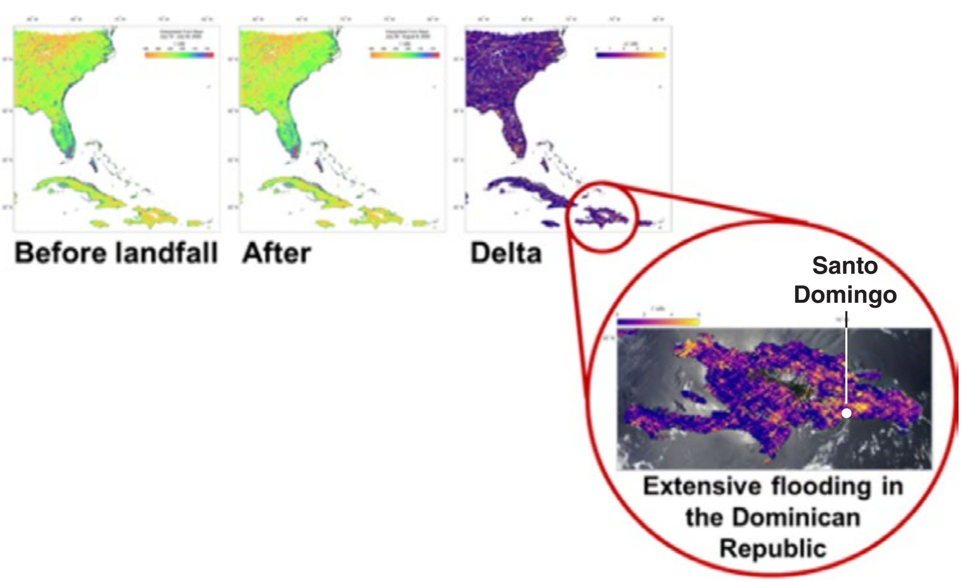
In recent issues, "The Editor's Corner" reported on NASA's ongoing effort to investigate the societal impacts of COVID-19 via remote sensing. Our May–June 2020 issue reported on the funding of the first several Rapid Response and Novel Research in Earth Science (RRNES) science investigations. In July–August 2020, we reported on how NASA has entered into a partnership with the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) to create a COVID-19 dashboard (*eodashboard.org*). In this issue, we report on eight more RRNES projects that have received funding—see the News story on page 27 of this issue.

The public health crisis unleashed by COVID-19 has unfortunately coincided with a series of significant natural disasters.[2] Even before COVID-19, world attention was focused on devastating fires that impacted Australia in late 2019 and early 2020. Then, a sequence of converging natural disasters hit closer to home this summer: The Western U.S. wildfires and the extremely active—and possibly record-setting—hurricane season in the Atlantic Basin (both of which continue as of this writing). NASA's Earth-observing satellites have been monitoring these phenomena and even their interactions—e.g., see **Figure 1** on page 36. An example of NASA observations allowing researchers to gain a better understanding of fire dynamics and smoke plume evolution is given in the News story on page 31 about the August Complex Fire in California. With regard to the series of 2020 Atlantic hurricanes, the NASA Earth Science Disasters Program featured relevant satellite imagery and datasets at *disasters.nasa.gov/tropical-cyclones*. This page includes links to pages on Hurricanes Isaias, Laura, Sally, and Delta, all of which made U.S. landfalls. (As of this writing, it appears Hurricane Zeta may be added to this list soon.)

[1] View the framework at *go.nasa.gov/37Sepsu*.

[2] Most of the "Recent Events" currently listed on the website for NASA's Earth Science Disasters Program (*disasters.nasa.gov*) relate to COVID-19, hurricanes, or fires.

continued on page 2



Shown here are Global Positioning System (GPS) surface reflectivity maps from NASA's Cyclone Global Navigation System Satellite (CYGNSS) mission made just before [*left*] and after [*middle*] Hurricane Isaias made landfall in the Dominican Republic on July 30, 2020. The difference (or Delta) between these Before and After maps [*right*] can be used to highlight the regions of most severe flooding. They can be seen in the close-up image of the Dominican Republic as the light gray region on the southeast side of the island near the capital city of Santo Domingo. **Image credit:** Clara Chew [University Corporation for Atmospheric Research]

In This Issue

Reminder: To view newsletter images in color, visit *eospso.nasa.gov/earth-observer-archive.*

NASA's Cyclone Global Navigation System Satellite (CYGNSS) mission was specifically developed to explore the inner workings of tropical cyclones and learn more about the factors that influence their intensity. Launched in 2016, and collecting data since March 2017, CYGNSS uses a low-inclination orbit and a constellation of microsatellites to make frequent measurements of developing tropical storms and throughout their life cycle. With eight satellites in the constellation, there are typically two or three overpasses of a storm every day. This summer and fall, CYGNSS has been making continuous measurements of ocean surface wind speed and flood inundation during the active 2020 Atlantic hurricane season. CYGNSS measurements over land can resolve inland water bodies, which allows the data to be used for practical applications, such as estimating storm-induced flooding—as shown in the images on the front cover of this issue. The combination of pre-landfall measurements of hurricane wind speed and post-landfall flood inundation maps are being used to constrain and test storm surge and flood inundation forecast models.

The Copernicus Sentinel-6 Michael Freilich satellite, a U.S.-European partnership involving several organizations, is scheduled for a November 10 launch aboard a SpaceX Falcon 9 rocket from Vandenberg Air Force Base in California. The spacecraft was flown from Germany and arrived at the SpaceX payload processing facility on September 24, 2020.[3] The Sentinel-6 Michael Freilich international collaboration (followed by Sentinel-6B, planned for a 2025 launch) will extend the nearly 30-year sea level time series that began in 1992 with the launch of the TOPEX/Poseidon mission and has continued with three more missions over the years: Jason-1, the Ocean Surface Topography Mission (OSTM)/Jason-2 and Jason-3. The satellite was named in honor of NASA's former Earth Science Division (ESD) director who passed away in August of this year and was a pioneering scientist in spaceborne ocean radar scatterometry.

NASA is also busy preparing for two future missions that were selected in 2016 as part of NASA's Earth Venture Instrument (EVI) program.[4] One will contribute to our knowledge of tropical cyclones and the other to our understanding of how different types of airborne particulate matter (PM)—e.g., from traffic, power plants, or wildfires—affect human health.

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission is a state-of-the-science observing platform that will measure vertical profiles of atmospheric temperature and moisture, as well as surface precipitation and tropical cyclone intensity, over

[3] More on the status of Copernicus Sentinel-6 Michael Freilich can be found at *go.nasa.gov/34uW6HQ*.

[4] NASA's Earth Venture program provides a means to develop new science-driven, competitively selected, low cost missions that will provide opportunity for investment in innovative Earth science to enhance our capability to better understand the current state of the Earth system and to enable continual improvement in the prediction of future changes. The three categories of Venture Class missions are: Instrument (EVI), Mission (EVM), and Suborbital (EVS).

the tropical latitudes. Currently, TROPICS is working toward a 2022 launch. The Science Team is testing the ground system, finalizing algorithms, and planning validation methods. TROPICS Applications and the Early Adopter Program continue to interact and discuss the value of TROPICS in applied sciences and short-term weather forecasting. Turn to page 15 to learn more about the status of the TROPICS mission and the applications planned for its data.

The Multi-Angle Imager for Aerosols (MAIA) investigation will add to our knowledge of airborne particles. The instrument, currently scheduled for a mid-2022 launch, contains a pointable pushbroom camera with 14 spectral bands ranging from the ultraviolet to shortwave-infrared. Three of the bands are polarimetric. Assembly, focusing, alignment, and environmental testing of the camera were recently completed in preparation for detailed calibration and characterization. By integrating retrieved aerosol properties with measurements from ground-based PM monitors and outputs of the WRF-Chem atmospheric model, ground data processing will generate 1-km resolution maps of sulfate, nitrate, elemental carbon, organic carbon, and dust concentrations for a globally distributed set of target areas. A team of epidemiologists will use birth, death, and hospitalization records to study linkages to human health in a dozen Primary Target Areas. A set of Secondary Target Areas has also been identified for air quality and climate studies. *The Earth Observer* plans a more detailed coverage of MAIA in an upcoming issue.

Last but not least, I am pleased to report that the feature article in this issue focuses on the NASA ESD's Airborne Science Program (ASP), which is a critical component of the division effort—flying in the "gap" between satellite and ground-based observations. Airborne Earth science goes back to the 1960s, when NASA retrofitted passenger and military aircraft with equipment that enabled collecting *in situ* and remote sensing data for the full range of Earth science disciplines. In addition to acquiring unique datasets, aircraft campaigns play a major role in supporting satellite missions through calibration (i.e., measurements) and validation (i.e., retrieved geophysical products) activities as well as providing a testbed for future satellite remote sensing instruments. The ASP's role in these activities includes Earth Venture Suborbital (EVS) missions that were implemented following the 2007 Earth Science Decadal Survey. Aircraft operations are continuing despite the ongoing pandemic.[5] Please turn to page 4 of this issue to read a comprehensive report on the ASP. ■

[5] To find out more about current ASP activities, see the latest issue of the *Explore Airborne Science* newsletter at *go.nasa.gov/3jsfvNW*.

List of Undefined Acronyms Used in The Editor's Corner and Table of Contents

COVID-19	2019 Novel Coronavirus Disease
EOS	Earth Observing System
JPL	NASA/Jet Propulsion Laboratory
OSU	Oregon State University
SARI	South/Southeast Asia Research Initiative
TOPEX	Ocean Topography Experiment
TROPICS	Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats
WRF-Chem	Weather Research and Forecasting Model coupled with Chemistry

Flying in the "Gap" Between Earth and Space: NASA's Airborne Science Program

Ernest Hilsenrath, University of Maryland, Baltimore County/Global Science and Technology, Inc., hilsenrath@umbc.edu

NASA's airborne assets are used to fill in a critical data gap, between satellites above and ground-based measurements below.

Introduction

Established as the nation's space agency, the link between NASA and space exploration is self-evident. What is not as well known, however, is that NASA also flies in the atmosphere below the "edge" of space, with significant investment in *suborbital* observations made from aircraft that carry instruments to observe phenomena on the ground and take measurements within the atmosphere to gain a "top-to-bottom" picture of the environment to help scientists understand how and why our planet is changing. NASA's airborne assets are used to fill in a critical data gap between satellites above and ground-based measurements below.

Figure 1. The top photo shows the NASA ER-2 on takeoff. This civilian version of the U-2 spy plane is capable of flying at altitudes greater than 70,000 ft (~21 km) making it an invaluable platform for simulating satellite measurements. The lower image shows the ER-2 in flight during FIREX-AQ, taking measurements high above a smoke plume in California. **Photo credits:** NASA

To give an idea how it works, consider the following scenario:

On a summer morning in July 2019, a NASA aircraft flies through the clear, thin air at 70,000 ft (~21 km) to investigate fires raging over the Northwestern U.S. Known as the ER-2 (shown in **Figure 1**), it is a civilian version of the U-2 reconnaissance aircraft that gained notoriety when it was used for reconnaissance flights over the former Soviet Union, Vietnam, and Cuba during the Cold War between the U.S. and the Soviet Union. Three other aircraft [two de Havilland DHC-6-300 "Twin Otters" from the National Oceanic and Atmospheric Administration (NOAA) and a DC-8 from NASA] fly at various altitudes beneath the ER-2, each equipped with instruments that measure fire and smoke characteristics from wild and agricultural fires. All of these aircraft activities are taking place under the umbrella of a joint NASA–NOAA field campaign called Fire Influence on Regional to Global Environments Experiment - Air Quality (FIREX-AQ).[1] The campaign is a coordinated effort involving U.S. scientists from NASA, NOAA, universities, industry, and representatives from similar institutions from around the world. Each aircraft flight is carefully planned so that the timings of the flights approximately match with overpasses by one or more NASA and international satellites that peer down over this ensemble of aircraft and over similar measurements being taken on the ground. The overall objective of these coordinated observations is to study the impacts of fire on air quality, weather, and climate and to provide tools for land-use managers to best deploy resources and make predictions not just of fire behavior but for agricultural and other purposes, as well.

This scenario demonstrates how NASA's Airborne Science Program (ASP), managed from NASA Headquarters, coordinates aircraft operations and science teams with their instruments to organize field campaigns. ASP primarily uses aircraft based at NASA's Armstrong Flight Research Center (AFRC). However, several other NASA field centers, including Ames Research Center (ARC), Goddard Space Flight Center (GSFC), Glenn Research Center (GRC), Johnson Space Center (JSC), Langley Research Center (LaRC), and Wallops Flight Facility (WFF), provide aircraft and participate in these campaigns.

[1] Further information on FIREX-AQ can be found at *https://espo.nasa.gov/firex-aq/content/FIREX-AQ*.

The importance of airborne campaigns to NASA's Earth Science Division (ESD) activities is well established, as the collected data support all ESD research disciplines, including Air, Climate, Water, Oceans, Ice, and Land. ASP science objectives include calibrating and validating (cal/val) satellite data, conducting campaigns for geophysical process studies, and testing new Earth-observing technologies.

This article provides a brief description of how NASA's aircraft-based Earth-science measurements are implemented. It begins with a brief history of how these measurements became an integral tool for Earth Science research[2] followed by a description on the various ways ASP supports NASA Earth science research. An example of this is when ASP coordinated the Korea-U.S. Air Quality (KORUS-AQ) campaign that took place in South Korea in 2016. The article also includes a discussion of the unique opportunities ASP provides for students of all ages to get involved in NASA airborne science research.

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History

In 1963 NASA and university scientists—envisioning the potential for research at ARC—proposed developing a high-flying jet aircraft for astronomy. This recommendation was met with enthusiasm by the astronomers, and soon thereafter NASA purchased a Convair 990 (CV-990) aircraft—one of the earliest four-engine jet passenger airliners—to conduct airborne astronomical observations. The aircraft was overhauled by removing passenger amenities and installing equipment for astronomical observations, such as an infrared telescope with a gyrostabilized heliostat. The aircraft was appropriately called *Galileo*, and its first mission was to observe the May 1965 solar eclipse over the South Atlantic Ocean.

Galileo flew both astronomy and Earth science missions from 1965 to 1973. In April 1973, when the aircraft was returning from a short flight to test oceanography instruments, Galileo collided with a Navy P-3 on approach to Moffett Field, which serves as an airport for both the U.S. Navy and NASA. Tragically, all personnel were lost. NASA replaced the Galileo with a similar CV-990, naming it *Galileo II*. Over time, the aircraft was used less for astronomy and more for Earth science. As with the first Galileo, the passenger aircraft amenities similarly gave way to instrument racks, data acquisition equipment, and advanced navigational systems, while optical and air-sampling ports replaced some of the windows.

Just like its predecessor, Galileo II flew a variety of missions at locations all around the world in support of Earth science. For example, in 1982 the aircraft explored global atmospheric effects from the Mexican El Chichón volcanic eruption. In the mid-1970s, Galileo II began satellite-support activities by becoming a platform for testing satellite instruments such as radiometers for the Nimbus series.[3] It also flew the first "cal/val" flights, which made near-coincident measurements using instruments similar to satellite instruments so that the data could be directly compared. These flights began in 1972, with the Earth Resources Technology Satellite-1 (ERTS-1), later renamed Landsat 1.

Building upon these early demonstrations of the effectiveness of aircraft for scientific purposes, NASA grew its fleet of Earth-observing platforms. Beginning in 1971 ARC added several more aircraft, including two ER-2s and two Learjet 25s. In addition to testing satellite instruments, the Learjets and ER-2, operating at 50,000 ft (~15 km) and 70,000 ft (~21 km), respectively, enabled the exploration of the upper atmosphere directly with *in situ* instruments—see *An Example of Airborne Research: Exploring the Earth's Ozone Layer* on page 7.

[2] Much of the content summarized in this section can be found in "Atmosphere of Freedom: 70 Years at the NASA Ames Research Center."

[3] To learn more about the Nimbus series of satellites, see "Nimbus Celebrates 50 Years" in the March–April 2015 issue of *The Earth Observer* [**Volume 27, Issue 2,** pp. 18–31] [*https://go.nasa.gov/3a9YUd7*].

In 1985 Galileo II would suffer a similar fate to its predecessor. In addition to Earth science research, the aircraft was also used for testing landing gear systems. As it was landing after a space shuttle landing gear test flight, the tires caught fire and burned the entire aircraft. Fortunately, there were no fatalities this time. Subsequently, NASA procured a DC-8 aircraft originally owned by Alitalia airlines and then by Braniff Airways. ARC modified the airliner—shown in **Figure 2**—into a flying laboratory to support what was then called NASA's Mission to Planet Earth. The DC-8 had more capability than Galileo or Galileo II—and was fully dedicated to Earth observations. This aircraft is still in use today.

Figure 2. Shown here are two ASP aircraft that have been custom designed to accommodate remote sensing and *in situ* instruments for making Earth observations. The top left photo shows ASP's DC-8. This is NASA's "workhorse" aircraft—both because it can carry heavy payloads and because it is frequently called upon for service. The lower left photo shows the windows on the DC-8 that were modified to accommodate air sampling probes that take *in situ* trace gas and aerosol measurements. The top right image shows the NASA Gulfstream-V (G-V) aircraft. The lower right photo shows the underbelly of the G-V that has been modified to accommodate a waveform scanning lidar to measure sea surface altimetry. This configuration of the G-V was used for Surface Water and Ocean Topography (SWOT) cal/val activities. More details about these two aircraft appear in **Table 1** on page 8. **Photo credits**: NASA

In May 1995 NASA announced the consolidation of most of its aircraft fleet—operational as well as experimental—at Dryden Flight Research Center (DFRC),[4] located at Edwards Air Force Base in the high deserts of southern California. This decision led to a large outcry of resistance from ARC, other NASA field centers, and the larger research community, claiming that science would be adversely impacted if aircraft used for science observations were moved from their original locations, and that the cost savings were overestimated.[5]

After further analysis and much discussion, the NASA centers came to a compromise, and only the DC-8, ER-2, and two Learjets were moved from ARC to what was then called DFRC, while the remaining aircraft continued their operations out of their respective centers. Subsequently, in response to NASA's growing fleet of Earth science satellite missions and their requirements for more-sophisticated cal/val and correlative measurements, ASP's aircraft fleet's capabilities evolved—significantly, with current capabilities listed in **Table 1**, found on page 8. To demonstrate the utility of such aircraft, a detailed example of the aircraft deployed for a specific airborne campaign, namely KORUS-AQ, is described on pages 12-13.

