Over Thirty Years Reporting on NASA's Earth Science Program

The Earth Observer

National Aeronautics and Space Administration

January – February 2022. Volume 34, Issue 1

The Editor's Corner

Steve Platnick
EOS Senior Project Scientist

Planned NASA Earth Science mission and instrument launches in the coming year include: the EMIT, TROPICS, and TEMPO Earth Venture Instrument missions;[1] the jointly developed NASA–CNES SWOT mission; and the OMPS–Limb instrument on NOAA's JPSS-2 satellite. An update on each of these is given below.

The Earth Science Mineral Dust Source Investigation (EMIT) is scheduled to launch via a SpaceX Falcon 9 resupply mission to the ISS on May 1, 2022. EMIT will be removed from the SpaceX Dragon capsule and installed on the ExPRESS Logistics Carrier 1 (ELC1)—one of the four primary hubs for externally-mounted instruments on the space station. EMIT will use a two-mirror telescope and Dyson imaging spectrometer to measure visible through shortwave infrared light reflecting from surfaces below. The data will be used to create maps of surface composition for arid land mineral dust source regions. The mission is planned to last at least 12 months.

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission comprises a constellation of six CubeSats. The TROPICS satellites will be deployed in pairs of two by three different Astra Space Rocket 3 launches from Kwajalein Atoll in the Marshall Islands—all expected to be completed by July 31, 2022. Together, they will be able to examine a storm's precipitation, temperature, and humidity as quickly as every 50 minutes—which is more frequent than current weather satellites making similar measurements. Scientists expect these data will help them understand the factors driving tropical cyclone intensification and will contribute to weather forecasting models.

One TROPICS satellite is already in orbit.[2] Launched in June 2021, the TROPICS Pathfinder, or proof of concept, satellite has been used to test the technology, communications systems, data processing, and data flow that will be used in the full TROPICS mission. The TROPICS Pathfinder has been collecting data since shortly after launch, including images of Hurricane Ida in August 2021, that demonstrates the promise of these small satellites.[3]

[1] EMIT, TROPICS, and TEMPO were all chosen as Earth Venture Instrument (EVI) missions. This is one of three categories under the Earth Venture program element, which facilitates development of small, targeted science investigations designed to complement NASA's larger research missions.
[2] The Pathfinder is a seventh TROPICS satellite, i.e., in addition to the six that are part of the full TROPICS mission.
[3] To learn more about TROPICS Pathfinder and plans for the full TROPICS mission—and to view the Hurricane Ida images—see "The Editor's Corner" in the July–August 2021 issue of *The Earth Observer* [**Volume 33**, **Issue 4**, pp.1–2].

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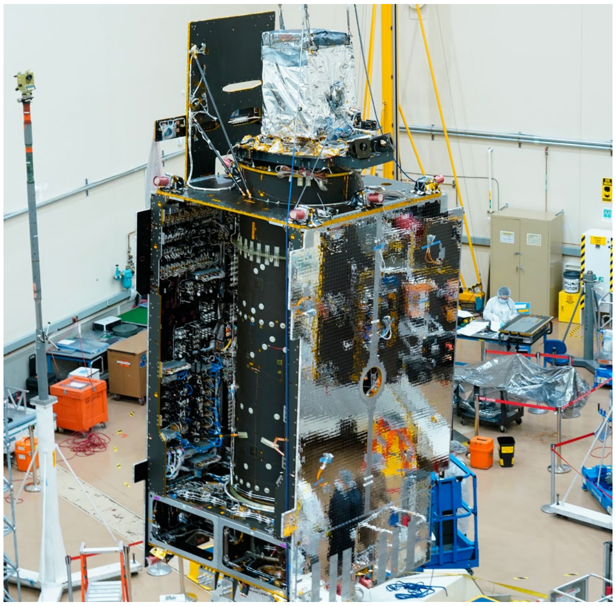

NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument is shown in a cleanroom at Maxar's facility in Palo Alto, CA, resting atop the Intelsat 40e satellite that will carry it into space enclosed in protective covering. Maxar's Space Program Delivery team is working to prepare the satellite and its payload for launch later this year. Once positioned in geostationary orbit, TEMPO will become part of an international air quality satellite virtual constellation (described in text) that will offer a more holistic view of how pollution is transported around the Northern Hemisphere. Ball Aerospace in Broomfield, CO built the TEMPO instrument. **Image credit:** Maxar.

In This Issue

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

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument is scheduled for launch later this year via an Intelsat 40e commercial satellite—see image on page 1. From geostationary orbit, TEMPO will maintain a view of the North American continent, monitoring air pollutants from Mexico City to the Canadian oil sands and from the Atlantic to the Pacific every daylight hour at relatively high spatial resolution. TEMPO is a grating spectrometer, sensitive to ultraviolet to near-infrared wavelengths. It will measure the spectra required to retrieve ozone, nitrogen dioxide, sulfur dioxide, formaldehyde, glyoxal, aerosols, cloud parameters, and surface ultraviolet-B radiation. TEMPO will thus be able to track the diurnal tropospheric ozone chemistry cycle and quantify the daytime temporal evolution of ozone precursor gases and aerosol loading. TEMPO will be part of a constellation of geostationary instruments measuring air quality over the Northern Hemisphere mid-latitudes that will also include the European Copernicus Sentinel-4 Ultraviolet Visible Near-infrared (UVN) spectrometer on Meteosat Third Generation and the Geostationary Environmental Monitoring Spectrometer (GEMS) on the South Korean Geo-KOMPSAT–2B (GK-2B) satellite.[4]

The Surface Water and Ocean Topography (SWOT) mission is also preparing to launch this year. The satellite is now fully integrated and is undergoing final system testing in Cannes, France. When tests are complete it will be shipped to Vandenberg Space Force Base in California for a planned November 2022 launch on a SpaceX Falcon 9 rocket. The mission is a collaboration between NASA and CNES with contributions from the Canadian Space Agency and the United Kingdom Space Agency. SWOT will conduct the first global survey of Earth's surface water and small-scale ocean topography using its K_a-band Radar Interferometer (KaRIn) to measure water height by bouncing radar pulses off the water's surface and simultaneously measuring the return signals with two different antennas. This *radar interferometry* technique allows scientists to precisely calculate the height of the water as the satellite looks straight down over a finite two-dimensional swath—which is an improvement over along-track, one-dimensional profiles of water height obtained by conventional radar altimeters (e.g., the Jason series). These data will help track regional shifts in sea level caused by small-scale ocean currents, monitoring changes in river flows and lake water storage, and determining freshwater availability in communities around the world.[5]

The Joint Polar Satellite System–2 (JPSS-2), flying NASA's Ozone Mapping and Profiling Suite–Limb (OMPS-Limb) instrument, is scheduled to launch in September 2022 from Vandenberg Space Force Base on a United Launch Alliance Atlas V *401* rocket. Once in orbit, JPSS-2 will become known as NOAA-21. It will join the Suomi National Polar-orbiting Partnership (Suomi NPP—which also flies an OMPS-Limb instrument) and NOAA-20 (formerly JPSS-1) platforms,

[4] To learn more about the plans for TEMPO, see *tempo.si.edu*. The website includes links to a fact sheet and brochure, as well as many other helpful resources.

[5] To learn more about SWOT and KaRIn, see "Summary of the SWOT Science Team Meeting" in the November–December 2019 issue of *The Earth Observer* [**Volume 29, Issue 6**, pp. 17–20—*go.nasa.gov/3pgXTug*].

further enhancing NOAA's capability to provide critical environmental data as well as NASA research and application efforts.[6]

In addition to these launches, NOAA's Geostationary Operational Environmental Satellite–T (GOES-T)—a NOAA-NASA development and acquisition effort—successfully launched on March 1, 2022 from Cape Canaveral, FL. GOES-T, the third in the GOES-R series, will become known as GOES-18 once it is in orbit, where it will join GOES-16 and -17 (formerly GOES-R and -S). GOES-18 will take over the GOES-West position from GOES-17.[7] While GOES-T has the same payload as its predecessors,[8] the Advanced Baseline Radiometer (ABI) imager has a redesigned radiator and loop heat pipes, and the GOES-T magnetometer is an updated version from its predecessors.

To learn more about these missions, see the News story on page 34 of this issue. The online version of this story includes URL links to websites on each mission.

In addition to all these upcoming satellite missions, our lead feature focuses on the CYGNSS mission which, as we reported in our last issue, celebrated the fifth anniversary in orbit on December 15, 2021.[9] The longevity of the mission—which was designed to last 24 months—has allowed for a major expansion of the scientific scope of the mission beyond its original focus on the measurement of hurricane winds. New areas of investigation include tropical and extratropical convective systems over ocean, soil moisture and freeze/thaw state over land, and the mapping of inland water bodies in dynamic seasonal wetlands and due to flood inundation. Turn to page 5 to learn more about the scientific and engineering achievements of this remarkable constellation of eight microsatellites after five years in orbit.

Also, March 17, 2022, will mark the twentieth anniversary of the launch of the Gravity Recovery and Climate Experiment (GRACE), which ended its 15-year mission in October 2017 after having collected 163 global monthly mass-change maps. GRACE Follow-On [GFO] launched in May 2018 with a primary mission objective to provide continuity for the global monthly GRACE mass-change observations via its Microwave Interferometer (MWI) intersatellite range-change observations. As of this writing, the GFO project team has processed and released 41 monthly gravity fields—the most recent being for December 2021. Between the two missions there is now a *nearly* continuous 20-year time series of global gravity and Mass Change measurements.[10] Turn to page 20 of this issue to read a summary of the most recent GFO Science Team Meeting, which—along with its usual programmatic and mission updates and science result presentations across a variety of disciplines—included a discussion of plans for future gravity missions.

NASA's suborbital observations continue as well. The Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Storms (IMPACTS) is currently conducting its second round of flights, which began in January and is planned until the end of February. As with other storms that have occurred during their investigation, the IMPACTS team conducted coordinated flights with two NASA aircraft to investigate the Nor'easter that impacted the U.S. East Coast on January 28–29, 2022. This was the Team's first opportunity to observe a classic Nor'easter as it unfolded. The NASA ER-2 flew above the storm collecting radar, radiometer, and lidar measurements while the NASA P3 Orion flew within the clouds collecting *in situ* microphysical data on snow particles and the conditions in which they form. IMPACTS is the first comprehensive study of snowstorms across the Eastern U.S. in over 30 years.

According to **Gerry Heymsfield** [GSFC—*IMPACTS Deputy Principal Investigator*], the storm was a challenging event to study because both aircraft had airport issues during the Nor'easter. The ER-2 had to wait until runway cross winds subsided in North Carolina, and NASA's Wallops Flight Facility (WFF) on Virginia's east coast received 9 inches of snow—making the runway unusable without plowing equipment. The P-3 ended up relocating to Wright–Patterson Air Force Base in Ohio before the snowfall and staying until February 1 (when the runway at WFF was clear). Overall, the mission was highly successful, and the data from the aircraft, ground-based mobile radar, and rawinsonde data will be of great interest to scientists. To learn more about IMPACTS and the flight into the Nor'easter, see the News Story on page 38 of this issue. *The Earth Observatory* also published an article about the Nor'easter and the IMPACTS flights at *go.nasa.gov/3JTltVN*.

At the close of 2021, NASA's Science Support Office (SSO) coordinated the first-ever NASA Science exhibit that had both in-person and virtual components—coined a *hybrid* event. Leveraging the American Geophysical Union (AGU) Fall Meeting's successful

[6] There are two more JPSS launches planned; JPSS-3 and -4 are in development and planned to launch in successive five-year periods after JPSS 2—which will extend JPSS observations into the 2030s.

[7] There is one more satellite in the GOES-R series; GOES-U is scheduled for launch in 2024.

[8] To learn more about GOES-T and the GOES-R series payload, see *www.nesdis.noaa.gov/goes-t-mission-overview*.

[9] To learn more, see "The Editor's Corner" in the November–December 2021 issue of *The Earth Observer* [**Volume 33**, **Issue 6**, p. 2].

[10] There is a slight data gap between the end of the GRACE mission and the beginning of the GFO mission.

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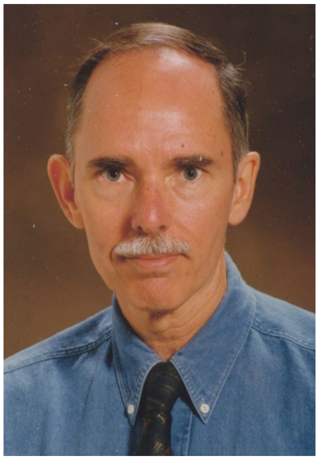
In Memoriam
Robert Curtis Harriss

The staff of *The Earth Observer* is deeply saddened to announce the passing of **Dr. Robert "Bob" Curtis Harriss** on December 24, 2021, after a long illness. Bob served 13 years as senior scientist at NASA's Langley Research Center [1978–1990] and science division director for the Earth sciences at NASA Headquarters [1994–1997]. He also served in academia on the faculty at Florida State University (FSU) prior to joining NASA, at the University of New Hampshire (UNH) between his NASA tenures, and at Texas A&M after his NASA career. He mentored many colleagues and students who are active in leadership roles in Earth science around the world.