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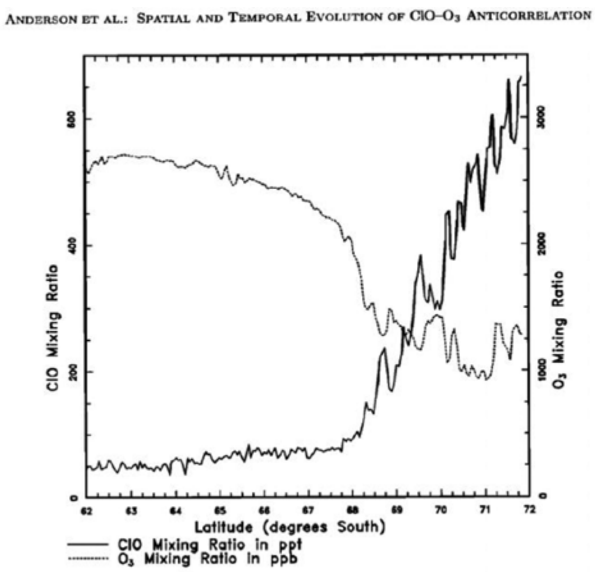
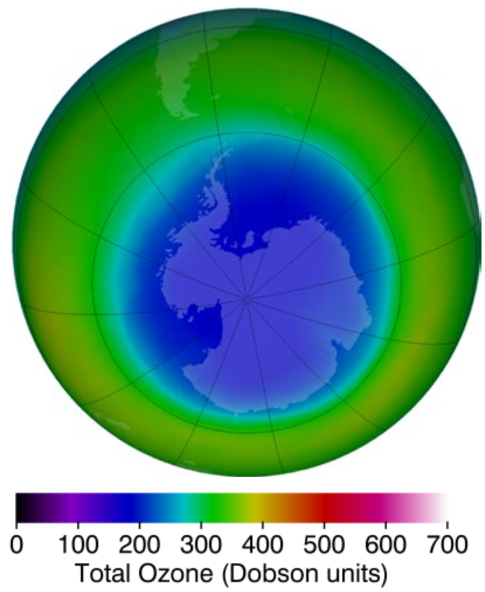
[4] NASA's DFRC was renamed Armstrong Flight Research Center in 2014 in honor of Astronaut Neil Armstrong.

[5] Further information on the consolidation of aircraft at DFRC can be found at *https://oig.nasa.gov/docs/HA-96-001.pdf.*

An Example of Aircraft Research: Exploring Earth's Ozone Layer

One research area where aircraft observations have made a significant contribution was the exploration of Earth's ozone layer, in particular by way of the Airborne Antarctic Ozone Experiment (AAOE). In August and September 1987, both the ER-2, flying at 70,000 ft, and the DC-8, flying at 40,000 ft, measured the concentrations and composition of stratospheric gases and aerosols over Antarctica. The data they collected led to the discovery that certain chemicals and aerosols were destroying stratospheric ozone and forming the now-infamous Antarctic ozone hole. The research continued with the two aircraft making similar measurements over the Arctic. The results from these aircraft missions, together with satellite data—examples of which are shown below—laid the foundation in 1987 for the international Montreal Protocol and subsequent amendments limiting the use of chemicals that deplete stratospheric ozone.





Aircraft measurements of atmospheric composition obtained during the AAOE in September 1987 played an important role in helping scientists determine the cause of the annual Antarctic ozone hole. The graph [*left*] shows the aircraft measurements of ozone (O_3) and chlorine monoxide (ClO) mixing ratios that were obtained as the airplane flew into the hole on September 20, 1987. The image [*right*] is the map of the Antarctic ozone hole obtained in September 1987 by the Total Ozone Mapping Spectrometer (TOMS) on Nimbus 7. Note the anticorrelation between ozone hole depth and chlorine monoxide concentrations. Ozone hole images like the one shown here have been collected on a regular basis since 1979, via several different NASA instruments on various NASA and non-NASA satellites. For more details, see *https://ozonewatch.gsfc.nasa.gov*. **Image credits**: *Journal of Geophysical Research, https://doi.org/10.1029/JD094iD09p11465* [*left*]; NASA Ozone Watch [*right*]

Commitment to Earth Science

NASA's ASP is an integral part of NASA's ESD research. The Program complements Earth science satellite missions and all Earth science disciplines, by way of the following ASP commitments to Earth science.

- *Support Satellite Calibration and Validation*. ASP provides aircraft platforms that enable essential calibration of Earth observing satellite instruments and the validation of their data-retrieval algorithms.
- *Support Satellite Sensor Development*. ASP provides opportunities for suborbital flights to test and refine new instrument technologies/algorithms—and thereby reduce risk—before committing satellite instruments to space flight.
- *Support Process Studies*. ASP organizes and conducts comprehensive airborne campaigns that allow for detailed investigations of geophysical processes and evaluation of models and predictions.
- *Develop the Next Generation of Scientists and Engineers.* ASP encourages the development of the future NASA workforce through hands-on involvement of graduate students, young scientists, and engineers in all aspects of Earth science investigations—see *Student Involvement: Future NASA Scientists and Engineers* on page 12.

"NASA is able to implement its world-class Airborne Science Program because of investments in five areas—platforms, sensors, systems, people, and opportunities. [The agency] can deploy a unique mix of physical and human resources into the field when and where needed to address important questions, bridge spatial scales, and advance our overall capabilities in Earth system science."

— **Jack Kaye** [NASA Headquarters—*Associate Director for Research of the ESD*]

Aircraft Capabilities

ASP currently supports seven aircraft at AFRC, GSFC/WFF, JSC, and LaRC—listed in **Table 1**. ASP-supported aircraft receive funding from NASA Headquarters for support costs and personnel, while the investigators fund mission-specific and flight-hour costs. ASP also coordinates with aircraft stationed at other NASA field centers—listed in **Table 2**. Performance, cost, and ability to meet science objectives are the criteria considered when selecting an aircraft.

Table 1. NASA aircraft operating under the auspices of the Airborne Science Program.

Platform Name * (Military Designation)	Center**	Max Flight Duration (Hours)	Useful Payload (lbs)	Max Altitude (ft)	Airspeed (knots)	Range (Nmi)
DC-8	AFRC	12	30,000	41,000	450	5400
ER-2 ***(2)******	AFRC	12	2900	>70,000	410	>5000
G-III (C-20A)	AFRC	7	2610	45,000	460	3400
G-III	JSC	7	2610	45,000	460	3400
G-III	LaRC	7	2610	45,000	460	3400
G-V	JSC	10	8000	51,000	500	>5000
P-3	WFF	14	14,700	32,000	400	38,000

Table 2. Other NASA aircraft and unpiloted aerial vehicles (UAV).

Platform Name* (Military Designation)	Center**	Max Flight Duration (Hours)	Useful Payload (lbs)	Max Altitude (ft)	Airspeed (knots)	Range (Nmi)
B-200 (UC-12B) "King Air"	LaRC	6.2	4100	31,000	260	1250
B-200	LaRC	6.2	4100	35,000	275	1250
B-200	AFRC	6	1850	30,000	272	1490
(C-130) "Hercules"	WFF	12	36,500	33,000	290	3000
Cessna 206H	WFF	5.7	1175	15,700	150	700
Dragon Eye UAV	ARC	1	1	500+	34	3
HU-25A "Guardian Falcon"	LaRC	5	3000	42,000	430	19,000
Matrice 600 UAV	ARC	1	6	8000	35	3
SIERRA-B UAV	ARC	10	100	12,000	60	600
Twin Otter	GRC	3	3600	25,000	140	450
Viking-400 UAV	ARC	11	100	15,000	60	600
WB-57 ***(3)******	JSC	6.5	8800	60,000+	410	2500

Notes on Tables 1 and 2.

***Acronyms for Aircraft Designations.** These typically represent the name of the company that manufactured them (e.g., B for Beechcraft; G for Gulfstream), the purpose of the aircraft (e.g., C for Cargo; P for Patrol), or some combination thereof. For example, ER stands for Earth Research; the WB-57 is a modified Bomber, with the W standing for Weather. A more detailed list of these aircraft with links to description of each aircraft type can be found at *https://go.nasa.gov/3j2P1Cg*. For a visual summary of the NASA aircraft, see *https://airbornescience.nasa.gov/tracker/#status*. (This site also lists several NOAA aircraft.)

****Acronyms for NASA Centers**. AFRC: Armstrong Flight Research Center; ARC: Ames Research Center; GRC: Glenn Research Center; JSC: Johnson Space Center; LaRC: Langley Research Center; WFF: Wallops Flight Facility.

(Numbers in bold, italicized parentheses)***. Denotes there is more than one identical version of this type of aircraft.

Each NASA aircraft has unique performance characteristics and can be custom fitted for each campaign. For example, ports for remote sensing instruments can replace windows. Several aircraft also have provisions for mounting air-sampling instruments around the exterior of the fuselage, placing them along much of the length of the aircraft—see bottom photos of Figure 2 on page 6.

Since 1987 the ASP has managed at least 45 campaigns around the world, including at both Poles.[6] As an example, **Figure 3** shows the regions and flight paths covered in 2016 (the year for the campaign example described later).

Figure 3. This is an example of the coverage of the 14 missions ASP deployed in 2016, the year for the example campaign described below. The black lines show the flight paths for that year. ASP also operated an unpiloted aerial vehicle (UAV; flight paths shown in red), which was subsequently deleted from the ASP fleet. **Image credit:** NASA

Since 1987, the ASP has managed at least 45 campaigns around the world—including at both Poles.

NASA maintains close relationships with other government agencies when there are common interests. For example, the agency has a long and fruitful history of collaboration with NOAA, e.g., with Earth observing satellite missions. When conducting aircraft campaigns, each agency often shares resources, making use of complementary capabilities. FIRE-AQ and AAOE are two examples discussed in this article. Other examples can be found at the website referenced in footnote 6.

Engineering and Operational Support

Once NASA approves a mission and instrument principal investigators are selected, ASP provides assistance and advice during all phases of the mission. Engineering support includes assisting with instrument integration into the aircraft including compartment selection, mounting, and window selection (if applicable). ASP also makes available access to its data network and provision of test flights.

In addition to engineering support, ASP can guide the aircraft selection process based on the mission's science requirements and aircraft capabilities. ASP personnel are also available to help develop a mission operations plan that includes aircraft type, flight plans, schedules, and cost. Application through the Science Operations Flight Request System[7] is ASP's formal process for a research scientist to request campaign support.

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[6] Links to details about each activity are provided by the campaign logos for all ASP-supported activities shown at *https://go.nasa.gov/375xw29*.

[7] To learn more about this system, visit *https://go.nasa.gov/2SZHLwt*.

Facility Instruments

Several NASA *facility instruments*—remote sensing systems that can support a variety of NASA science objectives—are available for use by mission and instrument scientists.[8] They include visible, infrared, and radar imagers, topography lidars, air temperature and humidity sounders, and other supporting measurement modalities. These facility instruments have a proven track record of performance and can make measurements that apply to several science disciplines. In this way, mission scientists do not need to develop their own instruments for their experiments. Some of these instruments are versatile enough that they can be deployed on several of the aircraft listed in Table 1 on page 8. This affords additional options for mission scientists to select an aircraft that meets their science requirements and still take advantage of the capabilities of a facility instrument.

An example of a widely used facility instrument is the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), a spatially scanning spectrometer that measures the upwelling spectral irradiance covering the wavelength range from 380 nm to 2500 nm. Data from this instrument can be applied to studies in the fields of oceanography, hydrology, geology, volcanology, soil and land management, and atmospheric composition.

MTS was first deployed in 2011 for the Airborne Tropical TRopopause EXperiment (ATTREX) campaign. Since that time it has been used in nearly every major NASA Earth airborne science investigation.

The Mission Tools Suite

ASP also supports the Mission Tools Suite (MTS),[9] which provides a means for visualizing the position of an aircraft during the course of a mission. Using MTS, an aircraft track can be positioned over satellite images or model output, thus providing an overall picture of the region where aircraft measurements are being made. The MTS can also be used preflight for mission planning or postflight for science data analysis. During flight, MTS provides the communication between aircraft and the ground, and integrates various information sources to a common operating venue. For example, communications between the inflight mission team and weather forecasters on the ground can help direct aircraft to the intended target area or help the team avoid certain areas because of poor viewing, all the while maintaining aircraft safety.

In addition to mapping and visualizing aircraft locations, MTS can plot various aircraft and instrument data as a function of time. A built-in chat feature helps facilitate real-time communication between mission team members during science campaigns.

MTS was first deployed in 2011 for the Airborne Tropical TRopopause EXperiment (ATTREX) campaign.[10] Since that time it has been used in nearly every major NASA Earth airborne science investigation. It is also regularly used by the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) for its annual tropical-storm tasking and hurricane-research program.

Figure 4 on page 11 shows an example of the MTS being used during the Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE), the objective of which is to characterize aerosol-cloud-meteorology interactions using *in situ* and remote sensing airborne measurements. The MTS screen shows the position of an aircraft during the course of the mission overlaid on a Geostationary Operational Environmental Satellite-16 (GOES-16) Channel 13 map. This channel is used for detecting clouds—day and night—and is particularly useful

[8] Further information about facility instruments can be found at *https://go.nasa.gov/3dCwU5m*.
[9] For more information on the MTS, visit *https://go.nasa.gov/2FCXfUk*.
[10] ATTREX was an Earth Venture Sub-Orbital (EVS) mission, which is a class of Earth science missions that focus on conducting research using aircraft, balloons, sounding rockets, and other suborbital assets. To learn more, see *https://essp.nasa.gov/projects*.

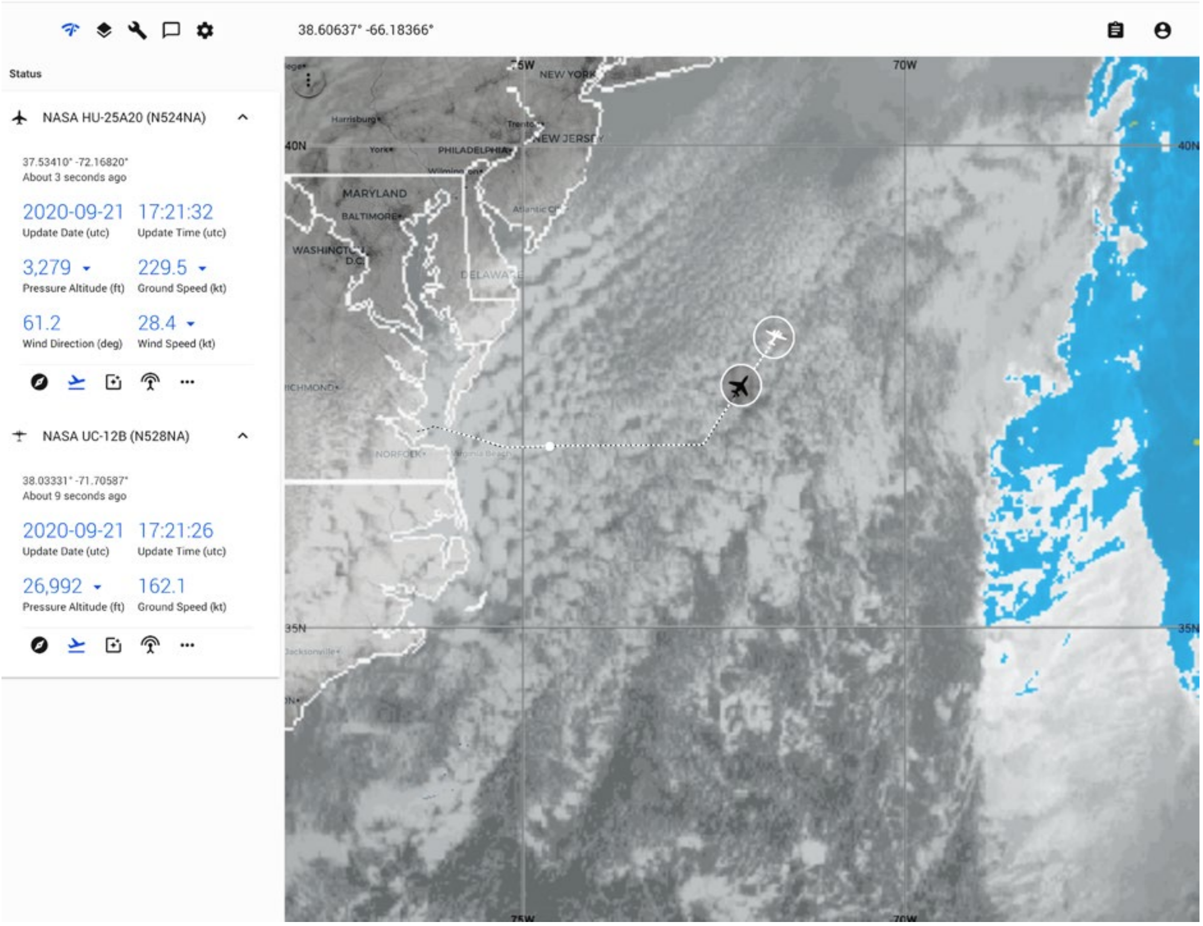

Figure 4. ACTIVATE deployed two aircraft over the western North Atlantic Ocean—the NASA LaRC HU-25 Falcon and B-200 King Air. The HU-25 acquires *in situ* measurements below, in, and above clouds. The B-200 flies above clouds mapped by GOES-16 Channel 13 to remotely measure aerosols and clouds. The coincident aircraft flight tracks are represented by the dotted line. The left-hand side of the screen displays the housekeeping telemetry information; the aircrafts' geolocation, altitude, ground speed, and wind measurements. **Image credit**: NASA

in retrievals of cloud-top height and estimating cloud particle sizes. This illustrates how MTS capabilities enable improved effectiveness of a flight mission, which then improves scientific return.

Earth Science Project Office

Often behind the scenes, but ever present, is ARC's Earth Science Project Office (ESPO). This office provides project management support for many ASP campaigns, including planning, implementation, and pre- and post-mission ground activities. Campaigns are often large, multi-aircraft, international missions. Therefore, a key role that ESPO plays is to enable communications among ASP personnel, mission managers and mission scientists, aircraft crew, embassy staff (if international), and airport managers. Ground activities include campaign logistics, e.g., workspace preparation for the mission teams, shipping, hotels, and transportation.

Before the campaign, ESPO does site visits to determine the best location for the deployment; makes local contacts, from air traffic controllers to hotels; arranges access; and ensures the availability of ground facilities for instrument scientists and mission managers. In cooperation with the science team, it also coordinates public affairs activities, public and VIP access to aircraft, educational outreach, and any other activities dealing with the public. Overall, the Office is the point of contact for the mission or project scientist to deal with any campaign issues or needs.

"The research data NASA collects are shared with the world. This is incredibly important, and we are thrilled to be part of it."

—**Marilyn Vasques**
[NASA's ARC—*Director of the Earth Science Project Office*]

Student Involvement: Future NASA Scientists and Engineers

ASP provides a unique opportunity for college undergraduates to participate in a NASA science project. The Student Airborne Research Program (SARP) provides hands-on research experience in all aspects of an airborne campaign—primarily using the DC-8. The program's goal is to inspire interest in NASA's Earth science research and aid in recruiting the next generation of scientists and engineers.

After a competitive selection, the student (who must be working toward a STEM-major degree), guided by a program faculty member, selects a research project connected to one of the science instruments set to fly on an ASP mission. The project involves flight planning, instrument integration and checkout, in-flight operation, and flight-data processing. The student works directly with a NASA or faculty scientist—see **photo** [*below*].

At the end of the program, students present their results and conclusions to an audience of NASA scientists, university faculty members, and fellow SARP students. Many students go on to present their SARP research results at national conferences, such as the American Geophysical Union Fall Meeting. The student experience with airborne science is a unique opportunity, as it covers many aspects of a satellite mission in just a few weeks, whereas implementing a space mission can take a decade or more. A video of students explaining their experience in their flying laboratory can be found at *https://youtu.be/o56_07rsyBY*.

The instrument scientist explains to Student Airborne Research Program participants the installation and operation of the Whole Air Sampler onboard NASA's DC-8. **Photo credit:** NASA

Many SARP alumni have gone on to get advanced degrees. Some work at NASA centers, national labs, and universities, and some have even returned to participate in an ASP flight-research campaign.

Kindergarten through twelfth-grade students also participate through ASP's outreach and education program, which connects classrooms from across the U.S. and around the world with a flight campaign while a mission is in progress. Students and teachers can track the position of participating aircraft in real time and view mission activities with live camera feed from the aircraft.

Find out more about SARP at *https://baeri.org/sarp*. For details on the 2020 SARP, see page 5 of the Fall 2020 issue of the Explore Airborne Science newsletter at *https://go.nasa.gov/2TwSf6Z*

An International Campaign: KORUS-AQ

Perhaps the best way to demonstrate the efficacy of ASP coordination and support for aircraft campaigns is to provide an example of a particularly complex one.

In May and June 2016, NASA teamed with Korea's National Institute of Environmental Research (NIER) to conduct the Korea-U.S. Air Quality (KORUS-AQ) campaign. This campaign was chosen as an example for this article because of the new science that would be revealed regarding an ever-increasing environmental concern. It also demonstrates how ASP campaign organizers and scientists planned and executed an international campaign to make observations from aircraft, satellites, and sea- and ground-based instruments. Planning also involved real-time air-quality modeling and meteorological forecasting to ensure success of each day's aircraft deployment.

South Korea was selected because it is an ideal location to carry out air-quality studies. The concentrated population of its megacity capital, Seoul, combined with the presence of rural farming communities throughout the country, provided the opportunity to study both natural and human-produced emissions. South Korea's location downwind of China also allowed the study of long-range transport of pollution into the peninsula.

The KORUS-AQ campaign team consisted of 293 scientists, engineers, flight crew, and other personnel from the U.S., South Korea, and 13 other countries. The campaign employed three aircraft carrying 37 different instruments that measured atmospheric gases, aerosols, and solar radiation, as well as remote-sensing instruments that simulated satellite measurements of the same constituents as measured by aircraft and on the ground.[11]

The DC-8 served as the primary aircraft for atmospheric sampling and remote sensing of gases and aerosols affecting air quality. It flew extensively across the Korean peninsula and surrounding waters at multiple altitudes, providing information on vertical distributions of the gases and aerosols. In addition to the U.S. instruments, the DC-8 hosted six Korean instruments that measured aerosol chemistry and pollution precursors. The second aircraft was LaRC's B-200 (or "King Air"), which carried two nadir-viewing remote sensors that simulated observations from geostationary orbit. The third aircraft was also a King Air, from Hanseo University in South Korea. Korean scientists onboard operated *in situ* instruments that measured pollutants also observable by satellites. The Korean aircraft likewise carried a remote sensing instrument that also measured local pollution using another instrument provided by NASA's GSFC. **Figure 5** illustrates the flight tracks from the three aircraft. The smaller, more nimble King Air aircraft were able to provide information on key pollutants in areas less accessible to the DC-8.

The KORUS-AQ campaign...employed three aircraft carrying 37 different instruments that measured atmospheric gases, aerosols, and solar radiation, as well as remote-sensing instruments that simulated satellite measurements of the same constituents as measured by aircraft and on the ground.

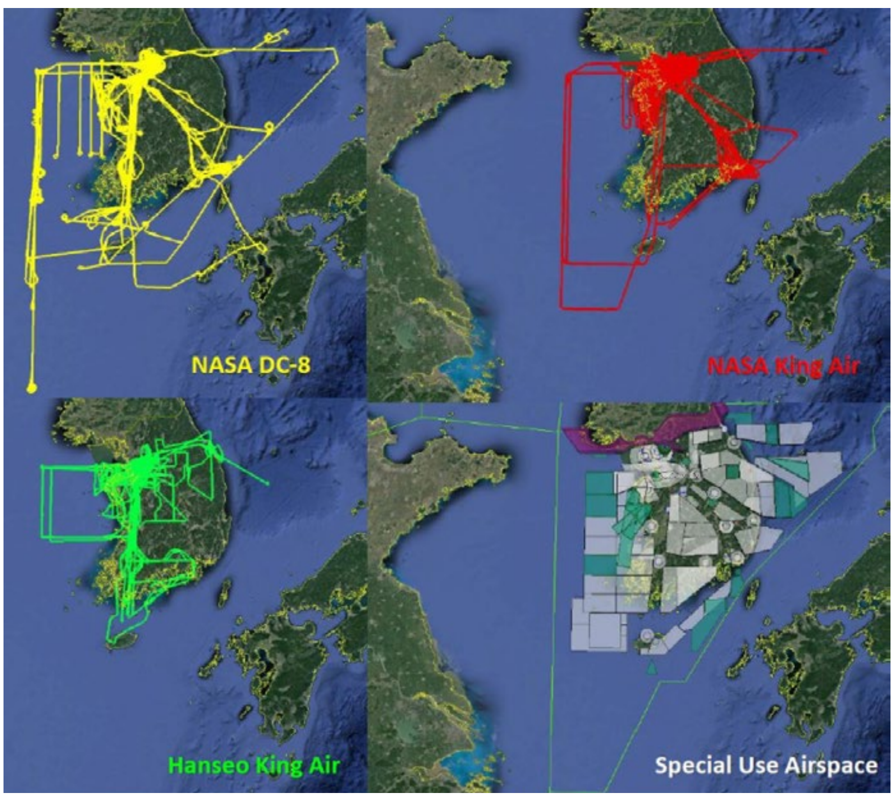

Figure 5. During KORUS-AQ, flights were conducted on 23 days during the 40-day period from May 2 to June 10, 2016. Flight paths are shown for the NASA DC-8, NASA King Air, and Hanseo King Air. Most flight days included all three aircraft. Heavy air traffic and restricted airspace required careful flight planning, which considered flight objectives for that day, air quality, complex terrain, meteorological forecasts, and air traffic control. "Special Use Airspace" required additional authorization. **Image credit**: NASA

[11] The aircraft measurements were used to simulate measurements from future satellites such as the planned geostationary Air Quality Constellation that comprises satellites from South Korea, Europe, and the U.S. For more details on this constellation, see "Geostationary Orbit as a New Venue for Earth Science Collaboration: A Report from the Eleventh CEOS Atmospheric Composition Constellation Workshop" in the July–August 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 4**, pp. 17–22—*https://go.nasa.gov/3nTUa3p*].

The aircraft observations were coordinated so that they could be compared to those obtained by satellites[12] and ground-based observations. Taken together, they represent the most comprehensive description of air quality ever obtained over a highly populated area. Pollution measurements, collected under a wide range of conditions across urban, rural, and coastal regions, allowed for detailed analysis. For example, the meteorological conditions during KORUS-AQ were favorable for understanding how local emissions contributed to local air quality conditions. One result showed that air quality models underestimate emissions (such as nitrogen dioxide[13]) when compared to the aircraft data. This result helped show how air quality is affected by both local emissions and long-range transport (e.g., from China and Japan). These findings are helping to develop strategies for reducing emissions that will ultimately lead to improved air quality.

Conclusion

Until the 1960s, most airborne observations were for astronomy. After that, however, airborne Earth observations grew significantly with NASA's acquisition of passenger and military jet aircraft that were retrofitted with equipment that enabled collecting *in situ* and remote sensing data. The program further grew, under the leadership of ASP, as NASA's Earth-science satellites became more complex and required more-sophisticated technology development and cal/val activities that covered the full range of Earth-science disciplines. ASP's DC-8 conducted over 140 missions from 1987 to mid-2019, surveying all of Earth's oceans and continents. This is a tribute to the overall success of the Program. For the near term, eleven missions that began in 2015 will continue at least through 2021.

ASP continues to upgrade its fleet to improve efficiency and safety and in response to the growing needs of the Earth Venture-Suborbital missions program that is part of NASA's Venture class of missions.

ASP continues to upgrade its fleet to improve efficiency and safety and in response to the growing needs of the Earth Venture-Suborbital missions program that is part of NASA's Venture class of missions—see Footnote 8. The most recent solicitation resulted in the selection (September 2018) of five proposals that will make full use of ASP aircraft, engineering, and planning resources. Finally, ASP anticipates supporting the priorities established in the 2017 Earth Science Decadal Survey[14] that require airborne observations.

Acknowledgments

The author would like to acknowledge personnel from ASP and ESPO for discussing their programs, sharing their personal experiences, and locating some of the figures and other content that appear in this article. Also, **Jay Al-Saadi** [LaRC—*KORUS-AQ Deputy Mission Scientist*] reviewed the section on KORUS-AQ to ensure its accuracy. Finally, the author appreciates the reviews and discerning comments from two individuals at NASA Headquarters: **Jack Kaye** [*Associate Director for Research of the ESD*] and **Bruce Tagg** [*Director of the Airborne Science Program*]. ■

[12] These satellites included the NASA–NOAA Suomi National Polar-orbiting Partnership (NPP), NOAA-20, and European Sentinel-5P, all of which carry similar air quality measuring instruments.

[13] Nitrogen dioxide (NO_2) is a gas that results from burning fossil fuels and is a precursor to ozone pollution. It can be measured from satellites as well as aircraft.

[14] The report is called "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space" and is available for download at *https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

Summary of the Second TROPICS Applications Workshop

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Emily Berndt, NASA's Marshall Space Flight Center, emily.b.berndt@nasa.gov

Introduction

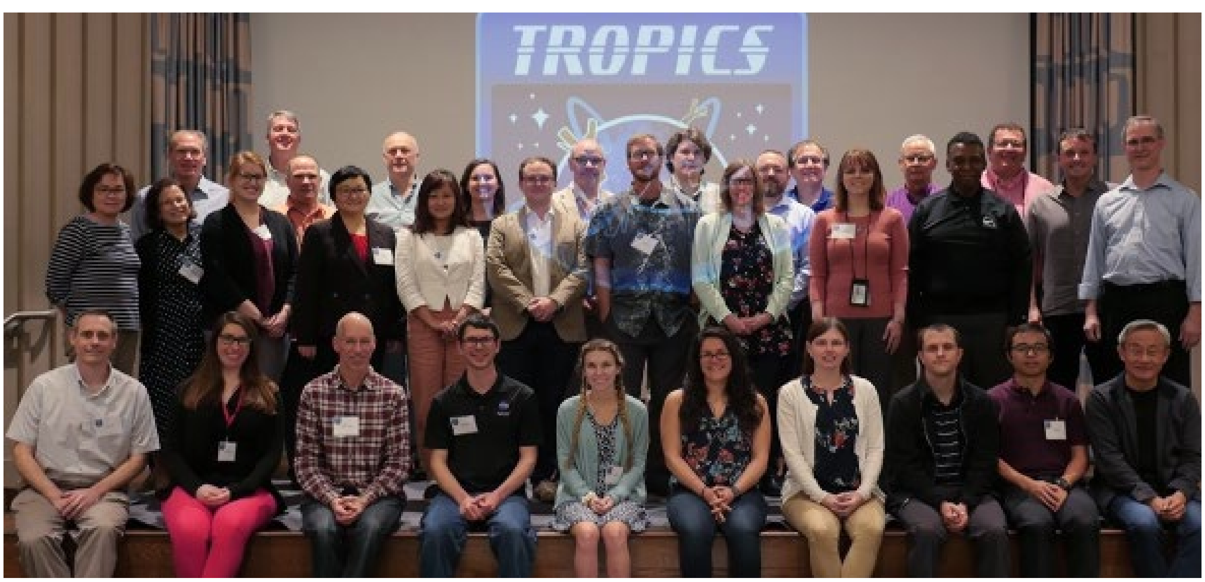
The NASA Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS)[1] mission is a state-of-the-science observing platform that will measure vertical profiles of atmospheric temperature and moisture, as well as surface precipitation and tropical cyclone (TC) intensity, over the tropical latitudes—see *https://tropics.ll.mit.edu/CMS/tropics* for more information. Led by **William Blackwell** [Massachusetts Institute of Technology Lincoln Laboratory (MIT LL)—*TROPICS Principal Investigator*], TROPICS is a Venture-class mission[2] funded by the NASA Earth Science Division (ESD) with an anticipated launch in the 2021–2022 time frame. Providing a median refresh rate of greater than 60 minutes, TROPICS will offer unprecedented temporal coverage compared to the current passive microwave constellation, which has a median refresh rate of approximately every 180 minutes, and will provide spatial resolution similar to current operational passive-microwave sounders.

On February 19-20, 2020, the ESD Applied Sciences Program held the second TROPICS Applications Workshop at the University of Miami's Rosenstiel School of Marine and Atmospheric Science in Miami, FL. The workshop was hosted by the University of Miami Cooperative Institute for Marine and Atmospheric Studies (UM, CIMAS). **Emily Berndt** [NASA's Marshall Space Flight Center (MSFC)—*Deputy Program Applications (DPA) Lead for TROPICS*] and **Jason Dunion** [National Oceanic and Atmospheric Administration (NOAA), University of Miami, Hurricane Research Division] organized the workshop.

The first TROPICS Applications Workshop took place in May 2017.[3] An Early Adopter program[4] for TROPICS was subsequently established in 2018. The goal of the Early Adopter program is to understand and demonstrate the utility of TROPICS data in applied research and operations before launch, to support early adopters in prelaunch applied research, to facilitate feedback on the value of mission data, and to accelerate the integration of TROPICS data into research and operations quickly after launch. The second workshop was designed to facilitate conversations between the TROPICS science and algorithm teams, early adopters, and members of the applied-science and end-user communities. It was intended to highlight potential postlaunch applications of the mission. Included among the 40 workshop attendees were algorithm developers, applied researchers, forecasters, and international

[1] Although the term Smallsat is used for the TROPICS acronym and throughout the article, to be more precise, the constellation is comprised of CubeSats, which are a specific category of Smallsats.
[2] For more information on Venture Class missions, visit *https://eospso.nasa.gov/mission-category/13*.

[3] To learn more, see the "First TROPICS Application Workshop Summary" in the November–December 2017 issue of *The Earth Observer* [**Volume 29**, **Issue 6**, pp. 22–25—*https://go.nasa.gov/3mNXn3Q*].
[4] NASA has established Early Adopter programs for many of its recent missions in an attempt to formalize partnerships with users of data early in the planning process, thus ensuring the greatest value for users of the mission's data.



Attendees at the second TROPICS Applications Workshop held in Miami, FL. **Photo credit:** University of Miami representatives from the Brazilian Instituto Nacional de Pesquisas Espaciais (INPE), Météo France, and the European Centre for Medium-Range Weather Forecasts (ECMWF).

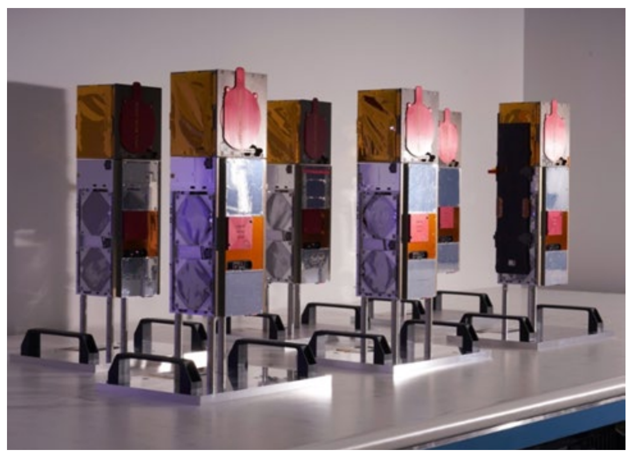
While the primary science objectives of the TROPICS mission focus on improved understanding and prediction of TC intensity and structure, there were also discussions regarding applications apart from TCs, such as those related to severe weather, flooding, and how TROPICS can complement existing satellite missions.

Given this history, objectives for the second TROPICS Applications Workshop included:

- introducing the end-user community to the expected value of TROPICS and learning how TROPICS observations can be used by their organizations;
- providing an opportunity for TROPICS Early Adopters to share preliminary results and provide feedback to the TROPICS science team; and
- identifying potential solutions to any technical and visualization needs, as well as potential barriers to data use, so that the use of TROPICS data can be accelerated postlaunch.

TROPICS Mission Overview

The TROPICS mission will provide nearly all-weather observations of three-dimensional temperature and moisture, as well as cloud ice and precipitation horizontal structure, at unprecedented temporal resolution. TROPICS is a constellation of six 3U Smallsats* [approximately 10 cm x 10 cm x 34 cm (or 4 in x 4 in x 13 in]—see photo below. Each flight unit will host a 12-channel passive-microwave spectrometer based on the Micro-sized Microwave Atmospheric Satellite 2 (MicroMAS-2).



Six of the seven completed TROPICS flight units, ready for launch. Six flight units will fly as part of the TROPICS constellation; the seventh *qualification unit* will launch ahead of TROPICS as a pathfinder mission. Photograph taken at Blue Canyon Technologies, in Boulder, CO. **Photo credit:** William Blackwell

The TROPICS Smallsats will fly in pairs in three low-Earth-orbital planes, providing a median temporal refresh of greater than 60 minutes over tropical latitudes. TROPICS temporal resolution represents a significant improvement over the approximately 180-minute (or 3-hour) temporal resolution of existing passive-microwave sensors, allowing for the assessment of rapid changes in storm development.

TROPICS will measure atmospheric temperature profiles using seven channels near the 118.75-GHz oxygen absorption line, water vapor profiles using three channels near the 183-GHz water-vapor absorption line, and precipitation measurements using channels near 90, 183, and 205 GHz. Characterization of precipitation-sized ice particles and low-level moisture are also included, using a single channel near 205 GHz. At nadir, the spatial resolution of the TROPICS Smallsats will be approximately 27 km (17 mi) for temperature and 17 km (11 mi) for moisture and precipitation. The swath width will be 2025 km (1258 mi). Both the spatial resolution and the swath width are similar to the Advanced Technology Microwave Sounder (ATMS), which is an instrument built for the Joint Polar Satellite System (JPSS)—a partnership between NASA and the National Oceanic and Atmospheric Administration (NOAA).**

By achieving a temporal resolution that is approaching that of geostationary satellites but at a much lower cost, TROPICS technology could impact the design of future Earth-observing missions.