Bob was an important scientific architect of NASA's role in contemporary Earth Systems Science. He conceived of and implemented the groundbreaking expeditions [1980–1990] of the Global Tropospheric Experiment (GTE), which was among the first of the multiscale aircraft- and ground-based observation programs for which NASA is famous.

Bob initiated and led the Atmospheric Boundary Layer Experiments (ABLE) during the 1980s. ABLE was the first mission series in GTE. It brought together multidisciplinary teams to address fundamental questions about how the biosphere regulates the chemical composition of the atmosphere, at scales from a few square meters to global coverage. Later GTE experiments, in the 1990s and early 2000s, were equally ambitious international efforts that measured the long-range transport of pollutants throughout the remote Atlantic and Pacific basins.[1]

GTE took place at a time when the Amazon forest was largely intact and the economic giants of Asia had not yet arisen—a world that no longer exists. The rigor, breadth, and precocious timing of GTE created benchmark data sets that we use today to assess the rate of environmental change.

In 1994, Bob returned to NASA from New Hampshire to take the helm of the Science Division of the Mission to Planet Earth. He helped unify NASA Earth Science research and analysis programs as NASA developed the ambitious Earth Observing System (EOS). EOS was undergoing major restructuring, and Bob was a key participant on the leadership team addressing these challenges and developing a plan that was supported by the Earth Science community. His efforts included extensive interactions with the scientists of the fledgling EOS program and close coordination with the Space Studies Board of the National Academy of Sciences. Bob's ability to work across the broad EOS communities was vitally important to its success. His efforts of three decades ago continue to pay dividends with the operation of the major EOS platforms (Terra, Aqua, Aura), all having lasted well beyond their planned lifetimes, and with the legacies of the many other EOS missions.

This photo was taken during the ABLE-2 campaign, which included flights of the NASA Electra aircraft over the Amazon basin. **Bob Harriss** is shown here running a carbon dioxide analyzer during one of those flights. This investigation showed, for the first time, that it was possible to take aircraft measurements of daily uptake of CO_2 flux over a large area like the Amazon and compare them with eddy flux measurements on the ground. **Image credit:** NASA LaRC

Many colleagues have written and commented on Bob's superb mentoring, describing him as respectful and always willing to share ideas and inspiration. Bob clearly had a transformative influence on their careers.

Bob was born in Brownsville, TX on January 5, 1941. He lived there until Texas had its historic drought [1949–1957], when the family was forced to leave their ranch and move to another near Lake Okeechobee, FL. Bob received a track scholarship to Georgia Tech, but then transferred to Florida State University, which later afforded him his first faculty position. Bob is survived by his wife, Sandra Harriss, and other family members, to whom the NASA community members send their sincere condolences.

Acknowledgment

The Earth Observer staff wishes to thank **Jack Kaye** and **Barry Lefer** [both at NASA Headquarters], **Patrick Crill** [Stockholm University], and **Steve Wofsy** [Harvard University] for providing the text and photos for this *In Memoriam*. ■

[1] A high-level summary of the GTE experiments can be found at *go.nasa.gov/3oyBacR*. To read a more detailed narrative summary of GTE—including several references to Bob Harriss's involvement—see Eric Conway's *Atmospheric Science at NASA: A History*, Chapter 6 [pp. 156–167] and Chapter 9 [pp. 283–285].

Eight Microsatellites, One Mission: CYGNSS—Five Years and Counting

Chris Ruf, University of Michigan, cruf@umich.edu
Clara Chew, University Corporation for Atmospheric Research, clarac@ucar.edu
Mahta Moghaddam, University of Southern California, mahta@usc.edu
Derek Posselt, NASA/Jet Propulsion Laboratory, dposselt@umich.edu
Zhaoxia Pu, University of Utah, zhaoxia.pu@utah.edu

Introduction

The Cyclone Global Navigation Satellite System (CYGNSS) constellation of eight small satellites was launched into low Earth orbit on December 15, 2016. It is the first NASA Earth Science mission to use a constellation of SmallSats.[1] The constellation consists of 8 spacecraft distributed around a common circular orbit at 520 km (323 mi) altitude and 35° inclination. The mean revisit time of the full constellation is ~7 hours. An illustration of the coverage provided after one orbit and one full day is shown in **Figure 1**. CYGNSS is also the first science mission to use observations of scattered signals from the constellation of Global Positioning System (GPS) satellites. Each CYGNSS satellite carries a bistatic radar receiver that measures GPS signals reflected from Earth's surface back into space. Often referred to as *passive radar*, this approach eliminates the need to carry a radar transmitter, which significantly lowers the per-satellite cost and makes possible the deployment of a constellation of spacecraft at a relatively low overall mission cost.[2]

The objectives of the initial two-year mission were to study how well GPS signals reflected from the ocean surface could measure the winds in hurricanes and how well those measurements could improve our ability to forecast a storm's development. This was the reason for the shallow orbit inclination, which maximizes time spent at the most hurricane-prone latitudes. In the five years it has been in orbit, CYGNSS has accomplished those objectives and significantly expanded the scope of its scientific investigations. GPS signals reflected from storm-free parts of the ocean and from land also contain valuable information about surface conditions. Many of the scientific applications of CYGNSS observations, both for hurricane prediction studies and otherwise, are summarized here. The discussion begins with some of the engineering highlights of the mission.

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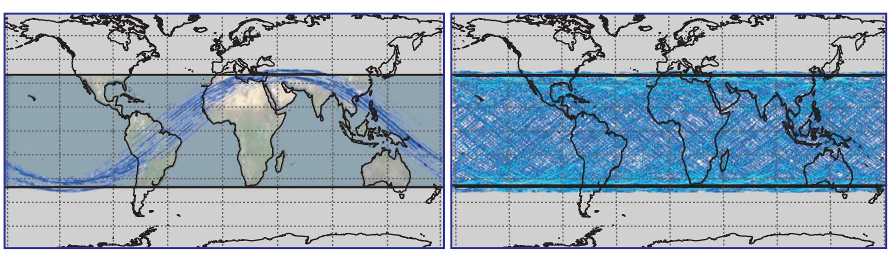

Figure 1. Spatial coverage by the full CYGNSS constellation of 8 spacecraft after one orbit, or 95 min [*left*], and after 24 hours [*right*]. **Image credit:** Chris Ruf/University of Michigan, Ann Arbor (U-M)

Engineering Details and Accomplishments

The CYGNSS constellation of spacecraft was designed by the Southwest Research Institute (SwRI) in San Antonio, TX, in partnership with the Space Physics Research Laboratory (SPRL) at the University of Michigan (U-M), and is currently operated

[1] To learn more about how SmallSats (specifically CubeSats) are being used for Earth Science applications, see "CubeSats and Their Roles in NASA's Earth Science Investigations," in the November–December 2020 issue of *The Earth* Observer [**Volume 32**, **Issue 6**, pp. 5–17—*go.nasa.gov/3tmwAig*].
[2] To learn more about the CYGNSS mission, see "Eight Microsatellites, One Mission: CYGNSS" in the November–December 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 6**, pp. 4–13—*go.nasa.gov/3v8SyZu*].

by SwRI out of their Boulder, CO, mission operations center, and SPRL out of their science operations center (SOC) in Ann Arbor, MI. Raw data are calibrated and converted to science data products at the SOC and then posted for public access at NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC). As the first NASA Earth Venture Mission the cost of the CYGNSS mission was strictly capped, so compromises were necessary to make the constellation affordable.[3] Notably, the CYGNSS satellites do not have active propulsion. Instead, differential drag is used to manage the spacing between them. As seen in **Figure 2**, the deployed solar panels make each spacecraft highly asymmetric. As a result, proper adjustment of their attitude can produce a 6:1 change in atmospheric drag from maximum to minimum. This feature is used to adjust the relative drag, orbital velocity, and, ultimately, separation between each spacecraft in the constellation.

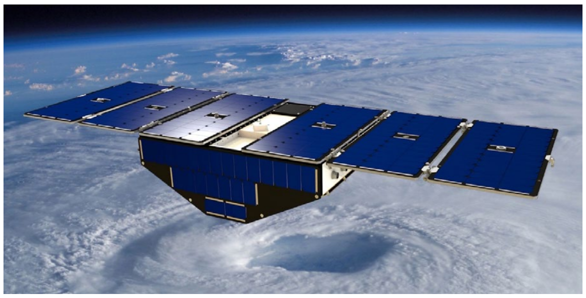

Figure 2. Illustration of a CYGNSS spacecraft in orbit with fully deployed solar panels. The solar panels allow for differential drag maneuvers to adjust relative spacecraft spacing in the constellation. **Image credit:** Chris Ruf/U-M

A second important compromise made in the engineering design is the exclusive use of commercial off-the-shelf electronic devices throughout the spacecraft, as opposed to the space-qualified and radiation-tolerant electronics that are more commonly used. This significantly reduced cost but resulted in an increase in susceptibility to radiation-induced upsets in orbit. To counter this susceptibility, several dozen autonomous fault-detection and -recovery schemes have been developed to continuously monitor the many embedded controllers distributed throughout each spacecraft. Early in the mission, upset-related events disrupted normal operations almost daily. Autonomous detection and recovery schemes are now quite mature and entire months without disruptions to continuously acquiring science data are common.

One immediate benefit of operating eight spacecraft is the frequency with which tropical cyclones can be sampled throughout their life cycle. This is illustrated in **Figure 3**, which shows when and how well CYGNSS sampled every major storm (Category 3 or greater) from 2018 to 2020.

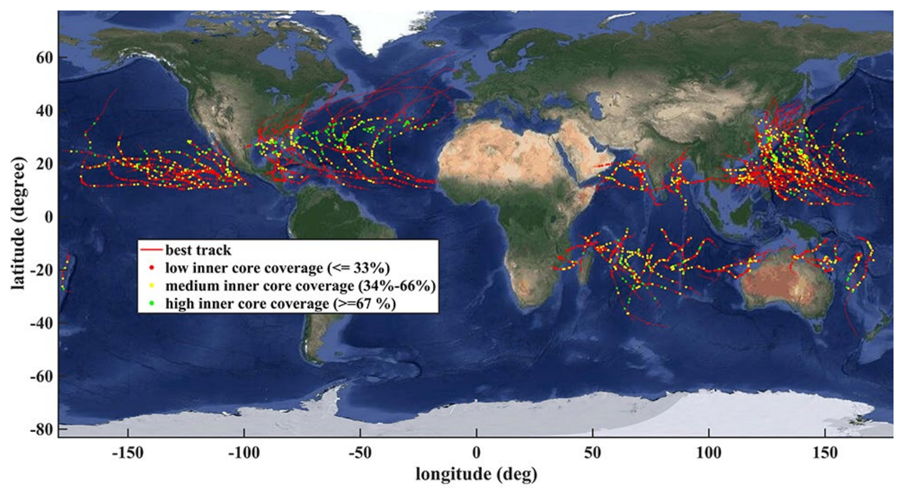

Figure 3. CYGNSS overpasses of all major storms during 2018-2020. The red lines are the track of each storm throughout its life cycle, the dots are when there was a CYGNSS overpass, and the color of the dot indicates the density of samples within the inner core of the storm. Every storm is sampled between one and three times a day, which helps monitor its development and capture sudden changes like rapid intensification. **Image credit:** April Warnock/SRI International (SRI)

One of the key benefits of the extended CYGNSS mission is that it allows the continuous operation of the constellation over a longer period, which opens up new possibilities for scientific investigations. Dense spatiotemporal sampling has supported measurement sensitivity studies to measure new environmental parameters and develop scientific uses for them. The following section summarizes a number of these studies.

[3] There are three categories under the Earth Venture Program element: Missions (designated EVM), of which CYGNSS was the first chosen; Instruments (EVI), designated for placement on other spacecraft or the International Space Station; and Suborbital (EVS) activities. To learn more about specific Earth Venture missions, see *go.nasa.gov/3FVU1nO*.

Scientific Accomplishments

While CYGNSS was originally intended to measure winds in hurricanes, it operates continuously—over storms or calm seas and over ocean or land. In fact, a large majority of its measurements are not over hurricanes. Uses of the data have expanded over time in many other directions. Over the ocean, new applications include studies of the Madden–Julian Oscillation (MJO) and diurnal patterns of tropical convection. Over land, new capabilities include estimating soil moisture and imaging inland waterbodies under vegetation canopies.

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Hurricane Prediction and Data Assimilation

With its seven-hour revisit time, CYGNSS observations of ocean-surface winds in the hurricane environment and inner core region facilitate both hurricane weather research and forecasting studies. CYGNSS wind products have been assimilated into various research and operational numerical weather prediction (NWP) models to demonstrate their usefulness in improving hurricane forecasting. Studies using the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction's (NCEP) Hurricane Weather Research and Forecasting (HWRF) regional model and a three-dimensional, hybrid ensemble-variational data-assimilation system have suggested that assimilation of the CYGNSS data results in improved hurricane track and intensity simulations of Hurricanes Harvey and Irma, both of which occurred in 2017. The improvements in the track and intensity forecasts are the result of improved representation of surface wind fields, hurricane inner-core structure—see **Figure 4**—and surface fluxes (not shown). These results indicate that CYGNSS Level-2 (L2) retrieved-wind data products could be a valuable data source for operational uses to complement available routine observations.