For more details on the TROPICS mission, visit *https://tropics.ll.mit.edu/CMS/tropics* and/or read the "First TROPICS Applications Workshop Meeting Summary" referenced in footnote 3 on page 15.

*CubeSats are built to standard dimensions (measured in Units, or "U") of 10 cm x 10 cm x 10 cm (~4 in x 4 in x 4 in). They typically weigh less than 1.33 kg (3 lbs) per U.

**ATMS currently flies on the Suomi National Polar-orbiting Partnership (NPP) and NOAA-20 (formerly JPSS-1) platforms. It is scheduled to fly on future JPSS platforms.

Workshop Overview

After some opening remarks from mission leaders and from a NASA Headquarters representative, the remainder of the two-day workshop consisted of five presentation sessions, each highlighting different future applications of TROPICS data, and three breakout sessions, which focused on discussions related to latency, end-user needs, and potential strengths and challenges related to Smallsats, respectively.

Presentations from the TROPICS science team and early adopters throughout the meeting demonstrated both preliminary results and potential applications of TROPICS data. Presentations from end-users provided a variety of perspectives on applications of the future mission. The workshop ended with a summary of the main action items and takeaways.

The remainder of this article presents high-level summaries of the presentation and breakout sessions. The meeting agenda and presentations can be found at *http://tropics.ccs.miami.edu/agenda*.

Opening Remarks

The meeting began with welcoming remarks from the host institution by **Jason Dunion** and **Benjamin Kirtman** [UM, CIMAS—*Associate Dean for Research*]. **Emily Berndt** then summarized the workshop objectives (on page 16).

John Murray [NASA Headquarters—*Associate Program Manager for Disasters*] spoke on behalf of NASA's Applied Science Program. He specifically focused on the NASA Disasters Program, which promotes the use of Earth observations to improve prediction of, preparation for, and response to natural and technological disasters.

William Blackwell provided an overview and status report on TROPICS—see *Tropics Mission Overview* on page 16. He reported that all seven of the Smallsats have now been completed. (Six of these are for the full TROPICS mission; the seventh unit, the *qualification unit*, will launch prior to the main TROPICS constellation in early 2021 and serve as a pathfinder mission.) With regard to the full TROPICS mission, payload, space vehicle, and ground-segment testing have shown that all Level 1 Science Requirements have been met and the systems work as expected. Thus far all systems are a "go" toward launch in the first half of 2022.

Proxy Data Presentations

This past year, the TROPICS science team released two proxy datasets designed to match the spatial and temporal coverage of TROPICS and to simulate the 12 TROPICS channel frequencies ranging from 91 to 205 GHz. One dataset is derived from the Weather Research and Forecasting (WRF) model's Hurricane Nature Run (HNR), shown in **Figure 1**; the other is based on remote sensing observations from the Chinese FengYun-3C (FY-3C) satellite. Both of these datasets have been made available to the community (*https://weather.msfc.nasa.gov/tropics/products_proxy.html*).

Early adopters presented preliminary results using both of these datasets—e.g., see "Profile of a Tropics Early Adopter" on page 18. For the numerical model data from the HNR, validation of the synthetic data with the full-model simulation shows that TROPICS proxy data simulate similar TC structure but underestimate

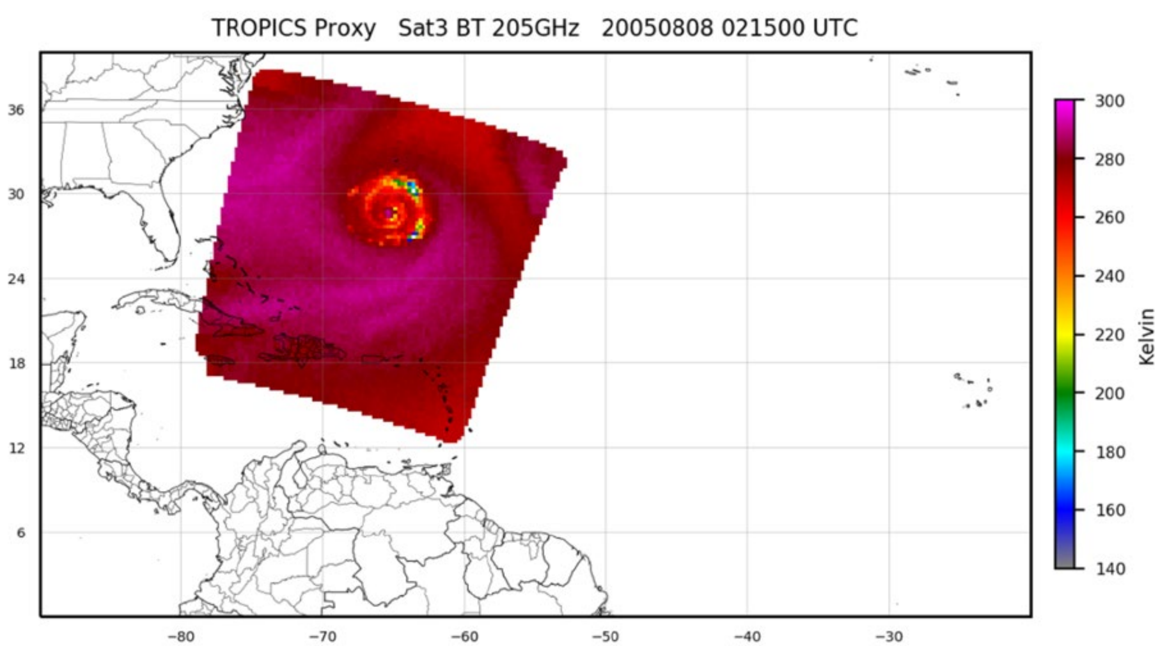


Figure 1. Example of the TROPICS proxy data from the Hurricane Nature Run model. A simulated overpass is demonstrated with the 205-GHz channel, with cooler brightness temperatures indicating the structure of convective clouds and warmer brightness temperatures indicating the ocean surface conditions. **Image credit:** NASA SPoRT

precipitation amounts. (This result appears to be caused by a warm bias of the synthetic brightness temperature data.) In addition, while the spatial resolution of TROPICS may limit the ability to track individual convective cores in a TC, the frequency of TROPICS overpasses allows for detection of the TC diurnal cycle, which is currently difficult to observe using low-Earth-orbit remote sensing platforms. Simulated TROPICS radiances also improve analyses and forecasts in the Hurricane Weather Research and Forecasting (HWRF) model, Version 3.6, improving the initial conditions for moisture, the position of the TC, short-term TC track forecasts, and TC track and intensity forecasts beyond 48 hours.

For the dataset that uses remote sensing observations from FY-3C, early adopters indicate clear benefit of assimilating 183-GHz channels in the ECMWF system, with the main impact of the 118-GHz channels seen in the improved short-range forecast of clouds.

Profile of a TROPICS Early Adopter: Hui Su

Hurricane track forecasts have become quite accurate in recent years, but hurricane intensity is still a growing edge for forecasters. Consider, for example, the recent case of Hurricane Laura. After impacting several islands in the Caribbean, it underwent a period of rapid intensification as it moved over the warm waters of the Gulf of Mexico. It then made U.S. landfall in Cameron, LA on August 26, 2020, as a Category 4 hurricane—and one of the strongest to ever impact Louisiana.

While the model track forecasts for Hurricane Laura—particularly those issued three-to-five days in advance of landfall—were remarkably accurate, the rapid intensification that occurred as the storm approached the Gulf Coast was not as well predicted.*

The research being conducted by **Hui Su** [NASA/Jet Propulsion Laboratory (JPL)] and her colleagues seeks to improve the gaps in our knowledge of the physical forces that govern hurricane intensity. Su is one of the 18 Early Adopters chosen for the TROPICS mission; the project she leads falls under the Tropical Cyclone and Tropical Dynamics applications focus area. Su's team worked to develop a prototype of rapid application of TROPICS data into operational forecast guidance using machine learning techniques. By using NASA's Modern Era Retrospective analysis for Research and Applications–2 (MERRA-2) model and Tropical Rainfall Measuring Mission (TRMM) precipitation data as proxies, her team demonstrated that future TROPICS measurements (e.g., environmental humidity, inner-core precipitable water, precipitation, ice-water path, liquid-water path, and tropopause temperature) could all serve as inputs to the machine learning models and lead to improved rapid intensity forecasts for tropical cyclones.

Su plans to continue to evaluate how TROPICS environmental parameters, precipitation, and radiances can improve TC intensity forecasts.

To learn more about this topic, see *https://go.nasa.gov/3jPoHwB*. More information on TROPICS Applications Focus Areas and the current list of TROPICS Early Adopters can be found at *https://weather.msfc.nasa.gov/tropics*. (Click on the icon for each focus area to see the respective Early Adopters.) To become a TROPICS Early Adopter, participate in quarterly applications telecons, or be added to the email list, contact **Emily Berndt** (*emily.b.berndt@nasa.gov*).

*To learn more, see *https://www.washingtonpost.com/weather/2020/08/27/national-hurricane-center-forecast-laura*.

TROPICS Early Adopter, Hui Su. **Photo credit:** Hui Su

Application Presentations 1: Tropical Cyclone Analysis and Forecasting

The frequent revisit rate of TROPICS provides more images of TC structure than the current passive microwave constellation, allowing for better measurement of TC structural evolution and center location, as well as more estimates of TC intensity. While participants stressed that a data latency less than three hours is optimal for TC assessment in real time, TROPICS data are still valuable for post analysis and preparation of final TC reports, such as those written by NOAA's National Hurricane Center (NHC).

Application Presentations 2: Terrestrial (or Land-Based)/Disasters/Severe Weather

Since the high temporal frequency of TROPICS will supplement precipitation data in regions that lack ground-based radar coverage, TROPICS could be valuable for both monitoring of and response to natural disasters, such as flooding and severe weather events. TROPICS also captures the structure of precipitation and may help improve rainfall estimates over both land and ocean. Using the HNR proxy data, both the 91- and 183-GHz TROPICS channels demonstrate an increase in rain rates with a decrease in brightness temperature, consistent with expectations. In addition, using the TROPICS oxygen channels (114.5–118.58 GHz) to model the brightness temperatures also demonstrates a good correlation with rain rates that can provide useful information, even though oxygen channels are not typically used in this context.

Application Presentations 3: Tropical Cyclone Modeling and Data Assimilation

Operational modeling groups suggest that assimilation of all-sky microwave radiances from TROPICS could potentially improve TC track and intensity forecasts. For example, results using all-sky assimilation of infrared water vapor radiances demonstrate a 58% reduction in errors in intensity forecast for Hurricane Patricia as compared to results obtained using a control simulation that did not include all-sky radiances. Both these model runs were done using the Naval Research Laboratory's (NRL) Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC) model—see **Figure 2**. To assimilate TROPICS data into operational models, attendees indicated that a data latency of less than four hours is ideal, and that data quality flags, uncertainties, and biases are also necessary.

Presentations on Synergy with Other Missions

Since the TROPICS constellation will offer rapid-refresh passive microwave measurements throughout the tropical latitudes, the mission has the potential to complement several existing satellite missions to support a variety of applications (e.g., TC forecasting, monitoring severe weather, precipitation-related disasters). For example, observations of the thermodynamic environment in the TC inner core and near-storm environment can complement wind speed observations from the SmallSat-based Cyclone Global Navigation Satellite System (CYGNSS), which uses GPS signals scattered by the ocean surface to measure ocean-surface wind speed in most naturally occurring precipitation conditions. This combination of thermal and wind speed information in the TC inner core at high temporal frequency could provide unique observations of TC evolution, including genesis and rapid-intensification phases. Passive microwave images (e.g., 90 GHz) from TROPICS may also help in both identifying the location of a TC center and estimating the TC intensity when the center is obscured by upper-level clouds in Geostationary Operational Environmental Satellite (GOES)-East and -West Advanced Baseline

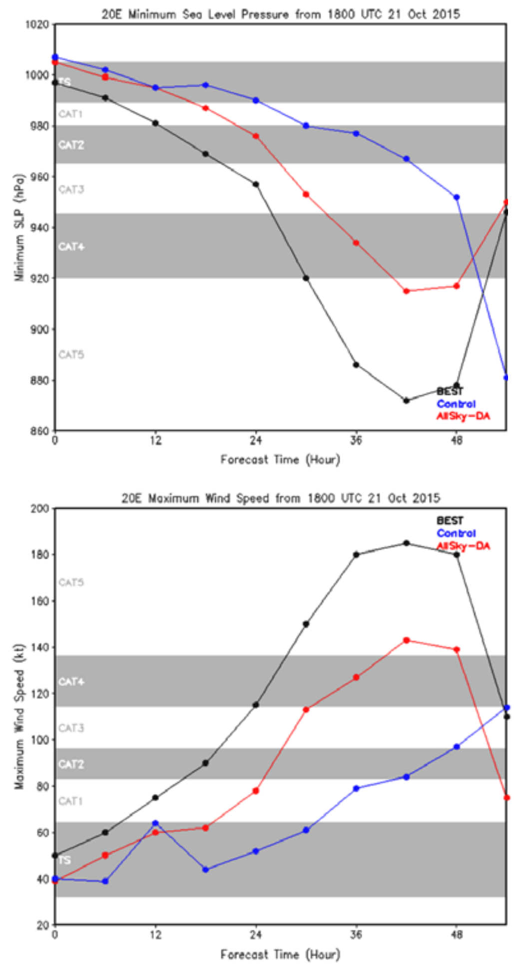


Figure 2. Comparison of intensity forecasts for Hurricane Patricia (2015) using all-sky infrared radiances in data assimilation (red line) and without all-sky infrared radiances in data assimilation (blue line), and the observed intensity trend of Hurricane Patricia (black line). Assimilating the all-sky infrared radiances in the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC) model significantly improves the simulated intensity based on both minimum sea level pressure [*top*] and maximum wind speed [*bottom*]. Reduced errors in both of these metrics produce improved model estimates. **Image credit:** Naval Research Laboratory

Imager (ABI) imagery. In addition, TROPICS rain-rate data could be used in conjunction with GOES Geostationary Lightning Mapper (GLM) lightning measurements to observe and track precipitation evolution and convection in both TCs and other regions of tropical convection with the potential to create destructive flooding.

Breakout Sessions

Three breakout sessions were held to capture: end-user perspectives related to latency; community needs for products, visualizations, and new tools; and potential strengths and limitations of integrating Smallsats into research and applications.

In the first breakout session, on Data Latency, workshop attendees agreed that most operational applications require a latency of better than 3-6 hours, with most users stating 30 minutes to 1 hour as an optimal latency to enable operational use of the data for making time-critical decisions.

The next breakout session, on End-user Needs, was designed to identify needs for additional products (including Level 3 or Level 4), visualizations, data formats, or tools that would facilitate the use of TROPICS data. Attendees stressed that making available a variety of data types and visualization would be ideal, along with the training resources that describe the utility and interpretation of different products. For large-scale tropical research and forecasting, monthly aggregated products of rainfall, moisture, and temperature would be useful. Attendees also expressed much interest in a "match-up database," allowing for quick comparison between TROPICS data and those from other missions.

The last breakout session focused on the potential strengths and limitations of utilizing Smallsats in applied research and operations. This discussion was a valuable first step in gathering user feedback on integrating Smallsat technology for their applications, as there are only a few Smallsat missions currently in orbit [e.g., Temporal Experiment for Storms and Tropical Systems - Demonstration (TEMPEST-D) and CYGNSS]. Overall, attendees agreed that the advantages of TROPICS include increased temporal coverage, availability of some familiar frequencies, and the usage of TROPICS (e.g., for validation of numerical models and satellite data products). Possible limitations include both calibration and a short mission lifetime. Since the time required to incorporate new data into data assimilation systems and user applications could be a significant fraction of the anticipated TROPICS mission lifetime, attendees strongly recommended launching the seventh TROPICS unit as an early pathfinder mission, which would allow for the opportunity of early integration of TROPICS data into their systems.

Summary

To close the meeting, **Emily Berndt** summarized the main action items and takeaways from the workshop. The primary takeaway centered on the recommendation to improve latency to enable real-time decision making related to weather forecasting, disaster preparation and response, and operational data assimilation. Additionally, there was a strong recommendation to launch the seventh qualification unit early, as an opportunity may arise to develop infrastructure and demonstrate capabilities prior to the launch of the full mission. Lastly, users recommended a variety of data formats to accelerate the integration of TROPICS data into applications given the shorter mission lifetime and the need for targeted training to understand new capabilities, such as the value of the 205-GHz channel for operational TC forecasting.

Conclusion

The second TROPICS Applications Workshop provided an opportunity to demonstrate the value and applications of the TROPICS mission and allowed for a variety of discussions between the science team, early adopters, and potential end-users. Prelaunch activities continue; these include evaluation of proxy datasets, applied research to understand new capabilities (e.g., the 205-GHz channel), refinement of precipitation algorithms and desired products, and the development of formats, requirements, tools, and error characteristics for operational data assimilation. With all of this effort extended prior to launch, the community will be well positioned to integrate TROPICS data into applied research and the operational environment as soon as they become available.

Acknowledgments

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Summary of the 2019 SARI Sustainable Forestry in South Asia Meeting

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Introduction

The countries of South Asia—including, for the purposes of this article, India, Bangladesh, Nepal, Sri Lanka, Bhutan, Pakistan, Afghanistan, and Myanmar—account for almost 25% of the world's population. In this region, as in other parts of the world, healthy forests—which are essential for healthy ecosystems, globally—are affected by increasing human-caused or -related effects through deforestation and afforestation. These changes are caused by physical, biological, agricultural, and social issues and actions, and combinations between them. The presence and direction of forest changes cannot be directly linked to population growth alone: Consider, for example, that a population increase in India actually resulted in forest growth, while many consequences of population growth have caused deforestation with varying intensities in other regions. Identifying and quantifying the drivers of deforestation and afforestation and understanding the impacts of these changes on the environment is therefore essential—and requires a holistic approach.

To discuss potential ways to address these issues, NASA's Land Cover/Land Use Change (LCLUC) Program—South/Southeast Asia Research Initiative (SARI, *https://www.sari.umd.edu*), in collaboration with other partners, listed below, organized a meeting titled *Sustainable Forestry in South Asia—Current Status, Science, and Conservation Priorities*. The meeting was held November 7–9, 2019, at the Tata Energy Research Institute (TERI) School of Advanced Studies (SAS), New Delhi, India. Collaborators included Virginia Polytechnic Institute and State University (hereinafter Virginia Tech), U.S.; the international Global Observations of Forest and Land-Use Dynamics (GOFC–GOLD) program; START,[1] U.S.; NASA SERVIR,[2] and the University of Illinois Urbana Champaign, U.S.; and various other universities and institutions in South Asia.

[1] START is not an acronym; this organization is a core international partner of the U.S. Global Change Research Program that seeks to realize a sustainable future through science (*https://start.org*).

[2] SERVIR is not an acronym; it means "to serve" in Spanish. The entity is a joint venture between NASA and the U.S Agency for International Development (USAID). It provides state-of-the-art, satellite-based Earth monitoring, imaging and mapping data, geospatial information, predictive models, and science applications to help improve environmental decision-making among developing nations in several locations around the world (*https://www.nasa.gov/mission_pages/servir/index.html*).

The three-day meeting was organized around the following sessions with presentations and panel discussions:

- mapping/monitoring of forest cover, plantations, and trees outside forests—including degradation in South Asian countries;
- greenhouse gas (GHG) emissions in the forestry sector and other land uses;
- forest fires and post-fire vegetation recovery dynamics;
- forest carbon inventories and management;
- forest ecosystem functions; and
- impact of land-use change on forest biodiversity, social forestry, community forest management, and conservation.

Altogether, 94 participants from eight different countries representing various universities, government, and nongovernmental organizations attended the meeting—see **Photo** on next page. This summary is organized by day and presents highlights from the 60 presentations across the various sessions and discussions. The daily reports are broken up roughly in terms of activities happening in the various South Asian countries. While not every presentation can be described, those selected give a flavor for what was discussed during the three-day event. The full meeting agenda and the presentations can be accessed at *https://sari.umd.edu/meetings/sustainable-forestry-south-asia*.

DAY ONE

The first day began with opening remarks to put the meeting in perspective. The rest of the day was devoted to a series of presentations from SARI forestry experts, describing the status of the forest cover of each nation represented and the need for policies and action to address country-specific forestry issues.

Opening Remarks

The meeting began with opening presentations from local host **Jai Garg** [TERI SAS, India—*Professor, Department of Natural Sciences*], **Krishna Vadrevu** [NASA's Marshall Space Flight Center (MSFC)—*SARI Project Lead*], **Ajay Mathur** [TERI, India—*Director General*],

Participants of the 2019 SARI Sustainable Forestry in South Asia Meeting in New Delhi, India. **Photo credit:** Krishna Vadrevu

Manipadma Datta [TERI SAS—*Vice-Chancellor*], **Siddhanta Das** [Ministry of Environment, Forests and Climate Change, Government of India—*Director General of Forests and Special Secretary*], **Prakash Chauhan** [Indian Institute of Remote Sensing (IIRS)—*Director*], and **Randolph Wynne** [Virginia Tech, U.S.—*Professor, Department of Forest Resources and Environmental Conservation*]. While each speaker addressed different topics (see online agenda for details), common themes throughout the opening remarks were the need for effective collaborations in the region and the use of geospatial tools for effective forest mapping and monitoring, with all activities to include building more collaborative projects involving SARI and U.S. scientists.

Status of Forest Cover and Resources in South Asian Countries

Prakash Chauhan [IIRS] chaired this session, with **Srishti Solanki** [Guru Gobind Singh (GGS) Indraprastha University, India] serving as rapporteur.

Forests play many beneficial roles for life on Earth. Among their many functions are providing ecosystem sustenance, serving as carbon sinks, and supplying resources for human activities. It is therefore a significant concern that, owing to human and otherwise naturally caused factors, deforestation is increasing in many areas. Understanding the nature and extent of forests on local regional, national, and global scales has become a subject of increasing importance.

To provide context for the meeting, several presentations described aspects of forest cover in South Asian countries.

Subhash Ashutosh [Forest Survey of India (FSI)—*Director General*] presented the latest assessment of forest resources of India. He stated that the FSI has been implementing the biennial forest cover mapping of the entire country using remote sensing data at 1:50,000 scale and releasing the India State of Forest Report (ISFR). Since 1987 there have been 16 assessments; the most recent was released in 2019. India is among the few countries in the world where forest cover is consistently increasing, although by small increments. With the increase in forest cover, there is also an annual increase in the carbon stock by about 19.5 million tons (17.6 million metric tons).

In Bangladesh, on the order of one-sixth of the land surface is forested, with the majority of that forested area being covered in natural mangroves. The National Forest Monitoring System (NFMS) was established in 2016, and satellite data, together with sample-based forest inventory, are used for forest mapping and monitoring. The analyses clearly demonstrate that from 2000 to 2015, there has been a roughly 2% reduction in tree cover with the highest carbon storage found in mangroves. Tree cover in Bangladesh is being monitored through collaboration with the University of Maryland, College Park using 30-m (98-ft) data from Landsat 7 and 8. The results suggest a decrease in tree cover of near 6% from 2000 to 2014.

In Nepal just over 31,400 community groups manage state-owned forests. Since local communities are involved in forest-management activities, forests are well protected and have low deforestation rates. Nepal stands out as the country where there are the most community- and participatory-based joint forest-management activities, which have proven successful. Most of the forest mapping activities are being carried out by Nepal's Department of Forest and the International Centre for Integrated Mountain Development (ICIMOD).

Myanmar is currently undergoing rapid economic development. Since 2011 the government has been focusing on sustainable forestry development through launching political, economic, and social reforms in line with the modern forestry concepts. However, because the population is so dependent on the use of forest products for their livelihoods, the deforestation is relatively high, with a roughly 15% loss from 1990 to 2015. A variety of remote sensing data were used for the 2015 assessment, including Landsat 8 and Indian remote sensing Linear Imaging Self Scanning (LISS)-3 sensor[3] data for the Forest Resource Assessment (FRA).

In Bhutan forest conservation has been a priority of government and local people for several years. The forest department's latest forest-cover assessment (from 2017) suggests that 71% of the total land area is forested with a mixture of broadleaf forests, blue pine, and mixed conifer. This amount of forest cover already exceeds the constitutional mandate to maintain 60% forest cover at all times. The United Nations' Food and Agriculture Organization datasets estimate there has been a slight (about 0.3%) increase in forest cover between 1990 and 2010. Recently, agriculture, mining, and quarrying activities have been threatening forest cover in different regions of Bhutan.

The forests of Sri Lanka include tropical rain forests, dry mixed evergreen forests, montane forests, submontane forests, and thorn forests and scrublands. The deforestation rate was just over 1% per year between 2000 and 2005. Important influences on deforestation include agricultural expansion, shifting cultivation, urbanization, felling trees for timber and fuelwood, and the mining industry.

In India the IIRS conducted a national-level, above-ground, forest-biomass assessment for 2010, based on having established nearly 6000 ground inventory plots across the country for biomass estimates. Eddy correlation towers were erected at two different locations, covering selected moist, mature deciduous forests and mixed deciduous forests to quantify the Net Ecosystem Exchange (NEE). The NEE represents the net carbon dioxide (CO_2) flux from the ecosystem to the atmosphere, measured as the net difference between the photosynthetic carbon (C) uptake and respiration. In addition, IIRS is involved in various capacity building and training activities.

Mapping and Monitoring of Forest Cover and Wetlands Including Degradation

Subhash Ashutosh chaired this session, with **Ridhi Saluja** [Wetlands International, India] serving as rapporteur.

There are other issues besides deforestation that require attention. The nature and distribution of forests change over time, with concomitant effects on ecologies, economies, and changes in hydrologic patterns and other biogeophysical phenomena. Understanding the factors that contribute to these changes and developing methods to take appropriate measurements to support that understanding is a key need.

Recent advances in remote sensing suggest that multispectral and hypertemporal satellite data and imaging spectroscopy can be used to map foliar (i.e., leaf) biochemical, morphological, and metabolic traits of plants. In particular, remote sensing from drone-mounted cameras has proven to be an effective means to capture a wide variety of foliar properties.

One result of such measurements is the observation that the areal coverage of mangroves in India decreased at the rate of 6.5% per year between 2000 and 2015. Related work showed that remote sensing, and geospatial technologies can be used effectively to aid in conservation measures.

In Central India, forest degradation is rampant. A remote-sensing-derived, bare-ground index, developed using high-resolution [e.g., 3-m (10-ft)] satellite data (in this case, from *Planet*, an American company that specializes in Earth imagery), has proven to be effective for mapping and monitoring degradation. Some have suggested that this forest degradation might be driven by human migration, but there is no evidence to support that hypothesis in this instance. However, in acknowledgment of this possibility, there is a need to enact strong policies to reduce anthropogenic pressure on forests. It is essential to consider cost-benefit analysis when implementing afforestation programs.

Quantifying carbon pools, fluxes, and net carbon balance in the forestry sector is challenging due to significant variability in the types of vegetation and the associated biomass. The National Carbon Project, organized under the International Geosphere–Biosphere Program (IGBP), used flux tower measurements that suggest about a 12% increase in *phytomass*, or carbon stored in trees, from 1994 to 2010. The increase in carbon is attributed to the almost 5% increase in forest cover.

Finally, in Nepal a study conducted by the East–West Center[4] suggests that between 1992 and 2016, tree cover nearly doubled—increasing from 26% to 45% of the nation's land area. The tree cover regeneration is attributed to community forestry activities. The East–West Center has developed improved methods for mapping forests in mountainous regions of Nepal as well as a database of physiographic and socioeconomic characteristics.

[3] LISS-3 flies in the Indian Space Research Organisation's (ISRO) Resourcesat–1 and Resourcesat–2 satellites.

[4] The East-West Center (*https://www.eastwestcenter.org*) promotes better relations and understanding among the people and nations of the U.S., Asia, and the Pacific through cooperative study, research, and dialogue.

DAY TWO

Two sessions took place on the second day of the meeting; the material presented is summarized here.

Trees Outside Forests, Plantations, and REDD+

Ruth DeFries [Columbia University] chaired this session, with **Satish Prasad** [GGS Indraprastha University, India] serving as rapporteur.

Plantations account for significant biomass types in South Asian countries, as trees exist beyond the boundaries of forests. Both vegetation types bring with them their own contributions to climate change mitigation and/or adaptation. Locating and characterizing such nonforest vegetation has utility in several areas, and acquiring suitable data is increasingly important in making supportable decisions.

In Andhra Pradesh, India, for example, plantation area has been increasing at the cost of croplands. Cloud-free Harmonized Landsat Sentinel-2 data at 10-m (33-ft) resolution is highly useful for mapping the plantations; however, high-quality, field-verified, classification training data are essential. Details on the economics of land-use transitions from agriculture to forest crops across the study area and probit modeling[5] suggest that tree planting is highly influenced by farm ownership, the number of plots owned, and land area. In Himachal Pradesh, India, people's choices have shifted towards planting species with valued community benefits, such as for food (e.g., walnuts), fuel (e.g., shisham) and fodder (e.g., grass tufts), in contrast to commercially valuable trees (e.g., pines). The latter was reportedly associated with increased fires and invasive species and decreased water availability while providing few benefits. Thus, the number of new pine plantations has decreased dramatically in recent years, both as a result of top-down policy changes and bottom-up advocacy.

Accounting for the economic benefits of trees outside forests (ToF) is essential for reducing emissions from deforestation and forest degradation (REDD) and carbon cycling studies. For mapping ToF, very high-resolution data and new allometric equations are required. For example, in Haryana, India, the Department of Science and Technology has been using very-high-resolution Cartosat-1[6] [2.5-m (8-ft) resolution] and Indian Remote Sensing (IRS) Program Resourcesat-2 LISS-4 [5.8-m (19-ft) resolution] data to map the ToF areas that are located on farmlands and built-up areas. Image fusion using these two datasets yields excellent results, accurate enough to map linear ToF formations, block ToF formations—and even individual trees.

In Myanmar, Forest Reference Level (FRL) and Forest Reference Emission Level (FREL) documentation was submitted to the United Nations' Framework Convention on Climate Change's (UNFCCC) REDD+ program in January 2018 and approved in November 2018.[7] The document can be accessed from the UN-REDD website (*https://www.un-redd.org*).[8] The document serves multiple purposes, such as summarizing national commitments for climate change mitigation, addressing deforestation and supporting multiple stakeholders in achieving the goal of reducing deforestation, and serving as strong documentation when seeking potential funding sources for result-based payments.

In Bangladesh the FRL development and consultation process started in 2016, with the final report submitted in July 2019. As an example of some successful results, the report noted that 86% of deforested areas was converted into shrubs with scattered trees, 6% to agriculture, 4% to rivers and drainage canals, and 2% to settlement areas.

Forest Carbon Cycle and Ecosystem Functions

Vinay Dadhwal [Indian Institute of Space Science and Technology, India] chaired this session, with **Sangeeta Bansal** [GGS Indraprastha University, India] serving as rapporteur.

For quantifying the carbon cycle, there is a strong need to integrate top-down and bottom-up approaches. Some of the important terms in the terrestrial carbon cycle include Net Ecosystem Productivity (NEP), defined as net primary productivity minus heterotrophic respiration, and Net Biome Productivity (NBP), which is NEP minus emissions due to land-use change and fires. Results from dynamic vegetation models suggest that the temperature variation drives the NEP of forests in South Asia. The mean carbon fluxes from 2000 to 2018 for the region show that NEP accounts for most of the total sinks, with NBP—while less—still a major contributor. A much smaller increase can be attributed to land-use changes; carbon as a source in the calculation came from fires. The uncertainties in carbon stocks and fluxes could be due to the land-use and -cover data, process-level understanding of biogeochemical phenomena, and interactions due to environmental and management variables used in the modeling studies.

[5] A probit model (also called *probit regression*) is a way to perform regression for binary variables—i.e., variables with two possible outcomes.

[6] The Cartosat satellites are a series of ISRO missions used for Earth resource management and defense applications. The first launch was in 2005; the most recent was in 2019.

[7] REDD+ is a voluntary framework for developing countries. It adds several other activities to the earlier-described REDD, with activities to address conservation, sustainable management of forests, and enhancement of forest carbon stocks. Most key REDD+ decisions were completed by 2013, with the resulting rulebook having been completed in 2015.

[8] The United Nations UN-REDD Collaborative Programme is a multilateral body that partners with developing countries to support them in establishing the technical capacities needed to implement REDD+ and to meet UNFCCC requirements for REDD+ results-based payments.

One of the hotspots for forest carbon as well as biodiversity in South Asia is the Himalayas. (The Eastern Himalayan forests were among 25 areas worldwide classified as biodiversity hot spots; that number has now increased to 36.) These mountains represent a large wilderness area with a cold climate that is rich in endemic species. For example, nearly 40% of the total 8000 species of flowering plants found there are endemic to the Himalayas. However, forests in the region have declined by nearly 5% within the span of four years, as reported in India's State of the Forestry Report from 2019.

The loss of biodiversity in the Himalayan region is a matter of great concern, yet its magnitude has not yet been quantified. Essential topics for further study in the region include carbon-sink estimation, forest fires, climate change impacts, community forest protection, soil and water conservation services, and assessing the impacts of invasive species on forest diversity. In addition, there is a need to develop multisite, multipartner projects using state-of-the-art methods and instrumentation.

Mangrove ecosystems represent a rich source of carbon. On the order of one-sixth of the land surface of Bangladesh is forested, with the majority of that area being mangroves. Mangrove coverage has declined over the last 100 years. Management efforts aimed at preventing continued loss of coverage—particularly in the mangrove-intensive intertidal Sundarban delta area on the southern coast of Bangladesh—are a challenge for foresters because of the greater dependency on forest products by local populations—which makes protecting them all the more important.

One of the different approaches being pursued for quantifying the amount of carbon in various phases of the carbon cycle is called Life Cycle Assessment (LCA), which is a complex and detailed process of breaking down all of the inputs that go into production of materials and looking at the environmental impacts associated with resource extraction, use, and disposal. There are several impacts, which include carbon emissions and water and air pollution. In the forestry sector, the use of LCA is important as the forests provide renewable materials (as long as there is forest replacement growth), e.g., building materials, pulp and paper, and energy. There is a need for LCA of different forest products, services, and resources in Asia to address the economic, environmental, and societal benefits at varied spatial scales.

DAY 3

Fires and Air Pollution in South Asian Countries

Krishna Vadrevu chaired this session, with **Ayushi Vijhani** [TERI SAS] serving as rapporteur.

The information presented in this session covered a range of topics, including the nature of vegetation fires, research priorities in South Asia, regional fire activity responses to climate and human factors, and the effects of fires on the generation of atmospheric pollutants, including aerosols and their properties. There was also discussion of real-time fire monitoring and burnt-area assessment.

The downwind effects of fires are a vital concern but understanding the upwind causes of fires is also worthy of significant attention, if only to prevent or mitigate those downwind effects. While the specific drivers of fires in South/Southeast Asia (S/SEA) can be linked to both natural (e.g., lightning) and human activities (e.g., biomass burning related to agricultural activity) that vary from country to country, anthropogenic fires dominate. Satellite data have been used to study fire trends in S/SEA. At the country level, the data suggest that India, Pakistan, Indonesia, and Myanmar have the most fires of all South Asian countries. Between 2012 and 2016, about 30% of S/SEA experienced recurrent fires, with the most occurring in Laos, Cambodia, Thailand, and Myanmar. Statistically significant increasing fire trends were found for India, Cambodia, and Vietnam; by contrast, only Timor Leste had a statistically significant decreasing trend.

In S/SEA, fires over croplands were equally frequent as those in forests, with increasing fires in India, Pakistan, and Vietnam. With regard to climate drivers, precipitation could explain more of the variations in fires than temperature, with stronger correlations in Southeast Asia than in South Asia.

In general, the mild-fire incidence in India's fire-prone areas is almost seven times greater than heavy and moderate fires combined. More research is required to understand the mechanisms that regulate fires, but the working approach is that most fires can be linked to human activities.

Social Forestry and Community Forest Management

Jeff Fox [East-West Center] chaired this session, with **Nandita Singh** [TERI SAS] serving as rapporteur.

The topics covered in this session included sociopolitical drivers of deforestation (e.g., property and other rights), the connection between local populations and their dependencies on forests, and the roles of and interactions between various stakeholder groups—all for personal and commercial economic benefit, as well as to limit threats to physical safety on all levels.

An excellent example of how stakeholders interact to the detriment of society by increasing deforestation is found in Myanmar, one of the most heavily forested countries in Asia, which has experienced increased logging with resultant deforestation over time. To try to determine how this happened, field research, household interviews, and focus group discussions in villages suggested that political transition created a window of uncertainty due to lack of control and regulation, with the attendant increases in deforestation.

To further forestry's social goals, cover-type categories used in mapping "good" (i.e., dense, healthy) and "bad" (i.e., degraded) forests are needed. For example, having such information will ease the transition in South Asia from measuring forest cover change to enabling sustainable forestry, and ease current concerns about how a focus on carbon distribution (i.e., biodiversity) can sideline other—potentially more critical—*social forestry*, which prioritizes the needs of local communities. At the very least, there is a need to disaggregate and re-aggregate the forest-cover maps to represent multiple values and clarify the actual ecological and social tradeoffs among ecosystem benefits, e.g., for timber, wood, fuel, and food.