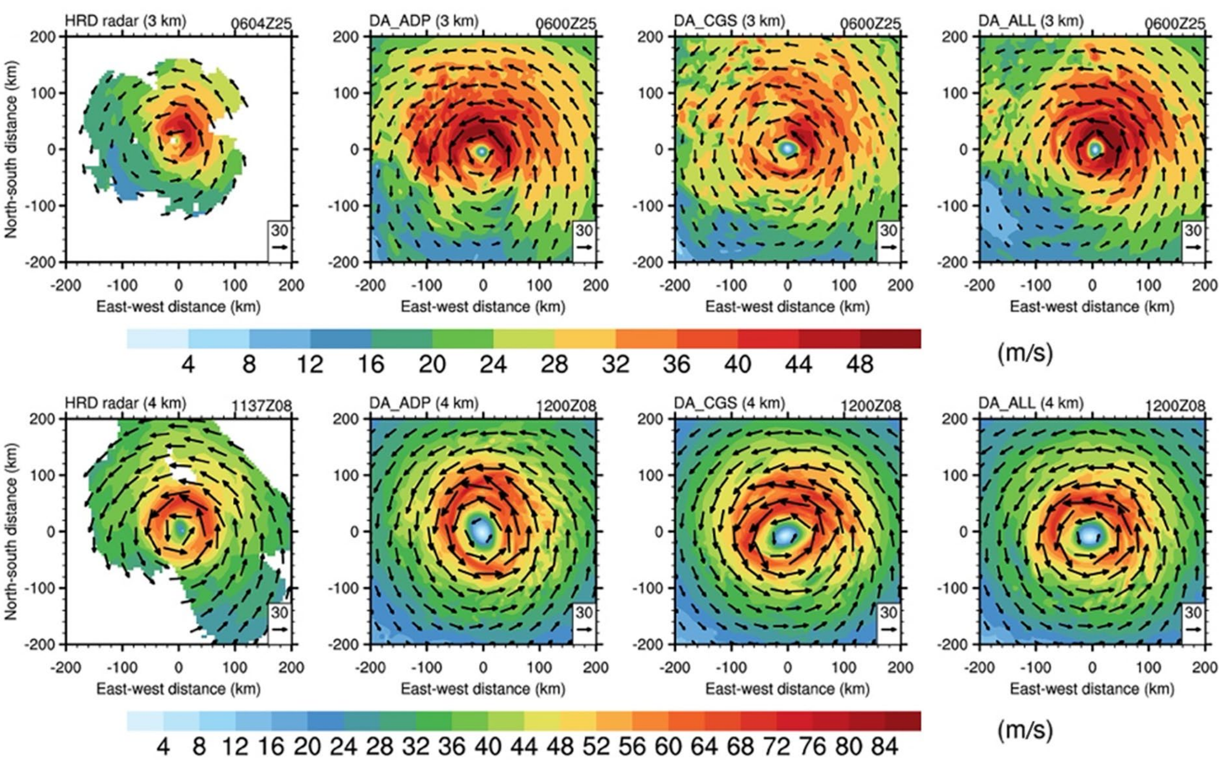

Figure 4. Impact of CYGNSS data assimilation on forecasts of hurricane inner cores using the National Centers for Environmental Prediction's (NCEP) Hurricane Weather Research and Forecasting (HWRF) model. This figure shows Hurricane Research Division radar analysis at the [*top row*] 3-km and [*bottom row*] 4-km height level of wind speeds (colored contours) and vectors of Hurricane Harvey at 0600 UTC August 25, 2021 [*top row, first column*], and Hurricane Irma at 1200 UTC September 8, 2017 [*bottom row, first column*] compared to three assimilation experiments: DA_AD, which assimilates conventional data only [*second column*], DA_CGS, which assimilates CYGNSS data only [*third column*], and DA_ALL, which assimilates both conventional and CYGNSS data [*fourth column*]. With both Harvey and Irma, azimuthal asymmetries in the wind field measured by the HRD radar are better represented by the CGS and ALL forecasts that assimilate CYGNSS winds. **Image credit:** Zhiqiang Cui/ University of Utah

An alternative approach has been developed to directly assimilate CYGNSS L1 engineering data, rather than L2 retrieved wind speed, using a two-dimensional variational analysis method. In addition to data assimilation efforts, CYGNSS data products are a valuable means to build a database for tropical cyclones (TC). Its L3 Storm Centric Gridded product is derived from the L2 retrieved ocean wind products. It determines wind speed from aggregated measurements made by the entire CYGNSS constellation. This data product is intended for historical storm analysis.

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Ocean-Surface Heat Fluxes

Ocean-surface heat fluxes can play a significant role in the formation and development of many marine-based weather systems. Traditionally, *in situ* observations, along with polar-orbiting spaceborne instruments, have been used to estimate latent and sensible heat fluxes (LHF and SHF, respectively) over the open ocean. However, their observations can be limited in time and space, and suffer from decreased reliability during significant weather events. Given that LHF and SHF are functions of wind speed, along with air–sea humidity and temperature differences, respectively, the improved wind speed measurements made possible by data provided by CYGNSS were used to develop a SHF product for the CYGNSS mission. This product and subsequent updates provide LHF and SHF estimates at every CYGNSS specular point over the oceans by using its L2 winds along with reanalysis data for the thermodynamic variables (i.e., temperature, humidity, air density) using the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2).

The LHF and SHF observations from CYGNSS have been the focal point in recent MJO convection and extratropical cyclone (ETC) analyses—as described in the next section. **Figure 5** shows CYGNSS wind speed and flux observations of a rapidly developing ETC in January 2018. While this ETC quickly shifted poleward, CYGNSS was still able to continually observe the equatorward side of the system, which featured the strongest winds and air–sea temperature differences, leading to strong LHF and SHF values. These observations from CYGNSS correlate with previous observations of ETCs and can provide key details about their impact on the genesis and evolution of these systems.

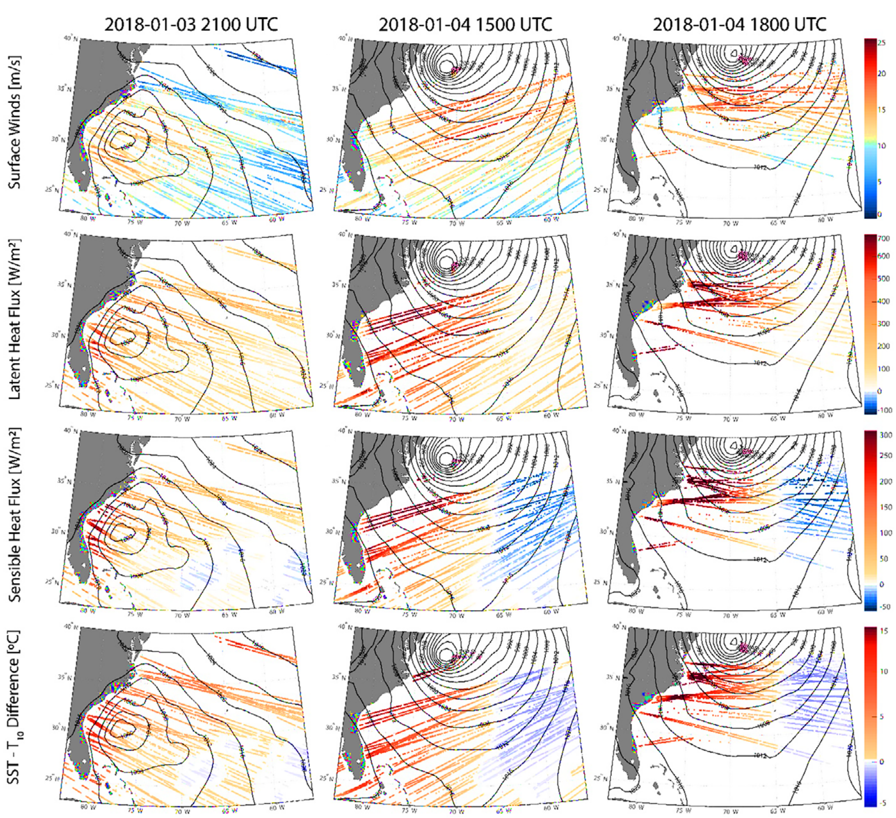

Figure 5. CYGNSS observations of surface wind observations (m/s) [*first row*], LHF (W/m^2) [*second row*], and SHF (W/m^2) [*third row*], along with temperature differences (°C) [*fourth row*] between the sea surface (SST) and 10 m (~33 ft) from MERRA-2 colocated at each specular point for an ETC in the western Atlantic Ocean at three different times on January 3–4, 2018: 2100 UTC January 3 [*first column*], 1500 UTC January 4 [*second column*], and 1800 UTC January 4 [*third column*]. CYGNSS observations span ±1.5 h from the time listed. **Image credit:** Juan Crespo/NASA/Jet Propulsion Laboratory

Tropical Meteorology and the Madden-Julian Oscillation

The tropical inclined orbit of the CYGNSS mission positions it ideally to observe a wide variety of tropical convective systems—i.e., more than just tropical cyclones. This includes convection, which is a critical part of the formation and evolution of the large-scale tropical circulation. One such tropical circulation feature is the MJO, which is a tropical Indian and west Pacific Ocean disturbance characterized by an eastward-propagating region of enhanced precipitation that repeats every 40–50 days, on average. Through teleconnections to other parts of the globe, the MJO modulates hurricanes in the Atlantic and Eastern Pacific, which can enhance flooding events and droughts, and other extreme weather events over North America. Although it was discovered in the early 1970s, a consensus on the underlying physics of the MJO remains elusive.

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CYGNSS observations have provided substantial insight into the dynamics of the MJO. Prior work has suggested that cloud radiative feedbacks to the moisture budget help to maintain the tropospheric moisture anomalies that sustain eastward-propagating MJO precipitation. However, other researchers have used CYGNSS wind-speed fields and associated surface fluxes to demonstrate that enhanced wind-induced surface fluxes in regions of MJO precipitation are almost as important for maintaining the MJO. **Figure 6** shows that CYGNSS-derived surface flux

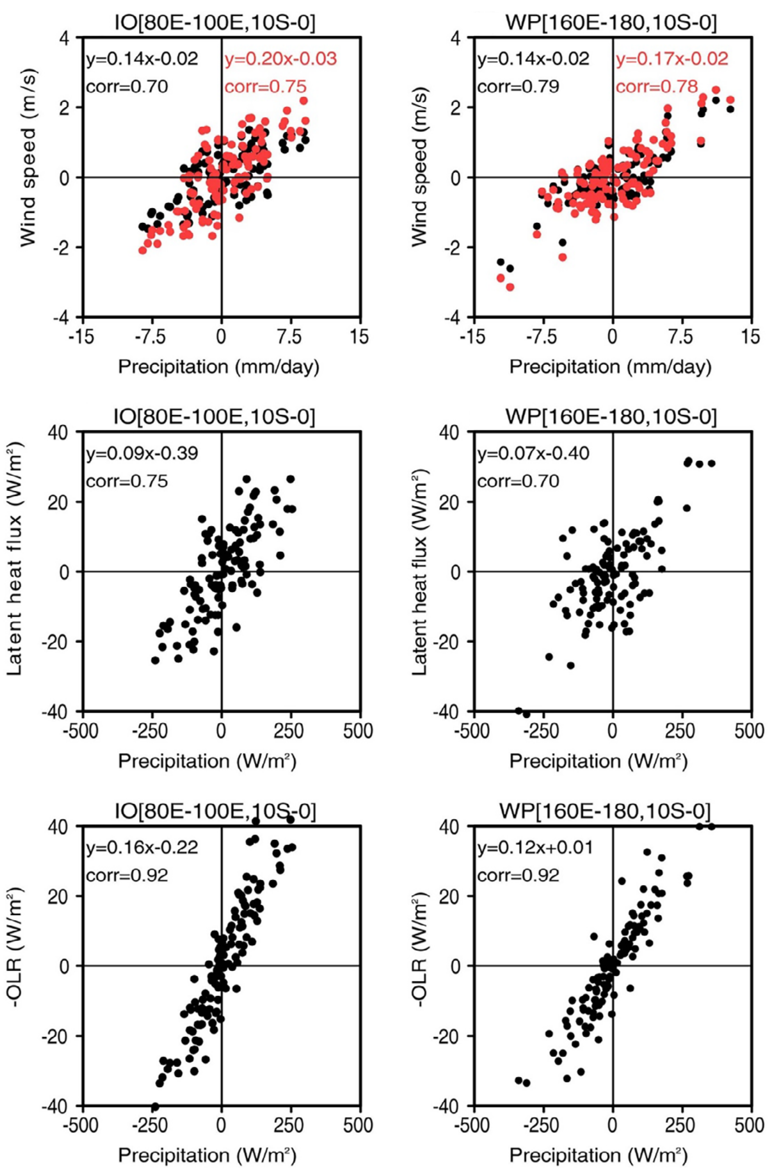

Figure 6. The top row contains scatterplots of November–April (2017–2019), 30-90-day bandpass filtered CYGNSS version 2.1 (red) and Climate Data Record version 1.0 (black) wind speed anomalies versus GPM precipitation anomalies averaged over the tropical Indian Ocean (IO; 80–100° E, 10° S–0) [*top left*] and West Pacific (WP; 160° E–180, 10° S–0) [*top right*]. Data from 2017-2019 are used and every fifth day is plotted. The two plots in the *middle row* show comparisons of CYGNSS surface latent heat flux (SLH) anomalies to GPM precipitation anomalies for the same locations as the top row. The two plots in the *bottom row* show comparisons of outgoing longwave radiation (OLR) anomalies to GPM precipitation anomalies for the same locations as the top row. The significant correlation demonstrated between SLH and precipitation—of the same order as that for OLR—suggests that surface winds also play an important role in MJO dynamics. **Image credit:** Hien Bui/Colorado State University

anomalies, which are approximately colocated with MJO precipitation, are on the order of 7–9% of MJO-timescale precipitation anomalies in the Indian and West Pacific Oceans (Figure 5, *middle row*). This is not that much lower than the contribution from column longwave radiation anomalies (Figure 6, *bottom row*), which are about 12–16% of MJO precipitation. In other parts of the tropics, such as the East Pacific warm pool during boreal summer, CYGNSS observations suggest that surface flux anomalies may be more important than radiative anomalies for maintaining MJO-timescale precipitation variations. CYGNSS observations will undoubtedly provide even greater insights into tropical dynamics as the data record grows.