In India, Community Forestry Rights (CFR)[9] should not be just about granting rights to individuals and institutions to own land; there should also be a concomitant commitment to sustain collective efforts for equitable resource outcomes. If the perceived collective benefit of institutional participation is high, the chance of joint mobilization for CFR will be high. Overall, CFR provisions still hold immense promise in balancing the power dynamics in India's forest governance. Thus, there is a need to identify all institutions with similar forest conservation goals and actively expedite CFR implementation.

An interesting approach to community-driven decision making and action is the Search for Action and Knowledge through Tribal Initiative (SAKTI), which is a voluntary, nongovernmental organization that started in 1985. The organization's aim is to empower indigenous communities and conserve natural resources in India. Over the last decade, SAKTI has evolved into a team comprising anthropologists, social scientists, linguists, spatial analysts, and project managers. The organization is addressing several issues pertinent to forest conservation, tribal land rights, water rights, governance of commons, and disaster preparedness in the region. More about SAKTI activities can be found at *http://www.sakti.in*.

The relationships between forest-dependent peoples (FP) and state forest departments (FD) are central to forestry practice, yet they are seldom the focus of research studies. A recent review and meta-analysis of 135 articles published between 1997 and 2017 revealed that research is attentive to the FP–FD relationship primarily in the context of decentralization or community participatory policies and projects. Well-designed policies, projects, institutions, and competent individuals create opportunities for partial, temporary, and symbolic transformation in the FP–FD relationship. However, structural power asymmetry between FD and FP—historically established, and reproduced through social inequalities and hierarchies—will continue.

[9] CFRs were established as part of the Indian Forest Rights Act of 2006. These have proven to be important for securing livelihoods of the forest communities and for strengthening local self-governance of forests and natural resources. The CFR link is a part of a collective initiative for collection and sharing of information on CFR from different states.

Summary and Conclusion

This meeting highlighted that SARI, the NASA LCLUC research initiative, is strengthening land-change science to support the needs and priorities for sustainable forestry research in South Asian countries by involving regional scientists. The meeting also helped to showcase the latest methodologies in ongoing forestry research in South Asia. Several presentations and discussion sessions suggested a need for increased emphasis on mapping and monitoring forests at regular intervals, focusing on local forestry research and case studies, addressing drivers and impacts of deforestation and afforestation, promoting interdisciplinary research, and addressing community forestry issues. The discussion sessions held during the meeting were an excellent opportunity for meeting participants (many of them the regional scientists mentioned earlier) to connect with remote sensing, forestry, and social science experts, for the benefit of both groups and, therefore, of society. It also engaged several early career researchers in the region in learning about remote sensing, spatial technologies, and community forestry. All participants strongly urged SARI to continue and increase support for such meetings as a means to build effective collaborations on forestry research and potential applications.

The local host **Jai Garg**; SARI lead, **Krishna Vadrevu**; and **Randolph Wynne** thanked all participants and sponsors. The next SARI meeting and training event is planned for late 2021.

Meeting Outputs

A Special Issue of Papers focusing on the Remote Sensing of Forestry in South Asia is being published in *Remote Sensing Applications Society and Environment* (Editors: Krishna Vadrevu, Jai Garg, and Randolph Wynne). The call for papers can be accessed from *https://www.journals.elsevier.com/remote-sensing-applications-society-and-environment/call-for-papers/remote-sensing-applications-society-and-environment*. ■

NASA Funds Eight New Projects Exploring Connections Between the Environment and COVID-19

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

Introduction

While scientists around the world are confined to their homes during the COVID-19 pandemic, Earth-observing satellites continue to orbit and send back images that reveal connections between the pandemic and the environment. "Satellites collect data all the time and don't require us to go out anywhere," said **Hannah Kerner** [University of Maryland, College Park].

Kerner is among eight researchers recently awarded a rapid-turnaround project grant,[1] which supports investigators as they explore how COVID-19 lockdown measures are impacting the environment and how the environment can affect how the virus is spread.

The newest group of projects includes six that are looking to satellite images to help reveal how COVID-19 lockdown measures are impacting food security, fire ecology, urban surface heat, clouds and warming, air pollution and precipitation, and water quality and aquatic ecosystems. Two projects are exploring how the environment could be impacting how the virus is spread by monitoring dust and weather.

NASA's Earth Science Division manages these projects that seek new ways to use Earth-observing data to better understand regional-to-global environmental, economic, and societal impacts of the COVID-19 pandemic.

Counting Crops During COVID

This year was looking to be a relatively normal year for crops until the pandemic and associated lockdown policies happened. Reduced air and ground travel caused the demand for ethanol to plummet, which caused corn prices to decline. Lockdown policies also made it harder for officials from the U.S. Department of Agriculture (USDA) to travel to farms and collect information about crop planting, progress, and conditions.

The subsequent lack of public information about crops caused uncertainty and volatility in agricultural markets and prices as growing seasons progressed. "Markets want to know how much of a specific kind of crop to expect," Kerner said.

Kerner and her team are looking to satellite data from the NASA–U.S. Geological Survey (USGS) Landsat, European Space Agency (ESA) Copernicus Sentinel-2, NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites, and Planet's satellites[2] to help supplement USDA's information.

"We're using satellite data and machine learning to map where and which crops are growing," Kerner said. Specifically, the investigators are monitoring key commodity crops, which are corn and soybeans in the U.S. and winter wheat in Russia.

Starting and Stopping Fires During Lockdown

There are far fewer intentional fires to boost biodiversity and reduce fuel loads in the Southeast this spring.

As COVID-19 lockdowns went into effect, the U.S. Forest Service temporarily suspended all of its intentional, or prescribed, burns on federal lands in the Southeast in March. State agencies in Mississippi, South Carolina, and North Carolina followed suit.

Ben Poulter [NASA's Goddard Space Flight Center] is using the Visible Infrared Imaging Radiometer Suite (VIIRS) on the NASA–National Oceanic and Atmospheric Administration (NOAA) Suomi National Polar-orbiting Partnership (NPP) satellite, as well as data from MODIS, to track fires across the country and better understand how COVID-19 social distancing policies, e.g., federal travel restrictions, have affected both prescribed burns on the East Coast and wildfires in the West.

Ultimately, his team wants to better understand how fewer fires in the Southeast could be affecting biodiversity, since some species rely on fires to thrive, thereby causing fuels to accumulate, potentially leading to more dangerous wildfires in the future.

[1] The projects described here were all funded through the Rapid Response to Earth System Events (RRESE) subelement of NASA's Research Opportunities in Space and Earth Science (ROSES) program [*A.28*]. To learn more, see pages A.28-1–A.28-6 of the *ROSES-2020 NASA Research Announcement* available at *https://go.nasa.gov/2SBnWf1*.

[2] Planet is a private company that operates Earth-observing satellites. Learn more at *https://www.planet.com/company/approach*.

On the other side of the country, the team is examining how COVID-19 policies are complicating fire suppression. As firefighting agencies have introduced social distancing practices to minimize the spread of COVID-19, e.g., eliminating large camps of firefighters living in close quarters, Poulter said, "it may become more difficult to fight fires in the Western states."

The team is also looking at how the total number of fires across the country could affect atmospheric chemistry. It will work with air quality scientists to determine if there will be an overall net increase or decrease in total carbon dioxide, among other pollutants, from wildfires in the West and prescribed fires in the East.

Fewer Cars Might Mean Hotter Surfaces

Christopher Potter [NASA's Ames Research Center] is looking at how California's shelter-in-place mandate in the San Francisco Bay Area has reduced the number of cars on the road and changed how parking lots, highways, and large industrial buildings' surfaces absorb sunlight and reflect infrared heat.

"It suddenly got so quiet," Potter said, "There was no traffic anywhere in late March and April."

Potter and his team are monitoring parking lots and other surfaces to see if they are hotter or cooler during the pandemic. Visible light from the sun hits the surface and then is absorbed and reradiated as heat—a process called *thermal heat flux*.

The team is using satellite thermal infrared sensor brightness temperatures from Landsat and land surface temperature from the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), which is a NASA sensor on the International Space Station, to map out large, flat urban features in the Bay Area and measure their thermal heat flux. He's also gathering on-the-ground measurements to *ground truth* the data—see **Figure**.

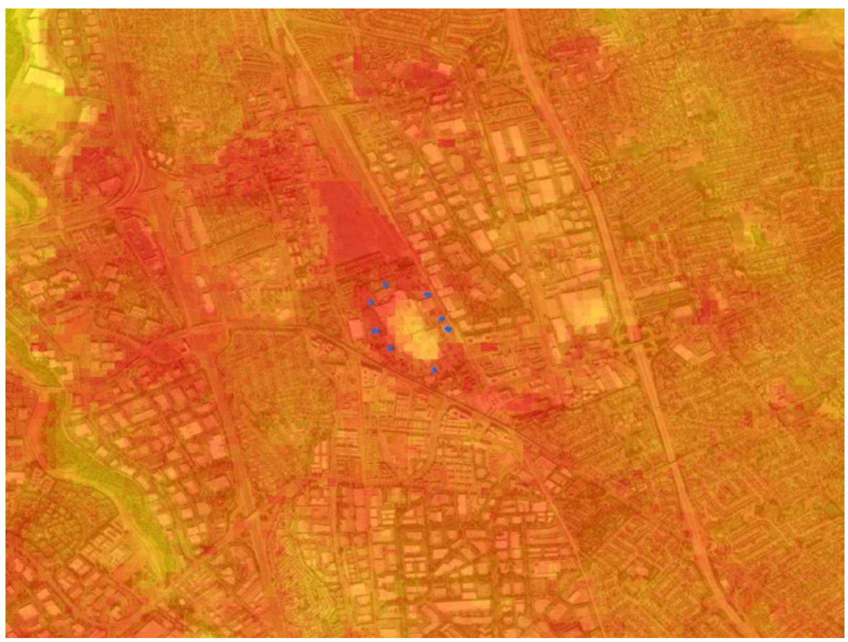

Figure. This image shows the ECOSTRESS land surface temperature variations measured on May 22, 2020, during the full lockdown period over an area centered on the Great Mall in Milpatas, CA. The blue dots represent ground truth measurements obtained on May 22, 2020, in large vacant parking lots. The orange shades show the highest temperatures on dark asphalt parking lots and roadways, and the yellow shades indicate lower temperatures in parklands and semi-vegetated areas. Bright white rooftops are in the middle shades. **Credit:** Christopher Potter [NASA's Ames Research Center]

Potter is asking questions such as: *If automobiles are parked and concentrated in giant lots, does the reflectance of the surface and/or the overall heat flux change?* Even shiny car windows may be enough to reflect sunlight, Potter said.

Potter and his team want to know how the entire Bay Area's *urban heat flux* has changed during the pandemic and how that change has contributed to a more or less healthy environment for the millions of people living in it. Understanding potential changes in the thermal heat flux is a key indicator of how COVID-19 has altered the Bay Area's environmental footprint, Potter said.

Fewer Planes and Fewer Clouds Could Make Things Cooler

When you look up at a clear blue sky and the conditions are just right, you might see a plane soaring above and leaving behind a distinct white trail of clouds.

Those clouds, or *contrails*, are produced by aircraft engine exhaust or changes in air pressure. **William Smith** and **Dave Duda** [both at NASA's Langley Research Center] have been studying contrails for a couple of decades. "Contrails are one of the only clouds we produce ourselves," Duda said. Although their effects vary and are difficult to quantify, their overall net effect is warming.

In response to COVID-19 travel bans and lockdown policies, we're flying a lot less and producing fewer contrails. Duda and Smith want to quantify this decrease to better understand how air traffic density impacts contrail formation and its radiative forcing. In other words: *Are fewer planes and fewer contrails helping to cool the atmosphere?*

The team is using an established contrail detection algorithm to estimate coverage over the contiguous U.S. and the North Atlantic air traffic corridor over the 2020 slowdown period and compare that to a baseline period a couple of years earlier when air traffic was unrestricted. Duda and Smith are also using MODIS to determine contrail optical properties to better understand how they reflect sunlight and trap energy from the surface and atmosphere below them.

The atmosphere must be sufficiently cold and moist for a contrail to form, so there are typically more contrails during the winter and spring. "Not all contrails are equal," Duda said. If one forms in the middle of clouds, it doesn't have a significant impact. "You see the biggest impact when there's an otherwise clear sky and a contrail adds cloudiness to it," Duda said.

Improving our understanding of how and when contrails form could help scientists inform airlines on ideal routes to fly planes. "It might be possible to reduce contrails and their effects by making occasional flight altitude or routing adjustments much like the airlines do now to avoid turbulence," Smith said.

Less Air Pollution May Mean Less Rain

Gabriele Villarini and **Wei Zhang** [both at University of Iowa] want to understand the connection between reduced air pollution during the pandemic and sharp decreases in precipitation in the western U.S.

Moisture in the atmosphere condenses around aerosols, or particles like dust, and falls to Earth as rain and snow. Fewer aerosols during the pandemic may have been responsible for the reduced precipitation in February and March 2020 across the western U.S., with areas receiving less than 50% of "normal" values—i.e., compared to a typical year. Understanding how the decrease in precipitation is related to reduced aerosols could be valuable to water resource managers.

Villarini is aiming to use NASA's satellite data on water vapor, precipitation, and aerosols as well as a comprehensive climate model that can combine atmospheric conditions such as moisture and temperature with chemical properties and processes that take place in the atmosphere. The model will help his team pinpoint the extent to which the reduction in aerosols is responsible for the decrease in precipitation as opposed to the natural variability in the climate system.

"This project will help us understand how COVID-19 is impacting the natural environment," Villarini said.

Finding a Human Imprint on Water Quality in Belize

The coastal area of Belize includes the largest barrier reef in the Northern Hemisphere, offshore atolls, several hundred sand cays, mangrove forests, coastal lagoons, and estuaries. It is one of the most biodiverse ecosystems in the Atlantic and is home to colorful fish and playful sea turtles, many of which are endangered.

Robert Griffin [University of Alabama, Huntsville] was working on a NASA project to study the reef's health when COVID-19 happened. "The pandemic created a natural experiment," Griffin said, to better understand how urban pollutants affect water quality and coral reef health.

Griffin and his team are studying how decreased tourism is impacting urban and agricultural sources of pollutants, such as nitrogen and phosphorus, to water quality off the coast of Belize.

In addition to on-the-ground data, the team is using Landsat images to note how the pandemic is affecting land use changes, which affects how many pollutants are produced and able to reach water bodies and ecosystems. Griffin is also using MODIS and VIIRS data to monitor water quality.

Griffin's team is working with Belize government officials to help guide coastal marine development for the upcoming five years. "This research could provide guidance for land use planners as they determine how to deal with urban non-point sources of pollution," e.g., nutrients and sediments, that end up in the water and impact coral reef systems, Griffin said.

Dust Storms, Society, and COVID-19

Pablo Méndez-Lázaro [University of Puerto Rico] is examining how the environment could affect the spread of the novel coronavirus that causes COVID-19. More specifically, he wants to know if seasonal African dust that travels to the Caribbean between May and August every year will have significant impacts on health and mortality associated with the virus.

African dust travels from the Sahara Desert, across the Atlantic Ocean, to Puerto Rico and the Caribbean. Microorganisms in the dust particles can be linked to infectious diseases.

Méndez-Lázaro and his team are working with epidemiologists, among many specialists, to better understand how African dust impacts public health. "We see this as a Rubik's Cube," Méndez-Lázaro said, to demonstrate how his research is one of various moving parts to understand a larger issue. "Each tiny, colored cube is a different part of the puzzle," focused on epidemiological research, societal studies, clinical studies, vaccine research, and environmental work, Méndez-Lázaro said.

The team is using VIIRS to measure aerosols in the atmosphere as a proxy for the dust clouds that arrive in the Caribbean. It's also using MODIS and the European Commission's Copernicus Atmosphere Monitoring System to characterize the aerosols.

Méndez-Lázaro is working closely with the Puerto Rico Department of Health, the National Weather Service's San Juan Office, as well as physicians and patients, to gather information on people who have contracted respiratory diseases through contact with African dust.

"We believe that there could be an exacerbation of COVID-19 patients in the Caribbean during African dust events," Méndez-Lázaro said, like the "Godzilla" event in June.

Weather, Air Quality, and COVID-19

Yulia R. Gel [University of Texas at Dallas] and **Huikyo Lee** [NASA/Jet Propulsion Laboratory], along with other collaborators, want to help clarify what environmental factors could impact a second wave of COVID-19 cases and determine how certain we can be with those conclusions.

Gel's interdisciplinary team is studying whether surface air temperature and humidity are impacting transmission rates, and, if they are, how they are doing it. The team is also teasing out a potential link between aerosols and COVID-19 severity and mortality.

Gel and her collaborators are using weather data from the Atmospheric Infrared Sounder (AIRS) on the Aqua satellite and Cross-track Infrared Sounder (CrIS) on the Suomi NPP satellite. The team will obtain aerosol data from the Multiangle Imaging SpectroRadiometer (MISR) and MODIS and use machine learning algorithms and advanced analyses to track the dynamics of the virus's spread and its mortality rate over space and time.

More specifically, Gel's team is using geometric deep learning algorithms, coupled with topological data analysis, which allow tracking of COVID-19 transmission patterns that are driven, for instance, by different population characteristics (like age, gender, ethnicity, and income), as well as environmental factors. The advanced tools allow the team to consider factors that are not accessible using conventional approaches based on geographic proximity.

Gel aims to provide a powerful software tool to help predict the seasonal COVID-19 progression on a regional to global scale, while quantifying a broad range of associated uncertainties.

Conclusion

These projects have been selected because—as defined in the ROSES 2020 NASA Research Announcement (NRA) cited above—they have "great urgency for action involving quick-response research on natural [or human-caused] extreme events and/or similar unanticipated or unpredictable events that fall outside the norm." While no one could have anticipated having to add a pandemic to the specific examples included in the language of the NRA, it certainly qualifies as an "unexpected large-scale event that has caused rapid environmental change." The eight COVID-19-related research examples cited in this article will all "require rapid, near-term data acquisition, field work, and/or other such research activities." Also, given the significance of these events, the results and data will need to be made publicly available as soon as possible.

More projects will be added to this list as time progresses. The current list, as well as future additions, can be found at *https://go.nasa.gov/2SJcxJP*. ■

NASA Observations Aid Efforts to Track California's Wildfire Smoke from Space

Sofie Bates, NASA's Goddard Space Flight Center, sofie.l.bates@nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

Introduction

Wildfires have been burning across the state of California for weeks—some of them becoming larger complexes as different fires merge. One of those was the August Complex Fire, which reportedly began as 37 distinct fires caused by lightning strikes in northern California on August 17, 2020.[1]

The August Complex Fire and others this fire season have been sending far-reaching plumes of wildfire smoke into the atmosphere that worsen air quality in California and beyond. Predicting where that smoke will travel and how bad the air will be downwind is a challenge, but Earth-observing satellites can help. Included among them are NASA's Terra and CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellites, and the joint NASA–National Oceanic and Atmospheric Administration (NOAA) Suomi National Polar-orbiting Partnership (NPP) satellite. Together, the instruments on these satellites provide glimpses at the smoke over time, which can help improve air quality predictions.

"The satellite instruments have the advantage of providing broad coverage and consistent measurement accuracy over time, as well as making their observations without any risk to the people taking the data," said **Ralph Kahn** [NASA's Goddard Space Flight Center]. A senior research scientist who studies aerosols, Kahn and other atmospheric scientists at NASA collect data about the fires from Earth-observing satellites used to improve models that predict how wildfire smoke will affect air quality downwind of the fires.

MISR: Assessing the Situation from Different Angles

One of the instruments on NASA's Terra satellite is the Multi-angle Imaging Spectroradiometer (MISR), which has nine different cameras pointing toward Earth at different angles. As Terra passed over the August Complex Fire on August 31, 2020, MISR collected snapshots of the smoke plume from different angles—see **Figure 1**.

Scientists look at those different perspectives to calculate the extent and height of the smoke plume

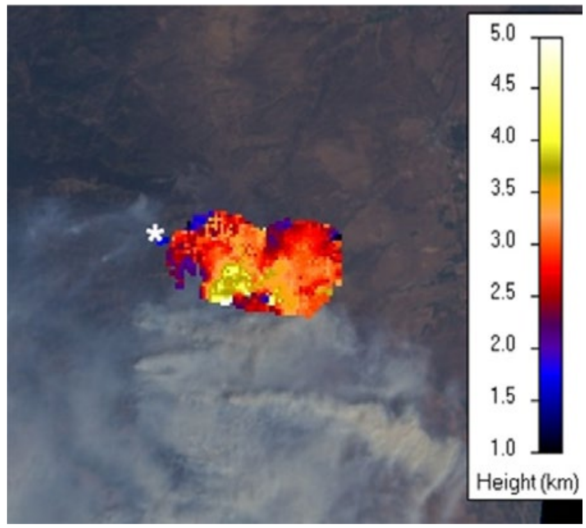

Figure 1. Scientists used MISR's various camera angles to calculate height throughout the smoke plumes emitted from the August Complex Fire on August 31, 2020. In the northern plume, the smoke surpassed 2.5 mi (4 km) at its highest point. **Credit:** Ralph Kahn *et al.*

downwind, as well as the height nearest the source of the fire, called the *injection height*. That information is essential for determining how far the smoke will travel.

"Smoke tends to stay aloft longer, travel farther, and have a larger environmental impact, perhaps far downwind, if it's injected higher into the atmosphere," said Kahn.

On August 31, 2020, the highest parts of the plume from the August Complex Fire reached approximately 2.5 mi (4 km) into the air—putting it above the *boundary layer* of the atmosphere, which is the layer of the atmosphere nearest to the Earth's surface. The fresh smoke plume extended at least 30 mi (45 km) east of the burning area near Mendocino National Forest in northern California. Over the previous few days, smoke from this fire had already traveled more than 310 mi (500 km) to the west and over 460 mi (750 km) east of the source, crossing into Utah and out over the Pacific Ocean.

The MISR instrument also collected information about the amount, size, and brightness of the particles within the smoke plume based on how the particles scatter light at different angles and wavelengths. These data give researchers information about the characteristics of the wildfire smoke in order to predict how it will move and

[1] **UPDATE**: As of this writing—over a month later on September 25, 2020—that fire was still burning.

affect air quality. For example, the southern part of the smoke plume emitted by the August Complex Fire on August 31 was made of mostly small, dark particles that are usually released when a fire is burning intensely. But as the plume moved downwind, the particles became larger and brighter, possibly because water or other gases emitted by the fires condensed on the smoke particles.

MODIS: A Snapshot of Wildfire Hotspots

Individual wildfires and large conflagrations of merged fires burning throughout the state—and the accumulated smoke they produce—make it difficult to see the actual flaming *hotspots* from space. But the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's Terra satellite[2] can see the longer wavelengths of nonvisible light, or *infrared radiation,* produced by the heat coming from actively burning wildfires. In other words, by comparing the higher infrared radiation from hotspots to the lower radiation coming from the surrounding area, MODIS can sometimes see through smoke even when our eyes can't.

As it passes over the Western U.S., MODIS can see a swath about 1430 mi (2300 km) wide—about the distance from central Utah to almost 70 mi (113 km) into the Pacific Ocean—providing valuable context about what's going on with the fires and smoke over the Western U.S. MODIS pinpointed multiple clusters of fire hotspots in the August Complex Fire, which had consumed over 240,000 acres (~970 km^2) by September 2, 2020—see **Figure 2**.

"The fire extent is huge in this case, and the smoke plumes can travel hundreds or even thousands of kilometers," said Kahn. "The satellites provide not only context, but also information about the relationships between different fires." During its pass overhead on August 31, 2020, MODIS captured the August Complex Fire as well as several other fires and larger complexes of fires burning to the north, south, and east. Seeing the relationships between the fires offers clues to which fires are likely to merge in subsequent days.

CALIPSO and Suomi NPP: Seeing the Extent of the Smoke

The smoke plumes from California's wildfires have engulfed many cities and towns throughout the state, turning the sky an apocalyptic shade of burnt orange. In other areas, the sky is a hazy gray, and flecks of ash float through the air. But in some regions of the West Coast, the sky looks relatively normal—even if there are smoke particles in the air—because there are too few smoke particles for our eyes to detect.

That's where NASA's CALIPSO satellite comes in. CALIPSO has a laser onboard that shoots bursts of laser light toward Earth. When that light hits something,

[2] MODIS also flies on NASA's Aqua satellite. The emphasis here is on the combined measurements of the wildfire from MODIS and MISR, which are both on Terra.

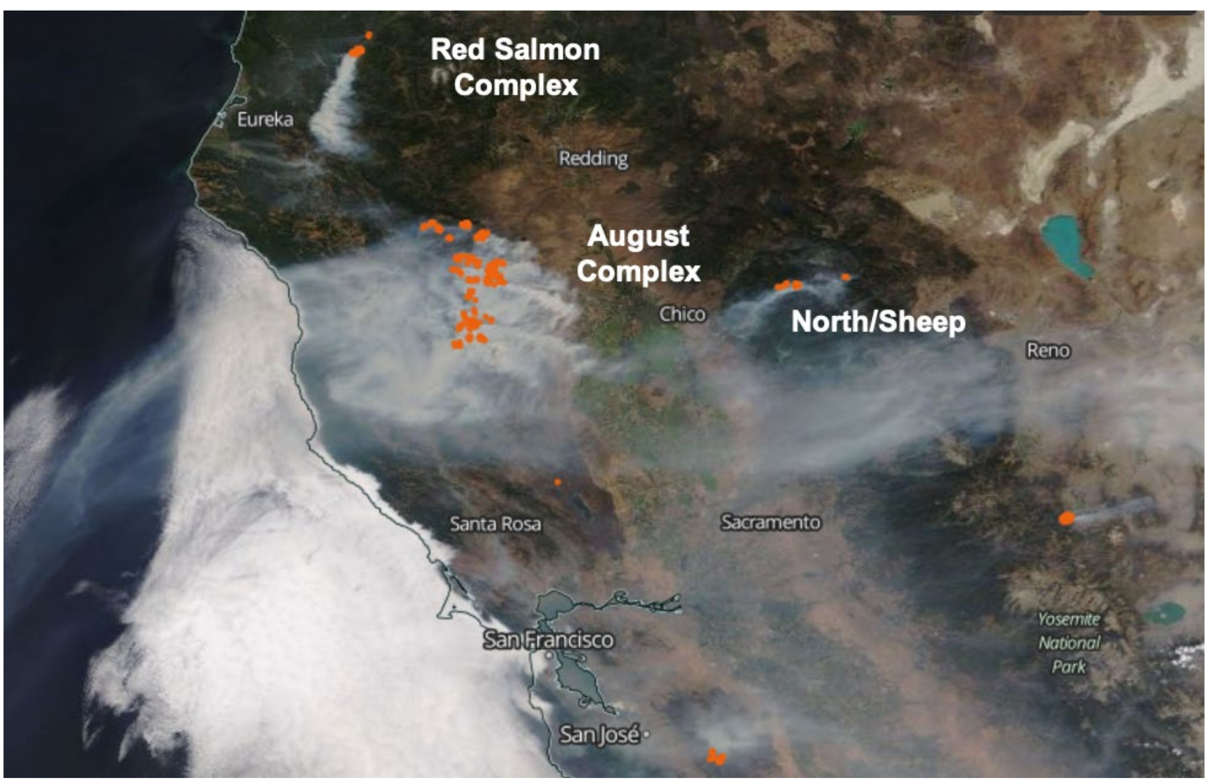

Figure 2. On August 31, 2020, MODIS detected several hotspots in the August Complex Fire in California, as well as several other actively burning areas to the north, west, and south. **Credit:** Ralph Kahn *et al.*

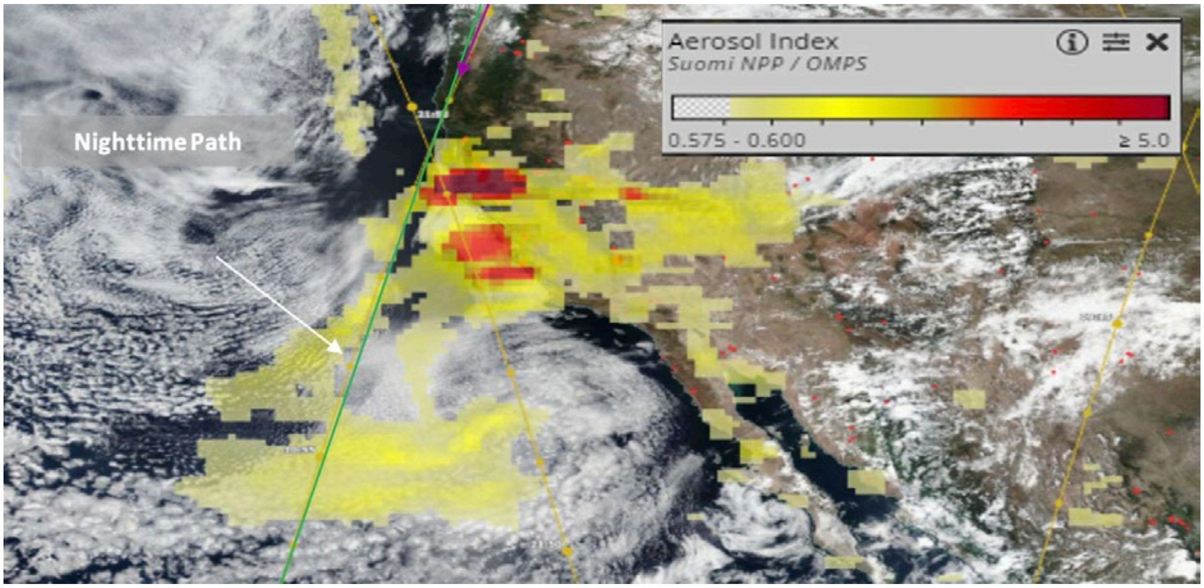

Figure 3. Using an onboard laser, the CALIPSO satellite can track how the smoke plume moves and gather information about the smoke particles it contains even when the plume is too thin for scientists to see with their own eyes. Shown here is the narrow CALIPSO ground track superimposed over the much broader swath of Aerosol Index data obtained by the Ozone Mapper and Profiler Suite (OMPS) on the Suomi National Polar-orbiting Partnership (NPP) platform. **Credit:** Ralph Kahn *et al.*

such as particles in a wildfire smoke plume, it is reflected back to sensors on CALIPSO. Although the laser light is too weak to cause any sort of damage, the light reflected back to the satellite by smoke particles tells scientists a lot about the smoke even when the plume is too transparent for them to see with their eyes. As the plume from the August Complex Fire was carried west, CALIPSO detected smoke several days old descending from about 2.5 mi (4 km) above land to within a mile of the ocean's surface as it crossed the California coastline—see **Figure 3**.

CALIPSO can tell the difference between clouds and smoke, which can sometimes be hard to do by looking at a satellite image. Knowing where the smoke is in relation to clouds allows researchers to see the interactions between clouds and smoke, which can affect the characteristics and spread of the smoke. For example, sometimes clouds ingest and modify smoke particles, and can even remove them from the air when it rains. Other times, dark wildfire smoke particles can absorb sunlight, becoming warm and heating the atmosphere, which can cause clouds to evaporate.

NASA's CALIPSO satellite captures detailed data, but it has a narrow field of vision. The satellite observes along a two-dimensional vertical "curtain" that slices through the smoke plume as it passes overhead, collecting detailed measurements of the type and position of wildfire smoke aerosols in the atmosphere. Scientists then turn to three sensors onboard Suomi NPP, collectively called the Ozone Mapping and Profiler Suite (OMPS), for context. Those sensors get a broader but less detailed view of what's going on with the smoke particles in Earth's atmosphere, which allows scientists to figure out what CALIPSO is homing in on and make better extrapolations based on CALIPSO's data.

Conclusion

The instruments onboard satellites in NASA's Earth-observing fleet provide extensive data—unavailable from any other source—enabling researchers to gain a better understanding of wildfire smoke and how it affects air quality. In cases like the current wildfires across California, NASA's atmospheric scientists studying the fires collaborate with the NASA Earth Science Disasters program to share their findings with firefighters and public health officials. The Disasters program partners with local and regional agencies on the ground, helping get the data from NASA's satellites into the hands of those who need them most.

"Our work is primarily helpful in improving the models that forecast air quality," said Kahn. "This is a team effort and when we can help, we certainly do." ■

NASA-Led Study Reveals the Causes of Sea Level Rise Since 1900

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

Scientists have gained new insights into the processes that have driven ocean level variations for over a century, helping us prepare for the rising seas of the future.

To make better predictions about the future impacts of sea level rise, new techniques are being developed to fill gaps in the historic record of sea level measurements. We know the factors that play a role in sea level rise: Melting glaciers and ice sheets add water to the seas, and warmer temperatures cause water to expand. Other factors are known to slow the rise, such as dams impounding water on the land, stymying its flow into the sea.

When each factor is added together, this estimate should match the sea level that scientists observe. Until now, however, the *sea level budget* has fallen short of the observed sea level rise, leading scientists to question why the budget wouldn't balance.

A new study published in *Nature* on August 19, 2020, titled "The Causes of Sea Level Rise Since 1900," seeks to balance this budget.[1] By gaining new insights to historic measurements, scientists can better forecast how each of these factors will affect sea level rise and how this rise will impact us in the future.

For example, in its recent flooding report,[2] the National Oceanic and Atmospheric Administration (NOAA) noted a rapid increase in sea-level-rise-related flooding events along U.S. coasts over the last 20 years, and they are expected to grow in extent, frequency, and depth as sea levels continue to rise.

Factors Driving Our Rising Seas

On reexamining each of the known contributors to sea level rise from 1900 to 2018, the research, led by NASA/Jet Propulsion Laboratory (JPL), uses improved estimates and applies satellite data to better understand historic measurements—see **Figure**.

The researchers found that estimates of global sea level variations based on tide-gauge observations had slightly overestimated global sea levels before the 1970s. (Located at coastal stations scattered around the globe, tide gauges are used to measure sea level height.) They also found that mountain glacier meltwater was adding

[1] To read the study, visit *https://www.nature.com/articles/s41586-020-2591-3*.

[2] To read the report, visit *https://tidesandcurrents.noaa.gov/publications/Techrpt_092_2019_State_of_US_High_Tide_Flooding_with_a_2020_Outlook_30June2020.pdf*.

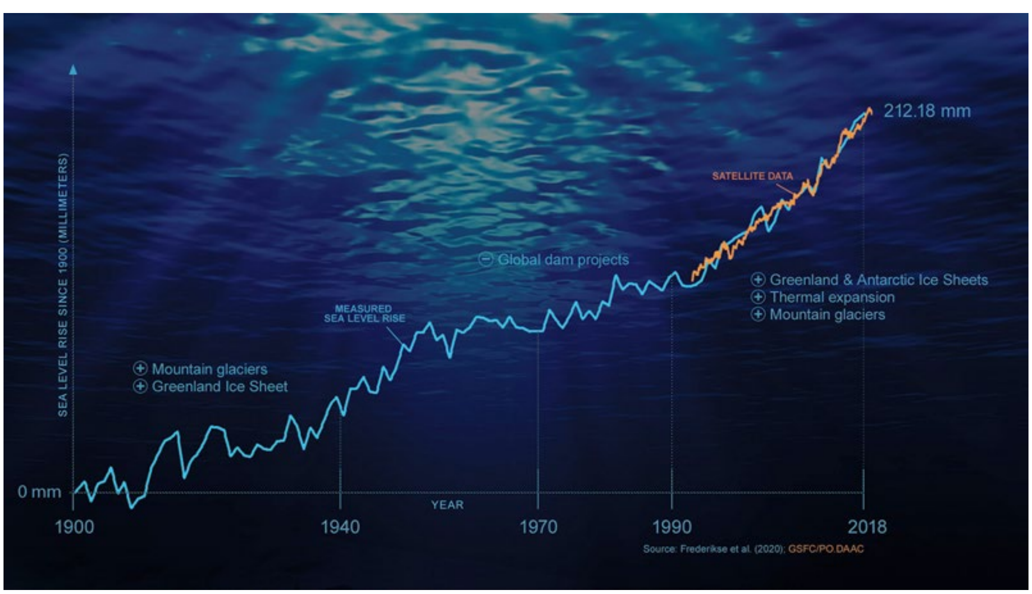

Figure. This infographic shows the rise in sea levels since 1900. Pre-1940, glaciers and Greenland meltwater dominated the rise; dam projects slowed the rise in the 1970s. Now, ice sheet and glacier melt plus thermal expansion dominate the rise. Tide-guage data are shown in blue and satellite data in orange. **Credit**: NASA/JPL more water to the oceans than previously realized but that the relative contribution of glaciers to sea level rise is slowly decreasing. And they discovered that glacier and Greenland ice sheet mass loss explain the increased rate of sea level rise before 1940.

In addition, the new study found that during the 1970s, when dam construction was at its peak, sea level rise slowed to a crawl. Dams create reservoirs that can impound freshwater that would normally flow straight into the sea.

"That was one of the biggest surprises for me," said lead researcher and postdoctoral fellow **Thomas Frederikse** [NASA/Jet Propulsion Laboratory (JPL)], referring to the peak in global dam projects at that time. "We impounded so much freshwater, humanity nearly brought sea level rise to a halt."

Since the 1990s, however, Greenland and Antarctic ice sheet mass loss and thermal expansion have accelerated sea level rise, while freshwater impoundment has decreased. As our climate continues to warm, the majority of this thermal energy is absorbed by the oceans, causing the volume of the water to expand. In fact, ice sheet melt and thermal expansion now account for about two-thirds of observed global mean sea level rise. Mountain glacier meltwater currently contributes another 20%, while declining freshwater water storage on land adds the remaining 10%.