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Extratropical Cyclones

While CYGNSS was designed to study tropical processes, it takes observations between 40° N and 40° S latitude, allowing it to collect data on a large number of low-latitude ETCs each year. An example of CYGNSS observations of one such storm was shown in Figure 5. Since before launch, the CYGNSS Science Team (ST) has been investigating what may be learned about ETCs from its ocean-surface wind and ocean-heat-flux measurements—in particular, how surface heat fluxes change as the cyclones age, to better understand the energy exchanges between the ocean and ETCs. This research used a database of extratropical cyclone tracks, colocated with CYGNSS observations of wind, SHF, and LHF for storms found in the lower latitudes of the extratropics. The analysis included composites of CYGNSS observations for thousands of storms and analyzed their wind structures and ocean surface LHF and SHF.

In each case, results from analyses of 500 of the cyclones that had CYGNSS observations within 1500 km (~930 mi) of the storm center and within 3 hours of storm identification showed that SHF was available in each of the three main periods of storm evolution: *early development,* which lasts from when the storm was first detected to 36 hours prior to peak; *intensification,* spanning the 36 hours prior to peak intensity; and *dissipation,* which lasts from 6 hours post-peak until the last time the storm is identified in the database. Cold-front centered composites of surface fluxes were then constructed.

Focusing on the difference in SHF and LHF between early development and intensification—**Figure 7** [*left column*]—the fluxes increase in the post-cold-frontal region

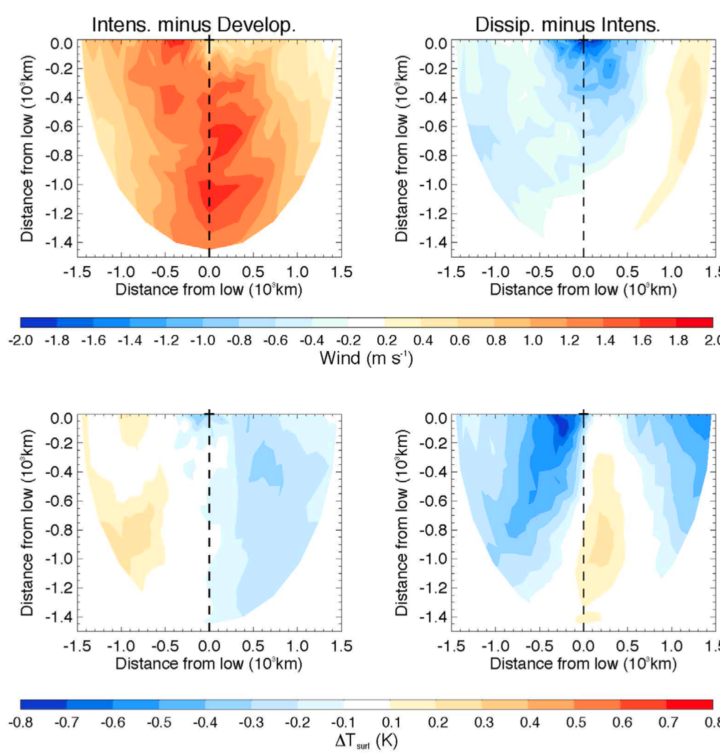

Figure 7. Difference in cold front-centered composites of CYGNSS SHF [*top row*] and LHF [*bottom row*] between intensifying and developing phases [*left*] and dissipating and intensifying phases [*right*] of extratropical cyclone (ETC) evolution. The vertical dashed lines indicate the location of the cold fronts. **Image credit:** Catherine Naud/NASA's Goddard Institute for Space Studies

and decrease in the warm sector, with the LHF also showing an increase along the cold front as the cyclones reach maturity. The increase is driven by an increase in wind speed and the decrease by a decrease in the air-sea temperature difference and resulting moisture flux. Between intensification and dissipation—**Figure 7** [*right column*]—the fluxes decrease everywhere in the cyclone except for a narrow band of increase along the cold fronts. In this case, the changes are driven mostly by changes in temperature and moisture contrasts.

These results highlight the importance of the cold front for sea–air energy exchanges throughout the life of an ETC.

Land Applications: Introduction

Even though CYGNSS was originally proposed for observing tropical cyclones, the utility of CYGNSS reflectometry for land applications has become increasingly evident since the launch of the mission, with products now being generated on both routine and experimental bases. The potential land applications of CYGNSS include surface- and root-zone soil moisture retrieval, freeze-thaw monitoring, and wetlands and inland water mapping.

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Soil Moisture

Data from CYGNSS have been shown to have immense value for retrieving soil moisture. The CYGNSS reflectivity data carry information about the dielectric constant of the ground surface, which in turn is directly proportional to soil moisture content. Members of the CYGNSS ST have developed a few different methods and associated products for surface soil moisture [i.e., the upper 5 cm (~2 in)]. The first such product was released by the University Corporation for Atmospheric Research (UCAR), available on a 36-km (22-mi) grid at 6-hour intervals, with the CYGNSS latitude coverage of ±38°. This product, based on data available since 2017, was developed by calibrating observations of surface reflectivity from CYGNSS to soil moisture retrievals from NASA's Soil Moisture Active Passive (SMAP) mission. The product has been validated using over 200 *in situ* soil moisture probes from 5 networks, with an overall unbiased root-mean-square error of 0.047 cm^3/cm^3. By comparison, the SMAP mission requirement for soil moisture retrieval uncertainty is 0.040 cm^3/cm^3—which means that the initial CYGNSS soil moisture product comes within ~18% of meeting the requirement set by the SMAP mission. Several other products are currently undergoing performance evaluation by the CYGNSS Soil Moisture Assessment Working group. These include products developed using a time-series method, a machine-learning scheme, as well as one based on a semi-empirical model using SMAP data.

Land Freeze/Thaw

A study carried out over an area in South America covering the Andes Mountains and the Argentinian Pampas has shown that CYGNSS is responsive to changes in surface permittivity, which is then leveraged to detect transitions of freeze–thaw surface state—see **Figure 8**. The CYGNSS observations were shown to have superior spatiotemporal sampling as compared to previous missions. The method used in this study was based on a Seasonal-Threshold Algorithm (STA) and validated using surface temperature data from the fifth-generation European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis (ERA5) land numerical reanalysis model.

Land Calibration/Validation and Model Intercomparison Activities

Following the selection of several land-focused projects by NASA through research solicitations in 2017 and again in 2020, a CYGNSS Land Applications Working Group was formed. The investigators in this working group have been developing various physics-based and data-driven algorithms to retrieve soil moisture, inundation and surface water, freeze–thaw state, and vegetation information from CYGNSS data. A calibration/validation (cal/val) plan was developed and partially implemented

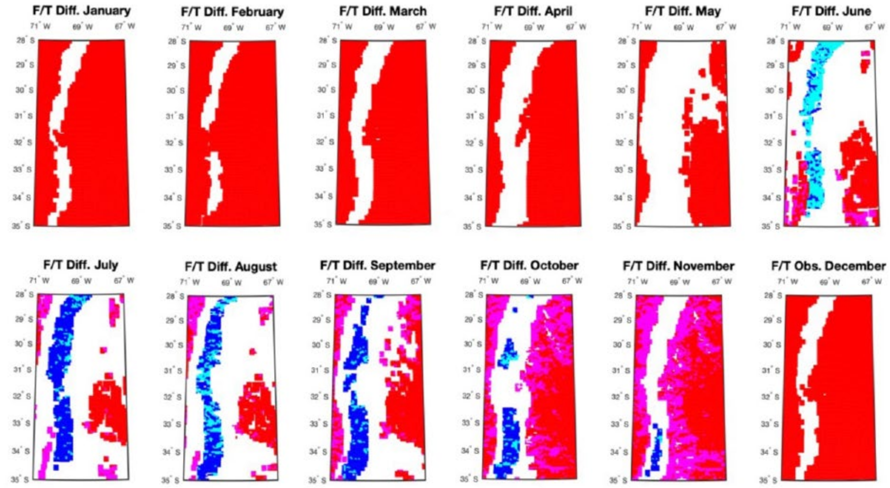


Figure 8. Imaging the annual freeze/thaw transition with CYGNSS in the Andes Mountains over the course of one year. The transition from thawed to frozen state in winter along the highest altitude ridge of the Andes is clearly captured, demonstrating this new remote sensing capability. **Image credit:** Hugo Carreno/U-M

for some of these products through the deployment of *in situ* soil moisture networks [e.g., Soil Moisture Sensing Controller And oPtimal Estimator (SoilsCAPE)] and associated field campaigns. The calibration/validation plan takes advantage of some existing *in situ* sites that were in use for the SMAP mission, but it also includes sites that are being established or augmented specifically to support the CYGNSS mission. The latter include San Luis Valley, CO, White Sands, NM, Walnut Gulch, AZ, (all in the U.S.); and Ararimu, Te Hiku, and Riverhead Forest in New Zealand.

The CYGNSS mission has also teamed up with the New Zealand Space Agency, the University of Auckland, and Air New Zealand (ANZ) to install radar receivers on ANZ commercial aircraft to acquire airborne measurements for synergistic use with CYGNSS observations; the effort is referred to as *Rongowai* (which means "The Sensing of Water" in native Maori).[4] These new airborne data will allow investigating the effects of landscape heterogeneity and the potential benefits of higher-resolution observations.

Recent studies by the CYGNSS ST have revealed that topography and land-surface heterogeneity have a significant influence on bistatic scattering over land and so must be properly accounted for when interpreting CYGNSS land observations.

Other activities are under way to cross compare and validate several electromagnetic scattering models of CYGNSS land observations that are under development. Recent studies by the CYGNSS ST have revealed that topography and land-surface heterogeneity have a significant influence on bistatic scattering over land and so must be properly accounted for when interpreting CYGNSS land observations. High-resolution digital elevation maps (DEMs) are being generated using airborne lidar measurements to address the need for detailed information about topography. The ST is also developing methods for scaling up local small-scale ("electromagnetic-scale" or centimeter-scale) roughness maps to the scales of CYGNSS Delay Doppler Map (DDM)[5] coverage. This will involve a proper accounting for the different spatial correlation lengths of the relevant roughness scales.

Mapping Inland Water Bodies, Wetlands, and Flooding

Soon after the launch of CYGNSS, researchers began mapping the reflected signal over the land surface and were struck by the apparent sensitivity of the CYGNSS data to small surface-water features, some as small as 100 m (~330 ft) wide. This finding has led to several successful efforts to use the data to map transitory flooding due to severe weather events, seasonal changes in wetland extent, and permanent water bodies that are hidden underneath dense vegetation canopies, which are difficult to image using existing sensors.

CYGNSS can detect standing water underneath dense vegetation due to its measurement wavelength—the relatively long L-band microwave signals [19 cm (7.5 in)] that

[4] Learn more about the *Rongowai* partnership at *geospatial.ac.nz/portfolio_page/rongowai*.
[5] DDMs are the output created by analysis of CYGNSS GPS data. Wind speed is estimated from the DDM by relating the region of strongest scattering to the ocean surface roughness. To learn more, see the sidebar on page 10 of the introductory article on CYGNSS, referenced earlier.

GPS satellites transmit can penetrate denser canopies than signals with shorter wavelengths, such as the C-band signals [5.6 cm (~2.2 in)], used by the European Space Agency's Sentinel satellites—see **Figure 9** for an illustration.