All told, sea levels have risen on average 1.6 mm (0.063 in) per year between 1900 and 2018. In fact, sea levels are rising at a faster rate than at any time in the twentieth century. But previous estimates of the mass of melting ice and thermal expansion of the ocean fell short of explaining this rate, particularly before the era of precise satellite observations of the world's oceans, creating a deficit in the historic sea level budget.

Finding a Balance

In simple terms, the sea level budget should balance if the known factors are accurately estimated and added together. It's a bit like balancing the transactions in your bank account: Added together, all the transactions in your statement should match the total. If they don't, you may have overlooked a transaction or two.

The same logic can be applied to the sea level budget: When each factor that affects sea level is added together, this estimate should match the sea level that scientists observe. Until now, however, the sea level budget has fallen short of the observed sea level rise.

"That was a problem," said Frederikse. "How could we trust projections of future sea level change without fully understanding what factors are driving the changes that we have seen in the past?"

Frederikse led an international team of scientists to develop a state-of-the-art framework that pulls together the advances in each area of study—from sea level models to satellite observations—to improve our understanding of the factors affecting sea level rise for the past 120 years.

The latest satellite observations came from the pair of NASA – German Aerospace Center (DLR) Gravity Recovery and Climate Experiment (GRACE) satellites that operated from 2002 to 2017, and their successor pair, the NASA – German Research Centre for Geosciences (GFZ) GRACE Follow-On (launched in 2018). Additional data from the series of TOPEX/Jason satellites—a joint effort of NASA and the French space agency Centre National d'Etudes Spatiales—that have operated continuously since 1992 were included in the analysis to enhance tide-gauge data.

"Tide-gauge data were the primary way to measure sea level before 1992, but sea level change isn't uniform around the globe, so there were uncertainties in the historic estimates," said **Sönke Dangendorf** [Old Dominion University], co-author of the study and assistant professor of oceanography. "Also, measuring each of the factors that contribute to global mean sea levels was very difficult, so it was hard to gain an accurate picture."

But over the past two decades, scientists have been "flooded" with satellite data, added Dangendorf, which has helped them[3] precisely track the physical processes that affect sea levels.

For example, GRACE and GRACE-FO measurements have accurately tracked global water mass changes, melting glaciers, ice sheets, and how much water is stored on land. Other satellite observations have tracked how regional ocean salinity changes and thermal expansion affect some parts of the world more than others. Up-and-down movements of Earth's crust influence the regional and global levels of the ocean as well, so these aspects were included in the team's analysis.

"With the GRACE and GRACE-FO data we can effectively back-extrapolate the relationship between these observations and how much sea level rises at a particular place," said coauthor of the study **Felix Landerer** [JPL—*Project Scientist for GRACE-FO*]. "All observations together give us a pretty accurate idea of what contributed to sea level change since 1900, and by how much." ■

[3] In addition to scientists from JPL and Old Dominion University, the project involved researchers from California Institute of Technology in the U.S., Université Catholique de Louvain in Belgium, University of Siegen in Germany, the National Oceanography Centre in the United Kingdom, Courant Institute in New York, Chinese Academy of Sciences, and Academia Sinica in Taiwan.

NASA Earth Science in the News

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EDITOR'S NOTE: This column is intended to provide a sampling of NASA Earth Science topics reported by online news sources during the past few months. Please note that editorial statements, opinions, or conclusions do not necessarily reflect the positions of NASA. There may be some slight editing in places primarily to match the style used in *The Earth Observer*.

The Antarctic Ozone Hole Is One of the Largest and Deepest in Recent Years, October 8, *cnn.com*. The ozone hole that typically grows over the Antarctic each September and October has become one of the largest and deepest in recent years—just one year after scientists recorded its smallest size since it was discovered. The 2020 ozone hole grew rapidly from mid-August and had grown to about 9.2 million mi^2 (~24 million km^2) when it peaked in early October, according to a statement from the World Meteorological Organization (WMO). It then shrank to about 8.9 million mi^2 (~23 million km^2)—more than twice the size of the U.S.—covering almost the entire Antarctic continent, the agency said. The WMO's Global Atmosphere Watch program works closely with the Copernicus Atmospheric Monitoring Service (CAMS), NASA, Environment and Climate Change Canada, and other partners to monitor Earth's ozone layer. The ozone layer in our atmosphere protects Earth from ultraviolet radiation. The depletion is directly related to the temperatures in the stratosphere, where the ozone layer sits, because the polar stratospheric clouds that play an important role in the process only form at temperatures below -108 °F (-78 °C). Ice crystals in the clouds react with compounds in the atmosphere that can then rapidly destroy ozone when they are exposed to sunlight, the WMO said. NASA said last year's ozone hole was particularly small because of unusual weather patterns that caused warmer stratospheric temperatures over Antarctica. The Antarctic ozone hole will shrink as temperatures warm up in the Southern Hemisphere where [as of this writing] it's currently spring, and will return to normal by December, the WMO said.

Climate Fires and Hurricanes Collide in this Shocking NASA Satellite Image, September 29, *space.com*. Smoke meets cyclones in a jarring new series of satellite images posted to NASA's Earth Observatory website—see **Figure 1**. In the images, which combine recent observations of the U.S. taken by several different NASA satellites from September 14 to 16, 2020, orange-tinted smoke from an immense series of wildfires on the West Coast sails clean across the country to "collide" with tropical cyclones on the other side. One image, from September 15, shows the two weather catastrophes directly interacting, as churning winds from Hurricane Paulette literally block wildfire smoke in the upper atmosphere from flowing further into the Atlantic Ocean. Meanwhile, Hurricane Sally—bearing down on the Gulf Coast at the time—pushes the smoke plume further north. When Paulette dissipated the following day, the smoke continued its eastward journey over the ocean. These composite pictures clearly paint the intensity of the ongoing hurricane and wildfire seasons battering North America, both of which have already made history.

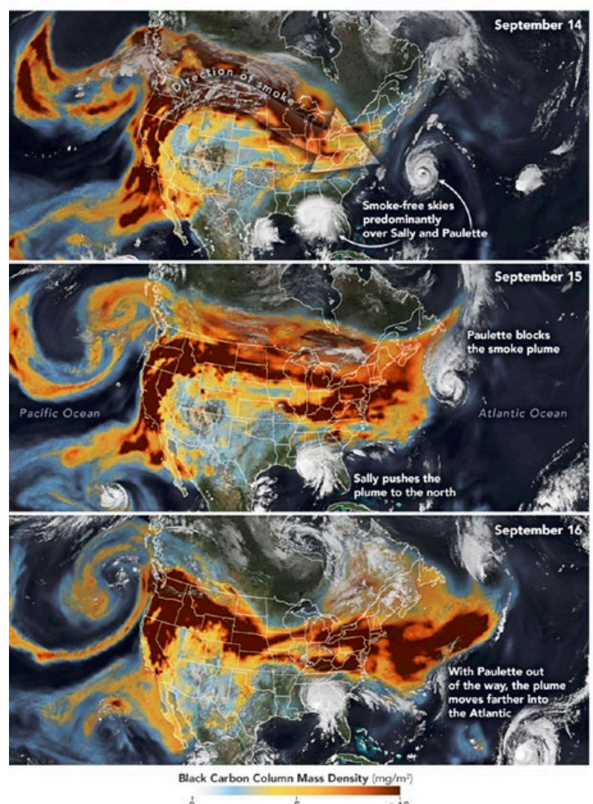

Figure 1. The series of images above shows the abundance and distribution of *black carbon*, a type of aerosol found in wildfire smoke, as it rode jet stream winds across the U.S. The black carbon data come from the Goddard Earth Observing System-Forward Processing (GEOS-FP) model, which assimilates information from satellite, aircraft, and ground-based observing systems. The Visible Infrared Imaging Radiometer Suite (VIIRS) on the National Oceanic and Atmospheric Administration (NOAA)–NASA Suomi National Polar-orbiting Partnership (NPP) satellite acquired the images of the storms. **Credit:** Joshua Stevens/NASA's Earth Observatory

As Temperatures Warm, the Arctic Is Becoming Greener, September 23, *slashgear.com*. Arctic summers are becoming warmer, and the result is a greener Arctic landscape. NASA has been using satellites to track global tundra ecosystems for decades. A new study found that the Arctic region is becoming greener as warmer air and soil temperatures lead to increased plant growth.[1] The Arctic is one of the coldest biomes on Earth, and NASA says it's one of the most rapidly warming as well. **Logan Berner** [Northern Arizona University], who led the study, says that the Arctic Greening that is occurring is a bellwether of global climatic change, calling it a biome-scale response to rising air temperatures. The study he and his team have published is the first to measure vegetation changes spanning the entire Arctic tundra from Alaska and Canada to Siberia using satellite data from Landsat. Researchers point out that greening can represent plants growing more and becoming denser and/or shrubs encroaching on typical tundra grasses and moss. The research was completed as part of the NASA Arctic Boreal Vulnerability Experiment (ABoVE) to understand better how ecosystems respond in warming environments and the broader social implications of such phenomena. Between 1995 and 2016 about 38% of the tundra sites across Alaska, Canada, and western Eurasia showed greening. Only 3% showed the opposite browning effect, meaning fewer actively growing plants. To include eastern Eurasian sites, they compared data starting in 2000, when Landsat satellites began regularly collecting images of that region. With this global view, 22% of sites greened between 2000 and 2016, while only 4% browned.

The Arctic Sea Ice Has Shrunk to the Second Lowest Number Ever Recorded, September 21, *cnn.com*. Scientists believe the Arctic sea ice, or the floating ice cover of the Arctic Ocean, has reached its minimum extent for the year, shrinking to the second lowest extent since record keeping began in 1978. The Arctic sea ice cover shrank to 1.44 million mi^2 (3.74 million km^2) by September 15, 2020, NASA and the National Snow and Ice Data Center (NSIDC) at the University of Colorado Boulder announced—see **Figure 2**. This is only 135,000 mi^2 (350,000 km^2) higher than the lowest extent reached in 2012.

Figure 2. In the Arctic Ocean, sea ice reached its 2020 minimum extent of 1.44 million mi^2 (3.74 million km^2) on September 15, 2020—the second-lowest extent since modern record keeping began. A Siberian heat wave in spring 2020 began this year's Arctic sea-ice melt season early, and with Arctic temperatures being 14–18 °F (8–10 °C) warmer than average, the ice extent kept declining. **Credit:** NASA's Scientific Visualization Studio

NASA Measures California Wildfire Temperatures from the Space Station, September 10, *foxnews.com*. NASA has measured California wildfire temperatures using an instrument on the International Space Station. The space agency's ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) imaged the fires, including the El Dorado fire near Yucaipa and the Valley Fire in Japatul Valley, according to NASA—see **Figure 3**. To learn more about how NASA sensors—including ECOSTRESS—are being used to study the California wildfires, see the News Story on page 31 of this issue.

Interested in getting your research out to the general public, educators, and the scientific community? Please contact ***Ellen Gray*** *on NASA's Earth Science News Team at* ellen.t.gray@nasa.gov *and let her know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of* **The Earth Observer**. ■

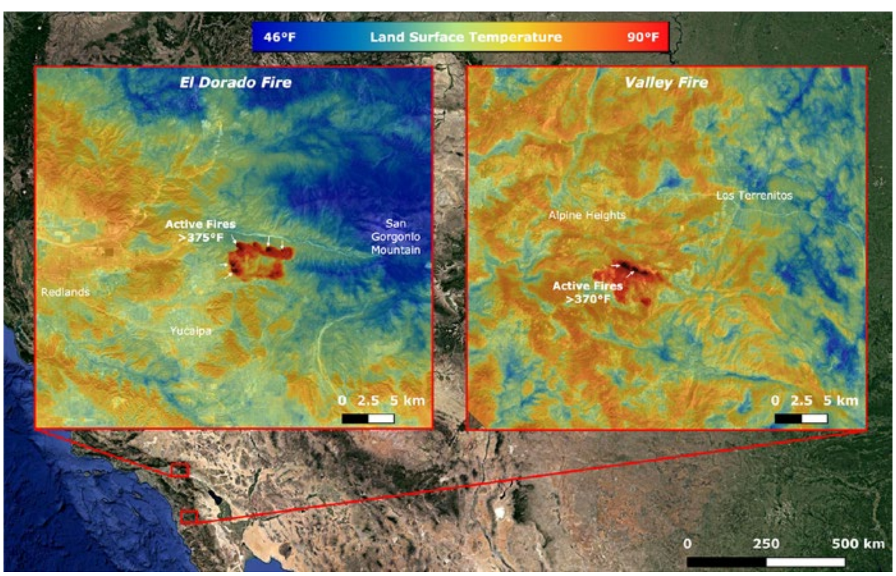

Figure 3. On September 6, 2020, NASA's ECOSTRESS imaged active fires across California, including the El Dorado fire near Yucaipa and the Valley fire in Japatul Valley in the southern part of the state. Both images, taken at 12:13 AM PDT, show multiple concentrated areas of surface temperatures (dark red shades) higher than 375 °F (191 °C). These high temperature regions were likely where the active fires were occurring. **Credit:** NASA/JPL

[1] To read the study, visit *https://www.nature.com/articles/s41467-020-18479-5*.

Data Pathfinders Link NASA Datasets with Users

Data Pathfinders

If you are new to using Earth science data, or even if you are more experienced, the sheer volume of datasets to sort through can be intimidating. How often have you thought: *Surely there are data out there for what I want to do. But how do I locate, access, and make use of them?*

Enter *Data Pathfinders*. Created by NASA's Earth Science Data Systems (ESDS) program, these "packages" of information provide a great introduction to many of the commonly used NASA datasets and how to access and use them. While they won't make you an expert in any one area, they will familiarize you with the datasets that are most applicable to particular applications, offer guidance on resolutions (i.e., spectral, spatial, and temporal), and provide direct links to the data sources. After getting started here, there are numerous NASA resources that can help develop your skills further. The pathfinders provide helpful links to open-source tools that can help you visualize and analyze datasets.

The following is a list of the Data Pathfinders that currently exist with links to more detailed information on each one. To learn more, visit *https://earthdata.nasa.gov/learn/pathfinders*.

Agricultural and Water Resources—*https://earthdata.nasa.gov/learn/pathfinders/agricultural-and-water-resources-data-pathfinder*. Directed toward agricultural and water resource managers, decision makers, and anyone interested in using NASA data to monitor crop production or water availability.

Biological Diversity and Ecological Forecasting—*https://earthdata.nasa.gov/learn/pathfinders/biodiversity*. Directed toward ecologists, conservation managers, decision makers, and anyone interested in using NASA data to monitor biodiversity and forecast changes to ecological communities.

COVID-19—*https://earthdata.nasa.gov/learn/pathfinders/covid-19*. Directed toward researchers investigating human response to the COVID-19 disease and the associated environmental changes.

Disasters—*https://earthdata.nasa.gov/learn/pathfinders/disasters*. Directed toward emergency management professionals, decision makers, and anyone interested in using NASA data to understand the vulnerability and exposure of a community to a disaster.

Geographic Information Systems (GIS) Data Pathfinder—*https://earthdata.nasa.gov/learn/pathfinders/gis-pathfinder*. Directed toward GIS users, as it provides NASA Earth science data in GIS-ready formats for easy integration and analysis in the primary tools employed by user communities.

Health and Air Quality—*https://earthdata.nasa.gov/learn/pathfinders/health-and-air-quality-data-pathfinder*. Directed toward air quality managers and public/environmental health managers as well as citizens interested in using NASA data to monitor air quality for a particular area and to correlate air quality to health conditions.

Water Quality—*https://earthdata.nasa.gov/learn/pathfinders/water-quality-data-pathfinder*. Directed toward water quality managers and researchers who have a critical need to monitor bodies of water locally, regionally, and globally.

Wildfires—*https://earthdata.nasa.gov/learn/pathfinders/wildfire-data-pathfinder*. Designed for use in applications related to fire monitoring and fire management.

Earth Science Meeting and Workshop Calendar

NASA Community

November 2–5, 2020
GPM-ACCP Transport and Logistics Workshop, *virtual*
https://gpm.nasa.gov/science/meetings

Global Science Community

December 1–17, 2020
AGU Fall Meeting, *virtual*
https://www.agu.org/fall-meeting

January 10–15, 2021
AMS Annual Meeting, *virtual*
https://annual.ametsoc.org/index.cfm/2021

Michael H. Freilich Memorial Fund Established by OSU Foundation

The Earth Observer recently reported on the passing of Michael Freilich, the former Director of NASA's Earth Science Division.[1] A passionate and tenacious Earth-systems scientist, Mike shaped decades of climate and remote-sensing research through his leadership at NASA and through the individual interactions he had with so many in our community. We are indebted to his vision, his leadership, and his enthusiasm for learning, which was infectious to all who interacted with him. Those who were fortunate to work closely with Mike drew inspiration from his intensity and his ability to recognize the gem in a sea of ideas, the unique spark in each individual, and the precise moment when an opportunity can be acted upon.

In recognition of Mike's accomplishments as a scientist and administrator, and his tireless commitment to mentoring and educating young scientists, we are passing along the news that the Oregon State University (OSU) Foundation has established the **Michael H. Freilich Memorial Fund**. The money raised will be used to support research experiences for members of historically underrepresented groups through an undergraduate fellowship in remote sensing research in the Earth sciences, including oceanography, atmospheric science, land-use change, and polar science. Online donations can be made at *https://ceoas.oregonstate.edu/michael-freilich-memorial-fund*.

[1] See the Editorial of the July–August 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 4**, p. 1]—*https://go.nasa.gov/2TvdRAs*.

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Article submissions, contributions to the meeting calendar, and other suggestions for content are welcomed. Contributions to the calendars should contain date, location (if meeting in person), URL, and point of contact if applicable. Newsletter content is due on the weekday closest to the first of the month preceding the publication—e.g., December 1 for the January–February issue; February 1 for March–April, and so on.

To subscribe to *The Earth Observer*, or to change your mailing address, please call **Cindy Trapp** at (301) 614-5559, or send a message to *Cynthia.trapp-1@nasa.gov*. If you would like to stop receiving a hard copy and be notified via email when future issues of *The Earth Observer* are available for download as a PDF, please send an email with the subject **"Go Green"** to *cynthia.trapp-1@nasa.gov*. Your name and email address will then be added to an electronic distribution list and you will receive a bi-monthly email indicating that the next issue is available for download. If you change your mind, the email notification will provide an option for returning to the printed version. Finally, note that print copies of *The Earth Observer* are no longer sent to addresses at GSFC; they will be emailed to the addresses we have in our database. If you are located at GSFC and still wish to receive a print copy, you may provide a home (or alternative) address to Cindy Trapp, and we can add it to our database.

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