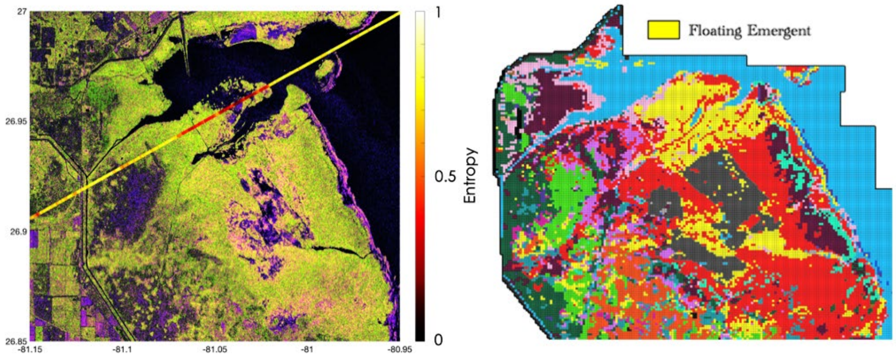


Figure 9. C-band Sentinel-1 backscatter image of Lake Okeechobee in Florida, with one CYGNSS track overlaid [*left*]. Yellow areas in the CYGNSS data correspond to floating emergent vegetation [*right*], indicating a response to the calm water beneath the vegetation. There is no corresponding change in the Sentinel-1 data, which is predominantly backscattered by the overlying vegetation. **Image credit:** Maurizio di Bisceglie/ University of Benevento

Researchers are leveraging this capability to map seasonal changes in wetland extent in tropical regions. Some of these efforts have included using these maps to estimate the amount of methane emitted by these wetlands. Wetlands are the largest natural source of methane (CH_4), a potent greenhouse gas, and quantifying wetland extent is important to accurately model methane emissions from these areas. Recently, researchers found that annual CH_4 emissions from the Sudd wetlands in South Sudan are actually greater than previously estimated—see **Figure 10**—thanks to new inundation maps derived from CYGNSS observations. Also, the CYGNSS-based modeled emissions are more consistent with *in situ* and satellite-derived data for atmospheric methane concentrations than when using other sources of data to characterize wetland extent in the model.

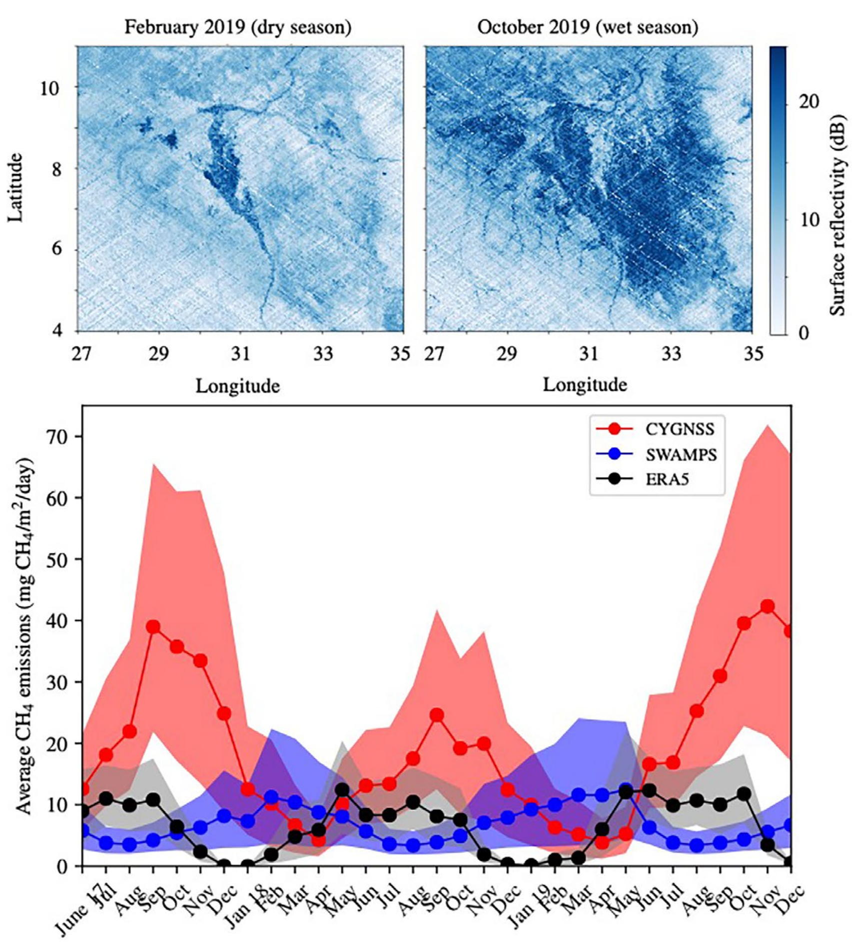


Figure 10. Surface reflectivity maps of the Sudd wetland in South Sudan obtained from CYGNSS data showing the area during the dry season [*top left*] and the wet season [*top right*]. The Wetland CH_4 Emissions and Uncertainty Atmospheric Chemistry and Transport (WetCHARTs) modeled methane emissions—using CYGNSS maps of the Sudd—are larger and show more seasonal variation than when using other wetland maps [*bottom*]. Using a static water mask derived from visible/ infrared imagers (SWAMPS) limits its seasonal variability and underestimates wetland extent under clouds and vegetation. Using a rainfall map created using the European Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis, version 5 [ERA5] to account for seasonal effects helps to produce a more realistic simulation of the complex relationship between rainfall and wetland inundation. The best results are found using dynamic maps of wetland extent derived from CYGNSS observations, which are direct, time varying measurements of the inundation that are insensitive to clouds and vegetation. **Image credit:** Cynthia Gerlein-Safdi/ University of California, Berkeley

In addition to improving methane emission models, there is preliminary evidence that under certain conditions CYGNSS reflectivity data could be an indicator of not only surface-water extent but also depth. In the Everglades particularly, the depth of water within the wetland complex is correlated with the surface-water extent, and researchers have used this relationship to estimate the depth of water within the Everglades—see **Figure 11**.

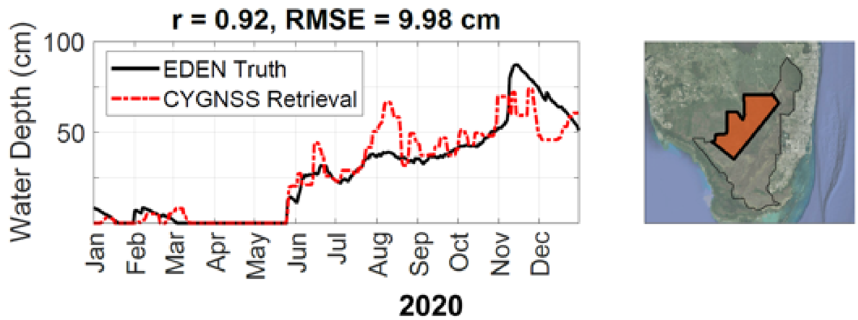


Figure 11. The graph on the left shows a time series of water depth data from the Everglades Depth Estimation Network (EDEN) (black line) with CYGNSS water depth retrievals overlaid (red dashed line). The image on the right is a depiction of the region used for the analysis within the Everglades (red region outlined in black). **Image credit:** Brandi Downs/The Ohio State University

Aside from their utility in wetlands mapping applications, the data from the CYGNSS satellites have also shown promise for mapping surface flooding. Optical sensors that are often used for flood mapping cannot penetrate clouds, preventing detection of flooded areas until after the weather event has passed. It is important to note that—although flooding from severe weather events can be both costly and devastating for communities—these transitory events are sometimes too short for single satellites to map them, as inundation maps produced by a single satellite overpass may not capture the extent of maximum flooding.

However, the constellation of CYGNSS satellites enables flooding maps to be created more rapidly and more frequently than from a single sensor and without obfuscation by cloud cover. **Figure 12** shows an example of flood inundation maps of Cuba produced by CYGNSS both before and after Hurricane Irma.

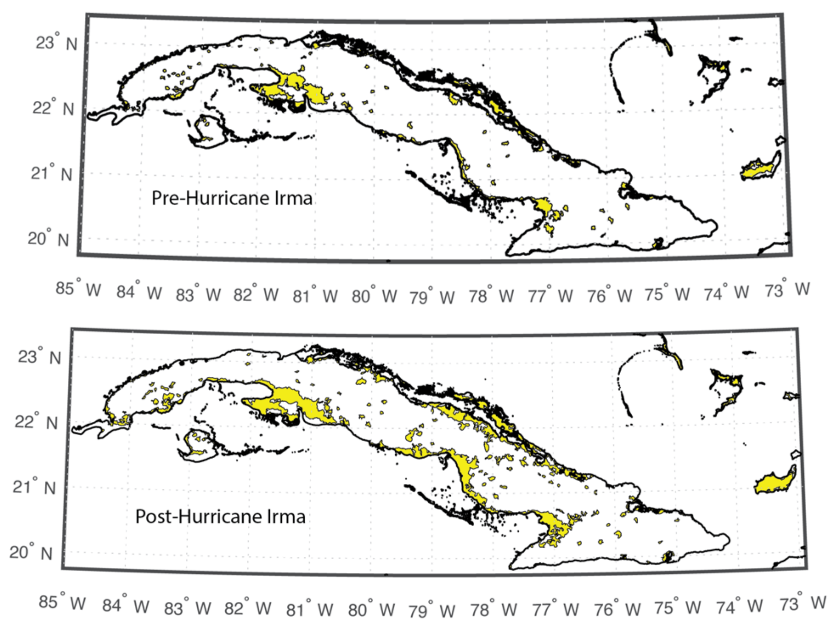


Figure 12. Yellow areas indicate inland surface water before [*top*] and after [*bottom*] Hurricane Irma in Cuba. **Image credit:** Clara Chew/UCAR

Several research groups are developing algorithms to map inland water bodies using CYGNSS data with a wide variety of approaches and end products. Validating these maps remains a subject of ongoing investigation, given that there are scant concurrent inundation maps at the same or similar spatiotemporal scales. However, preliminary validation efforts have been promising. **Figure 13** on page 15, shows a Southeastern U.S. regional comparison between an annual CYGNSS-derived inundation map and an upscaled inundation map from Landsat 8—the two maps agree quite well.

Although the CYGNSS satellites were not designed for inland water-body mapping, the success of these efforts has opened an entirely new area of study for reflected global navigation satellite system (GNSS-R) technology, which will undoubtedly continue to grow in the future.

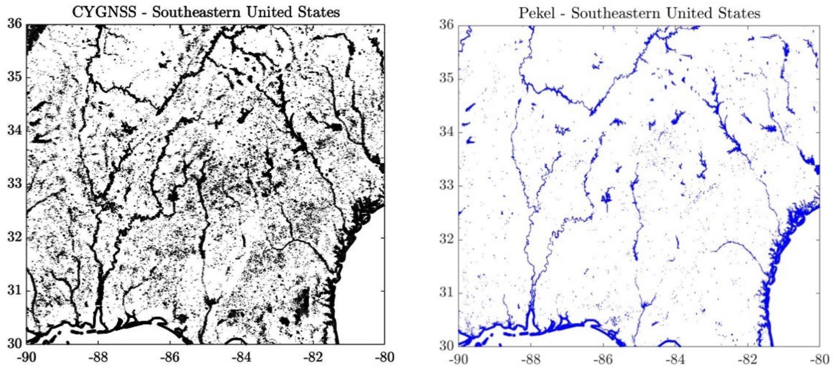


Figure 13. A Southeastern U.S. regional comparison of a CYGNSS-derived inundation map for 2019 [*left*] alongside an upscaled, concurrent inundation map from the Surface Water Explorer, which uses optical remote sensing data from Landsat 8 [*right*]. **Image credit:** Clara Chew/UCAR

What the Future Holds

Five years ago, CYGNSS began as a novel mission designed to study hurricanes in a new way—a constellation of eight small satellites using reflected GPS navigation signals to create a large network of bistatic radars in space. Reflections from the ocean surface contain information about surface roughness, from which the wind speed at the surface can be determined. Two distinguishing characteristics of the CYGNSS wind measurements are its ability to penetrate through rain, made possible by the use of GPS signals, and its low revisit time of seven hours on average, made possible by the large number of satellites in the CYGNSS and GPS constellations. Measuring near-surface winds often in and near storms has allowed hurricanes to be better characterized and their evolution to be forecast with greater accuracy.

Although the CYGNSS satellites were not designed for inland water body mapping, the success of these efforts has opened an entirely new area of study for reflected global navigation satellite system (GNSS-R) technology, which will undoubtedly continue to grow in the future.

Early in the mission, it became clear that the original hurricane science objectives were only a part of what was possible. For example, ocean measurements away from storms have uncovered a relationship between surface level heat flux and the precipitation associated with the MJO. Measurements near extratropical cyclones have also revealed a relationship between ETCs and the cold fronts that often accompany them. Measurements of GPS reflections over land have enabled new investigations associated with the presence and extent of inland water bodies, including the ability to image flood inundation after hurricane landfalls and seasonal wetland flooding associated with enhanced methane emission. Reflections from the land itself have also been shown to contain information about its near-surface soil moisture content, with applications in both hydrology and agriculture.

The first five years of in-orbit operations have produced valuable results over both ocean and land, some of which were anticipated but others unexpected. Who knows what other new sensitivities will be uncovered in the next five years? The possibilities are exciting to consider, and now have a firm basis on which to proceed.

Acknowledgment

The authors wish to acknowledge the contributions of **Hugo Carreno-Luengo** [U-M], **Juan Cespo** [NASA/Jet Propulsion Laboratory], **Mauricio di Bisceglie** [University of Benevento, *Italy*], **Brandi Downs** [The Ohio State University], **Cynthia Gerlein-Safdi** [University of California, Berkeley], **Eric Maloney** [Colorado State University], **Catherine Naud** [NASA's Goddard Institute for Space Studies], and **April Warnock** [SRI International].

NASA Science at the First Hybrid AGU Fall Meeting

Heather Hanson, NASA's Goddard Space Flight Center/Global Science & Technology, Inc., heather.h.hanson@nasa.gov

Introduction

For the second time since the start of the COVID pandemic in 2020, the American Geophysical Union (AGU) Fall Meeting occurred during its normal December timeframe. While last year's event was the first virtual Fall Meeting,[1] this year marked yet another first and a step towards normalcy—or perhaps a new normal—offering in-person as well as virtual participation. Coined a *hybrid* event, the 2021 AGU Fall Meeting was held December 13–17, 2021, in New Orleans, LA, and "online everywhere."

Leveraging AGU's successful hybrid conference format, NASA's Science Support Office (SSO) team coordinated the first-ever NASA Science exhibit that had both in-person and virtual components. To support the virtual NASA Science exhibit, the SSO used the agency-approved virtual event platform to host content.[2] In another first, the virtual NASA Science exhibit, developed with AGU attendees in mind, was free and open to the public—i.e., while the NASA Science exhibit was accessible through the AGU virtual platform, it was hosted by NASA and therefore existed outside the AGU conference pay wall. With opportunities for such broadened participation, both the in-person and virtual NASA Science exhibits offered live and prerecorded content.

The In-Person NASA Science Exhibit

NASA Science was among 141 in-person exhibits and 31 virtual exhibits in the Exhibit Hall. The NASA Science exhibit space measured 50x50 ft (~15x15 m). The health and safety of all exhibitors and attendees were top priorities, made clear by social-distancing signage, floor stickers, and a social-distancing floorplan and one-way walking path. The exhibit featured NASA's Hyperwall,[3] a Learning Area for demonstrations and tutorials, and a traditional table-style area where attendees could visit eight different tables to engage with a variety of NASA subject matter experts representing various disciplines within NASA's Science Mission Directorate (SMD)—see **Figure 1**.

[1] To read about the NASA Science virtual exhibit at the 2020 AGU Fall Meeting, see "NASA Science at the First Virtual AGU Fall Meeting" in the January-February 2021 issue of *The Earth Observer* [**Volume 33, Issue 1**, pp. 4-9—*go.nasa.gov/3nJEKjQ*].

[2] The agency's first virtual event to use the agency virtual platform tool was Earth Day 2021. See "Connected by Earth: Summary of NASA's 2021 Virtual Earth Day Event," in the May-June 2021 issue of *The Earth Observer* [**Volume 33, Issue 3**, pp. 4–11—*go.nasa.gov/35lpjaY*].

[3] NASA's Hyperwall is a video wall capable of displaying multiple high-definition data visualizations and/or images simultaneously across an arrangement of screens. To view the full library of Hyperwall visualizations and stories, visit *svs.gsfc.nasa.gov/hw*.

Figure 1. [*Left*] Signage throughout the NASA Science exhibit reminded attendees to practice social distancing and wear a mask. The overhead photography shot of the NASA Science exhibit [*photo on right*] at the AGU Fall 2021 Meeting shows the exhibit's three main areas—the Hyperwall [*front middle*], partially-enclosed Learning Area [*back middle*], and traditional table area [*left*]. **Credit:** NASA

Throughout the week the Hyperwall featured 36 storytelling talks, including 8 presentations delivered by the winners of the *2021 AGU Michael Freilich Student Visualization Competition*—see **Photos 1-3**. The Learning Area was set up to mimic a classroom, with socially distanced tables and chairs, and featured 26 demonstrations throughout the event—see **Photo 4** below and **Photo 5** on page 18. The table area featured content representing many SMD focus areas, including Earth Science, Planetary Science, Heliophysics, Astrophysics, Small Satellites, and Student Opportunities—see **Photo 6** on page 18. In addition, copies of the *2022 NASA Science Planning Guide* as well as NASA's new 350-page book, *50 Years of Solar System Exploration: Historical Perspectives,* were distributed to exhibit attendees—see **Photos 7-9** on page 18.

The exhibit design incorporated a "reduce, reuse, and recycle" approach that included reducing energy consumption (e.g., using LED monitors—and no monitors at all in the table area), reducing the number of print products and increasing digital literature via QR codes, reusing exhibit structures (e.g., the Hyperwall, lamppost signage, tablecloths), and using recyclable materials when possible (e.g., a cardboard enclosure for the Learning Area). In addition, exhibit staff encouraged attendees to take only what they needed, to choose digital literature when possible, and to recycle all materials when finished.

Despite the smaller-than-usual crowd (approximate in-person attendance was 8000 compared to roughly 20,000 in years past), the depth and breadth of NASA Science was on full display at the first in-person AGU Fall Meeting in two years. Attendees once again marveled at visualizations on the NASA Hyperwall, heard stories from NASA scientists, talked face-to-face with NASA experts, and had opportunities to take NASA Science engagement products home, either in the form of digital literature or a copy of the *2022 NASA Science Planning Guide*. To view more photos from the event, visit *go.nasa.gov/3rAPX7l*.

Photo 1. Karen St. Germain [NASA Headquarters—*Director of the Earth Science Division*] delivered the first Hyperwall talk, titled "NASA Earth Observations, Models, and Predictive Capabilities," on opening night. **Photo credit:** NASA

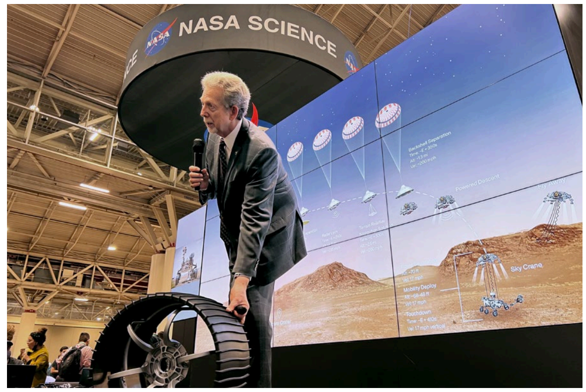


Photo 2. James Green [NASA Headquarters—*Chief Scientist*] showed a model of a Mars rover tire in front of the NASA Hyperwall during his talk titled "Perseverance and Ingenuity on Mars." **Photo credit:** NASA

Photo 3. [*Far right*] **Karen St. Germain** [NASA Headquarters—*Director of the Earth Science Division*] and [*far left*] **Randy Fiser** [AGU—*Executive Director*] stand with the winners of the *2021 AGU Michael Freilich Student Visualization Competition*. **Photo credit:** NASA

Photo 4. [*Standing center*] **Brian Campbell** [NASA's Goddard Space Flight Center (GSFC)—*Senior Outreach Specialist*] demonstrated "NASA Missions, Environmental Observations, and GLOBE" in the Learning Area with [*back right*] **Peter Falcon** [NASA/Jet Propulsion Laboratory—*Senior Outreach Specialist*]. **Photo credit:** NASA

Photo 5. While most Learning Area demonstrations were delivered to attendees passively seated at tables (Photo 4), the NASA SMD Community of Practice for Education (SCoPE) team invited attendees to get active and "Go Fishing!" The SCoPE Project (*go.nasa.gov/3tL4NL5*) connects NASA experts with educational communications projects. This interactive experience allowed early- and late-career scientists to "fish" for the names of different NASA subject matter experts. Each player won a prize while learning more about the NASA Science Activation Program. **Photo credit:** NASA

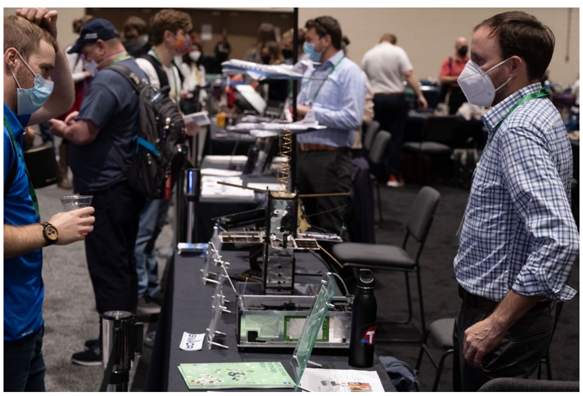


Photo 6. [*Right*] **Philip Larkin** [GSFC—*Technology Development Manager for the Earth Science Technology Office (ESTO)*] talked to attendees about ESTO-funded and -affiliated projects. **Photo credit:** NASA

Photo 7. Kevin Durham [GSFC—*Senior Exhibit Specialist for the Science Support Office*] handed out copies of the *2022 NASA Science Planning Guide*. Visit *go.nasa.gov/3rDD8ef* for more information on how to download copies in English or Spanish, or to purchase a copy from the Government Printing Office. **Credit:** NASA

Photos 8 and 9. James Green [NASA Headquarters—*Chief Scientist*] signed 300 copies of the book *50 Years of Solar System Exploration: Historical Perspectives* at the exhibit for AGU attendees. Visit *go.nasa.gov/3fKCZyi* to download a *.pdf* or *.epub* version of the book. **Photo credit:** NASA

The Virtual NASA Science Exhibit

The virtual NASA Science exhibit at the AGU Fall Meeting was open in tandem with the in-person AGU conference, from December 13-17, 2021. Figures on page 19 illustrate the virtual exhibit space. The online exhibit featured six different content rooms (Science Theater, Learning Area, Science News, Social, Science Data, and Get Involved), a NASA Help Desk, and NASA Science Chat—see **Figure 2**. Like the in-person NASA Hyperwall, the virtual Science Theater featured 39 prerecorded videos, allowing attendees to hear directly from scientists and subject matter experts—see **Figure 3**. Similarly, the Learning Area featured 17 prerecorded demonstrations to mimic the in-person Learning Area demos—see **Figure 4**. Other rooms such as Science News, Social, Science Data, and Get Involved featured various links to curated NASA resources. A digital link to the *2022 NASA Science Planning Guide* was readily available in the attendee's *virtual briefcase* (a tool often built into online conference platforms that allows attendees to collect digital media in one spot). The virtual exhibit had a total of 278 registered attendees, including 15 staff members who helped monitor the NASA Science Chat at various times during the conference. To view the virtual NASA Science exhibit guide, including the agenda for daily chat topics and times, visit *go.nasa.gov/3qKCM4q*.

Figure 2. With online access, virtual attendees could navigate from the Main Lobby [*above*] to six different rooms as well as the NASA Help Desk and NASA Science chat area by clicking on different titles in the Main Lobby graphic, or by using the navigation bar at the bottom of the page. **Credit:** NASA

Figure 3. The virtual Science Theater room featured 39 prerecorded videos (available at *go.nasa.gov/3nJGaLc*) as well as access to live chats with NASA experts. **Credit:** NASA

Figure 4. The virtual Learning Area room featured 17 prerecorded videos (available at *go.nasa.gov/33WuuOd)* as well as access to live chats with NASA experts. **Credit:** NASA

Summary

Since the 2019 AGU Fall Meeting—i.e., since just before COVID, NASA's SSO has made tremendous progress in its ability to reach scientific audiences and the public in both in-person and virtual settings. Even amid an ongoing pandemic, the doorway to NASA Science remains wide open; the office's capacity to share the science has never been greater; and hybrid events are likely to become the new normal. The SSO's commitment to its mission to share NASA Science with the world remains strong, and we look forward to broadening our reach and impact in 2022. ■

Summary of the 2021 GRACE Follow-On Science Team Meeting

Felix Landerer, NASA/Jet Propulsion Laboratory, felix.landerer@jpl.nasa.gov

Introduction

The 2021 Gravity Recovery and Climate Experiment (GRACE) Follow-On [GFO] Science Team Meeting (STM) occurred over four days in October 2021. Due to the ongoing COVID-19 pandemic, a face-to-face meeting—originally planned to take place in Pasadena, CA—once again could not be realized. Instead, as in the previous year, the 2021 meeting took place in a fully virtual format, organized by NASA/Jet Propulsion Laboratory (JPL) team members. Over 220 registered participants (a new record!) from over 15 countries participated in the meeting.

To accommodate the international participants' schedules across different time zones, and to help alleviate video-conference fatigue, the meeting was conducted over four dates: October 12, 13, 19, and 20. Each date offered a 2-hour-and-45-minute "live" session run via WebEx. During the live sessions, presenters gave short 5-minute talks (over 75 total) of high-level overviews of new results from the GFO data record. As of December 2021 these extend the 15-year GRACE data record with 39 monthly gravity and mass-change fields. The discussion of discoveries and updates covered the combined GRACE and GRACE-FO [GGFO] climate data record, which now spans nearly 20 years.

The first live session of the GFO STM opened on October 12 with a GFO project status session addressing mission and flight segment technical status, future science plans, and updates on the latest GGFO Release 06 (RL06) data from the Science Data System (SDS) centers. Over the following three live sessions the meeting consisted of 66 contributed science presentations.

In addition to the live WebEx sessions, the ST used a virtual meeting platform to host content (e.g., presentation materials and posters) and to allow for virtual real-time collaboration among participants. The platform was open 24/7 for two weeks after the first live session. Each participant was assigned a customizable, game-like avatar used to navigate the virtual environment, which included a poster hall, virtual booths (described below), and meeting rooms. Of particular interest, the virtual meeting platform allowed small-group, video-chat sessions based on proximity of the avatars—i.e., if two or more avatars were in the same room simultaneously, they could easily initiate a video chat with one another. Participant's feedback after the STM were very positive about this opportunity to mimic real-world interactions during a virtual meeting.

Each WebEx presenter had a corresponding virtual booth to host their presentation material and engage with up to ten participants in video-chat discussions about the research results. Additionally, virtual meeting rooms offered a whiteboard and screenshare tools for interactive collaboration between participants. For example, this feature allowed 30 participants from various GGFO science data processing centers to interactively discuss and coordinate aspects of the Level-2 (L2) data processing of monthly GFO gravity fields.

ST members and other attendees contributed abstracts that were used to compile the following summary, which starts with an update on the status of GFO, followed by highlights from the four live science sessions. The complete GFO STM program, abstracts, and presentations are available at *go.nasa.gov/3o8Bajj*.

Update on GRACE Follow-On

The twin GFO satellites, launched on May 22, 2018, continue to track Earth's water movements and global surface mass changes that arise from climatic, anthropogenic, and tectonic changes. GFO also enables new insights into variations of ice sheet and glacier mass, land water storage, and changes in sea level and ocean currents. These measurements have important applications and implications for everyday life. GFO is a U.S.–German collaboration between NASA and the German Research Centre for Geosciences [GeoForschungsZentrum (GFZ)].

As of December 2021, the GFO project team has processed and released 39 monthly gravity fields—the most recent being for October 2021. The primary mission objective for GFO is to provide continuity for the monthly GRACE mass-change observations (2002–2017) via its Microwave Interferometer (MWI) inter-satellite range-change observations. GFO also operates a novel Laser-Ranging Interferometer (LRI) as a technology demonstration for future GRACE-like missions and more accurate satellite-to-satellite ranging observations. The LRI has been successfully operated in parallel with the MWI, has returned excellent quality data, and has proven to be very stable and reliable operationally. GFO is in its primary mission science operations phase, which will last until 2023, i.e., five years after launch.

Programmatic, Mission, and Operations Updates

As has been done in previous meetings, the live session on the first meeting day began with opening remarks, followed by detailed assessments of the GFO mission and operations status from the core SDS centers and flight operations teams.

GRACE Follow-On and GRACE Project Status

Meeting host **Felix Landerer** [JPL—*GFO Project Scientist*] and **Frank Flechtner** [GFZ—*GFO Mission Manager,* Germany] welcomed participants and opened the meeting. Then Landerer provided an overview of the GFO satellites and their instrument status, summarizing the performance of the main science instruments: the MWI [including Global Positioning Systems (GPS)], accelerometers, and star cameras. He reported that—despite noise-contaminated accelerometer measurements on one of the two GFO spacecraft—the mission continues to meet its goal of extending the GRACE mass-change and gravity data record at equivalent precision and spatiotemporal sampling. The overall science instrument and flight system performance during the mission has been stable, and monthly mass-change data have been delivered to users ahead of schedule (on average, within 40 days instead of the 60-day requirement). The global mass changes observed by GFO continue to be largely consistent with independent mass-change estimates derived from precipitation and temperature data. Landerer also noted that the GRACE and GFO missions' SDS team expects to release an improved, reprocessed accelerometer calibration in spring 2022 to correct a small seasonal bias that the ST has identified in the mass-change data record for some regions, e.g., Antarctica.

After the opening presentations came a series of status reports on programmatic mission operations, science operations, and SDS processing. **Krzysztof Snopek** [GFZ] reported on the ground and mission operations at the German Space Operations Center (GSOC), which is responsible for GFO spacecraft operations. While in-person access for GSOC operators had to be limited due to COVID restrictions, all essential flight operations, software updates, and planned calibrations were successfully scheduled and carried out. **Himanshu Save** [University of Texas, Center for Space Research (CSR)] provided an overview and assessment of the science operations. Overall, 2021 was a successful year, with software updates to MWI improving its operations along with continuous nominal data collections. **Christopher McCullough** [JPL] reviewed the status of GGFO L1 reprocessing at JPL, including improvements made to the LRI L1 data processing as well as accelerometer calibrations.

Samuel Francis [JPL—*LRI Instrument Team*] provided a status update of the experimental LRI performance and its highly precise ranging measurements—which provide as much as 30 times more-accurate satellite-to-satellite ranging than the MWI. The in-orbit LRI experience has been very positive: the LRI is collecting science data in parallel to the MWI, and operating mostly autonomously. Due to the low noise levels even at high frequencies, the LRI data are also being used to support center-of-mass and thruster calibrations to augment accelerometer measurements.

Representatives of the three GFO mission SDS centers (JPL, GFZ, and CSR) summarized the status of the latest RL06 L2 gravity-field products, including an overview of background dealiasing models (GFZ), the new mascons[1] (JPL), and new data-processing strategies, e.g., via range acceleration (CSR) and using the novel LRI ranging observations (JPL, CSR). The gravity-field results from the LRI measurements are consistent with the primary microwave-ranging processing and demonstrate potential for advances by exploiting the very-low noise level of the LRI measurement.

The GRACE team provided an update on the final release—Release-07 (RL07)—of the 2002–2017 GRACE data processing, which is in progress and now slated for delivery in mid-2022.

Science Presentations

The live sessions on the second and third meeting days each consisted of several five-minute presentations, centered around different thematic topics, including: GRACE and GFO instruments and operations; analysis techniques and bridging the gap between GRACE and GFO; and science analysis of mass-transport data in the fields of hydrology, oceanography, glaciology, and solid-Earth physics.

Throughout many of the presentations, interdisciplinary and multi-instrument analysis underscored the unique complementary value of GGFO mass-change observations in combination with other remote sensing data (e.g., satellite altimetry or precipitation observations) and *in situ* data (e.g., surface deformation or ocean temperature profiles). Several of the presentations—particularly in the hydrology session—featured results (e.g., groundwater monitoring) that advance applications science from GGFO in the broader context of NASA's Applied Sciences Program.

Analysis Techniques and Bridging the Gap

This session included several presentations by the SDS centers and ST members, highlighting progress in science data calibration (e.g., to recover the noisy accelerometer data), and capitalizing on the extended GFO time series to compare the capabilities to measure intersatellite range acceleration signals in space and time from the MWI and LRI. With LRI's instrument noise over a factor of 10 lower than for MWI, it provides meaningful geophysical information at slightly finer spatial scales—i.e., 280 km (174 mi) for LRI versus 340 km (211 mi) for the MWI.

Several representatives from GGFO processing centers[2] presented updated gravity-field time-series data, which

[1] A *mascon*, or mass concentration block, is a form of gravity field basis function to which GGFO's intersatellite ranging observations are fit. Learn more at *go.nasa.gov/2M9d2gx*.
[2] The SDS centers mentioned earlier are a subgroup of this larger group of data processing centers for GGFO.

capitalize on improved parameterizations and background models (e.g., for tides) to produce improved retrievals. Incorporating other satellite-based geodetic observations, continental-scale mascons from satellite laser-ranging (SLR) data enable an extended mass-change time series dating back to 1994, bridging GGFO data gaps, and independently validating GGFO gravity estimates. With growing interest and demand for long, multidecadal time series of mass change, machine learning was used to compute a new global reconstruction of long-term (1979–2020) total water storage (TWS) fields using multiple hydrometeorological variables including—as inputs—precipitation, land temperature, sea surface temperature, soil moisture, evaporation, runoff, and several climate indices.

There were reports on progress in processing, validating, and delivering the GFO GPS Radio Occultation (GPS-RO) data products used in weather and climate applications—similar to what was done with GRACE GPS-RO data. Occultations from the leading GFO satellite are available and processed in near-real time for weather service centers dating back to mid-2019. Setting occultations from the trailing GFO satellite have been continuously enabled since September 2021 and will be operational in early 2022 after a test phase. Both satellites deliver about 250 global distributed atmospheric refractivity and temperature profiles up to an altitude of 60 km (37 mi).

The NASA-JPL Physical Oceanography Distributed Active Archive Center (PO.DAAC) team presented the plan to migrate all GGFO data products to the NASA Earthdata Cloud by mid-2022. The colocation of data storage, tools, and services will allow easy access to data and analysis capabilities in the cloud, limiting the need to download data, thereby allowing a more flexible and scalable approach to working with large datasets, programs, and operating systems, while also reducing redundancy by using a common infrastructure with native cloud services. In addition to cloud-based data services from PO.DAAC, ST members are releasing open-source software to perform core geodetic tasks, such as gravity-field recovery from satellite and terrestrial data, the determination of low-Earth-orbiting satellite orbits from global navigation satellite system (GNSS) measurements, and the computation of GNSS constellations and ground station networks.

Hydrology

This session highlighted new hydrology research results and applications using GGFO data, often in combination with other measurements or model results.

Technologies such as active or passive microwave remote sensing [e.g., from NASA's Soil Moisture Active Passive (SMAP) and the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) satellites] are limited to investigating the upper few centimeters of the soil. Conversely, satellite gravimetry (e.g., from GGFO) can detect changes in the full TWS column—but cannot distinguish between storage variations occurring at different depths. Integrating data from both these sources into the analysis can lead to new insights into the underlying hydrological dynamics and a better understanding of processes wherein subsurface water storage change occurs. For example, time lags between TWS and surface soil moisture reveal differences in the temporal dynamics of TWS at a variety of depths. A similar disaggregation approach was applied to data from California's Central Valley—one of the most important agricultural regions in the U.S. Results revealed that groundwater depletion continued unabated in recent years, with rates at least as great as in previous drought periods.

To improve the spatial resolution and increase the utility of GGFO observations, elastic displacements of Earth's surface—observed using GPS-measured surface deformation—can be incorporated into the analysis. In the future, surface deformation data from Interferometric Synthetic Aperture Radar (InSAR) satellite measurements will be folded into the joint data analysis,[3] enabling increased spatial coverage and improved representation of land hydrology in computer models. Another promising avenue for improved spatial resolution of long-term TWS changes was shown to be the direct co-estimation of long-term trends during GGFO gravity field estimation processes.

Other efforts to effectively downscale TWS data from GGFO involve data assimilation. To support the identification and quantification of hydrological droughts a new Global Land Water Storage (GLWS) dataset, which is in development, was previewed at the meeting.[4] The GLWS provides global monthly TWS fields and disaggregated components (i.e., surface water, soil moisture, and groundwater) at 50-km (31-mi) spatial resolution. Reliable predictions of TWS changes over the next couple of years would be extremely valuable for a variety of applications, e.g., agriculture and water management. A comparison between decadal predictions from the Coupled Model Intercomparison Project (CMIP) and GGFO observations revealed that climate model simulations that start from real-world conditions (e.g., as observed with GGFO) clearly outperform climate projections that are not initialized with observations—see **Figure 1**. This demonstrates that TWS observations from GGFO are useful for validating and/or calibrating climate models.

[3] Examples include data from the European Space Agency's Copernicus Sentinel-1 missions and the upcoming NASA–Indian Space Research Organization (ISRO) Synthetic Aperture Radar [NISAR] mission.

[4] Release 001 of the GLWS has not yet been publicly released.

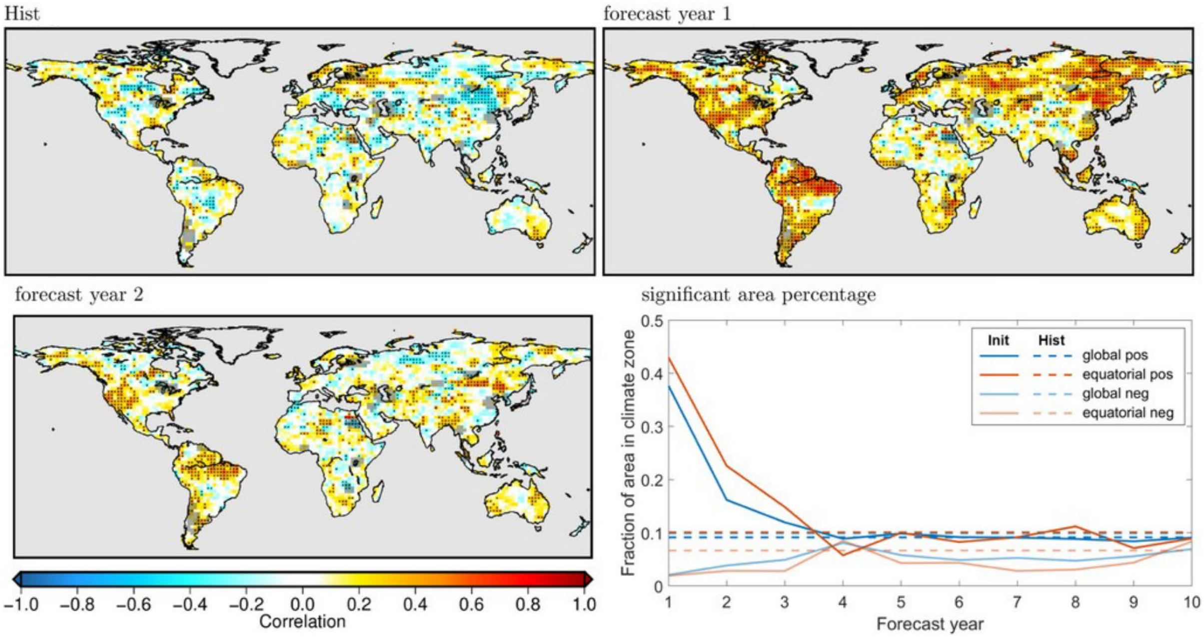


Figure 1. Global maps of correlation of the total water storage (TWS) anomaly time series (which includes the GGFO data) with TWS calculations from climate computer simulations. The *top left* map shows the results compared to an *uninitialized* simulation—meaning that the climate simulation simply mimics the real-world climate in a statistical sense. The other two maps show results comparing to simulations *initialized*, or started, using TWS observations (e.g., those from GGFO) to help them mimic the current and near-term state of the world. These simulations produce one-year [*top right*] and two-year [*bottom left*] TWS forecasts. (This process is similar to how a long-range weather-forecast works.) The results show that using TWS observations to start the simulation can achieve useful TWS forecasts one year in advance [*top right*] and—for some regions—even two years in advance [*bottom left*]. The graph [*bottom right*] shows the percentage of land area with significantly positive and negative correlation as a function of forecast lead time for the global land area and the equatorial climate zone. To view this figure in color, visit *eospso.nasa.gov/earth-observer-archive*. **Image credit**: Laura Jensen/HafenCity University, Hamburg, Germany, doi.org/10.1175/JCLI-D-20-0042.1

Several presentations highlighted important contributions that GGFO TWS observations can make toward revealing connections between water dynamics on land, rainfall, and *evapotranspiration* (ET)—evaporation from the land surface plus transpiration from plants. For example, one contributor reported that an analysis of independent observations taken over the Congo Basin—which hosts the driest rainforest in the world—implies a potential resilience of rainforests to interannual rainfall anomalies.[5] Another presenter, studying global grassland areas, found that plant rooting depths change with seasonal TWS changes during water-limited times. These results indicate that TWS can buffer the impacts of drought on plant growth, which may be an important mechanism to consider in improving computer climate simulations of drought effects.

Cryosphere

The cryosphere session consisted of two dedicated contributions. The first described an analysis conducted with data over Antarctica to assess how increasing atmospheric and ocean temperatures—due to changes in large-scale circulation patterns in the Southern Hemisphere—impact the ice-mass balance. Of particular interest is the ice-dynamic component, which is critical to understanding its associated contributions to future global sea level rise. Currently, significant ice-mass loss and acceleration of ice flow are observed in the Amundsen Sea Embayment in West Antarctica. In East Antarctica, such processes have so far been spatially restricted to smaller regions, e.g., glaciers feeding the Amery Ice Shelf. The researchers confirmed that the Amundsen Sea Embayment and Bellingshausen Sea regions have significant ice-dynamic acceleration. Including this acceleration in future sea-level-rise predictions yields 7.6 ± 2.9 cm [~3.0 ± 1.1 in] sea level rise by 2100—which is two times larger than a simple straight-line extrapolation of current Antarctic mass loss trends.

The second contributor provided an update on the state of mass balance of the Greenland and Antarctic ice sheets and the world's glaciers and ice caps from 2002 to the present, using GGFO data. Independent estimates of ice-sheet mass balance from satellite altimetry [e.g., NASA's Ice, Clouds and land Elevation Satellite (ICESat) and the European Space Agency's (ESA) CryoSat-2], field campaigns [e.g., NASA's Operation IceBridge], and the mass budget method (MBM) from several regional and global climate models confirmed that with the necessary GGFO accelerometer

[5] Measurements included deuterium levels from the Atmospheric Infrared Sounder (AIRS) on Aqua, precipitation data from the Tropical Rainfall Measurement Mission (TRMM), and TWS data from GRACE.

calibrations (discussed above), the combined GGFO data record is consistent with other observations.

Solid Earth Sciences

As the GGFO data record gets longer, typically more subtle and slower solid-Earth processes [e.g., glacial isostatic adjustment (GIA)][6] as well as deep-interior geophysical phenomena can begin to be examined and quantified more accurately. Mass-change signals from far below the surface are lumped together with those from near the surface and are picked up by GGFO measurements. Therefore, solid-Earth effects need to be accurately accounted for and separated from surface-mass changes to ascertain water and ice mass changes over land. To that end, knowledge of the material properties of Earth's crust and mantle are vital. One presenter showed the potential importance of anelastic-viscoelastic effects (which can be derived from seismological data) to surface-mass changes from GGFO observations—in particular over ocean basins. A second presenter also examined the role of anelastic deformation effects, with a focus on ocean tides. The study revealed that mid-ocean ridge regions and some coastal areas of North and Central America are most prominently impacted, and including these effects brings predicted amplitudes of the tide-induced vertical displacement into better agreement with GPS-observed displacements. Overall, the impact of solid Earth's anelastic material behavior plays a larger role than previously understood. Therefore, more complex formulations for solid-Earth processes may need to be considered for some regions to calculate accurate surface-mass change trends in the future.

[6] GIA refers to the gradual response of the solid Earth to the deglaciation of historic ice sheets

Oceanography

In the oceanography session, presenters discussed the combination of GGFO, satellite altimeters (e.g., from the joint NASA–European Sentinel-6 Michael Freilich mission), and *in situ* ocean floats (e.g., Argo) to investigate variations in ocean current and sea level—see **Figure 2**. Several studies investigated the *global sea level budget*—the sum of density and mass-change contributions to sea level—and its closure. The results indicate that Argo salinity data collected since 2016 contain errors, leading to nonclosure in the sea level budget. However, correcting for these errors improved the agreement across the three observing systems (GGFO, Sentinel-6 Michael Freilich, and Argo). Two presenters examined the amount of heat gained in the Earth system since 2005, i.e., the *Earth energy imbalance* (EEI). Space-geodetic values of EEI were reported to be in the range of 0.84±0.2 W/m^2, with a tendency to increase (i.e., faster warming) in recent years.

Another presenter showed results from a high-resolution ocean model analysis that revealed significant

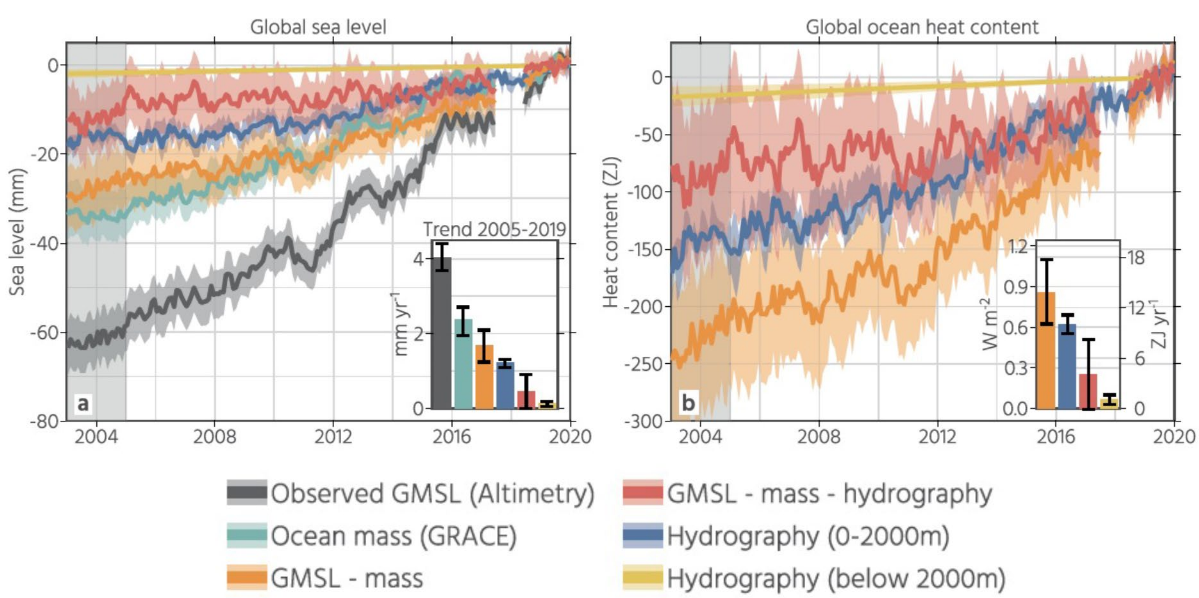


Figure 2. The *left* panel shows the individual components of the global sea-level budget, which is derived using observations of global mean sea level (GMSL) from satellite altimeters (e.g., Sentinel-6 Michael Freilich), satellite ocean mass measurements (e.g., GRACE), and measurements of temperature at depth (hydrography) from ocean floats (e.g., Argo), as well as from combinations thereof—as defined in the key. The *right* panel shows the associated ocean heat content (OHC) time series derived from the same sources. These two measurements can be combined to infer the overall heat uptake by the Earth's oceans—which accounts for over 90% of current global warming (identified in the key below the graph). The inset bar graphs in each panel show trends in the various components of each measurement between 2005 and 2019. Over this period, sea level has increased by about 4 mm/yr (~0.2 in/yr), with a contribution of 2.4 mm/yr (~0.1 in/yr) from net ocean mass gain (e.g., due to land-ice melt), and about 1.4 mm/yr (~0.05 in/yr) from ocean warming. The net heat gain by the Earth's climate system—also described as *Earth energy imbalance*—is about 0.9 W/m^2. All time series are shown relative to their respective mean values in 2019. To view this figure in color, visit *eospso.nasa.gov/earth-observer-archive*. **Image credit**: Maria Hakuba/JPL, doi.org/10.1029/2021GL093624

chaotic ocean eddy effects over as much as 25% of the global ocean, which might need to be considered to achieve improved accuracy in the monthly data processing of GGFO mass-change fields. Additional presenters described how low-frequency, ocean-bottom pressures respond to barometric pressure loading from the atmosphere, how estimates of global mean sea level can be affected by analysis choices of the land–ocean boundary, how so-called "sea-level fingerprints" can be used to extract ocean-dynamic signals from the GGFO mass-change observations, how deep-ocean currents surrounding Antarctica fluctuate based on GGFO ocean-bottom pressure observations, and how GGFO data downscaling has promising applications for monitoring intraseasonal and interannual variability of deep-ocean mass transports.

Future Gravity Missions and Concepts

The final live session took place on the fourth and final meeting date and explored future mission development and concepts, including mission design and new instruments. This discussion included concepts from NASA, ESA, the Deutsches Zentrum für Luft- und Raumfahrt (DLR) [German Aerospace Center], and several others, as detailed below.

NASA: Mass Change Designated Observable

The 2017 NASA Earth Science Decadal Survey Report highlighted mass-transport monitoring through gravity change (Mass Change) as one of five *designated observables* (i.e., top priorities for study) in Earth observations for the next decade in collaboration with international partners.[7] Given the intentional focus on future Mass Change missions, this session included a discussion of plans for future gravity mission designs and how to ensure data continuity and consistency from GFO to the next gravity mission(s). Several promising international mission architecture studies are currently underway, assessing a broad range of concepts, instrument advances and maturity, as well as partnership opportunities to realize gapless, higher-capability mass-change observations based on science and application targets. To help ensure that there will be no data gap after GFO, a launch date of no later than 2027 is highly desirable for the next Mass Change mission.

The team behind NASA's Mass Change Designated Observable (MCDO) Study (which recently concluded) provided a summary of their activities. The team developed a Science and Applications Traceability Matrix (SATM) and investigated the viability of different future mission architecture classes through a quantitative numerical simulation framework. The output of the Applications Team's efforts will be a Community Assessment Report to identify and characterize existing and potential user communities, assess their data needs, and establish pathways for sustained engagement.

ESA: Mass-Change and Geoscience International Constellation

Meanwhile, at its most recent Ministerial Conference ESA decided to investigate a European Next-Generation Gravity Mission (NGGM) in Phase A as its first Mission of Opportunity. The Mass-change And Geoscience International Constellation (MAGIC) is a joint investigation with the NASA MCDO Study, resulting in a jointly accorded Mission Requirements Document (MRD) that responds to global user community needs. These studies will evaluate several potential mission constellations as well as improvements to data processing strategies to enhance the retrieval of mass change observations of both short (e.g., floods) and longer (e.g., ice melt) timescales.

DLR/NASA: GRACE-I

There was a status update on the "GRACE-I" concept. The "I" in the acronym stands for ICARUS, which stands for International Cooperation for Animal Research Using Space. The DLR is currently performing a Phase-0 study of GRACE-I in close collaboration with JPL and other NASA Centers. The idea is to have a GRACE-like concept combined with an optional ICARUS payload for use in their efforts to monitor biodiversity. GRACE-I will be a single pair of satellites based on a fully redundant LRI. It could then be a component of a more capable constellation of other Mass Change satellite missions to provide gap-less, long-term observations of this important climate variable with increased resolution in space and time.

Successful LRI Technology Demonstration

The technology demonstration LRI on GFO surpasses performance requirements, autonomously maintains its intersatellite laser link, and continues to perform without any issues. For the next Mass Change mission, it is anticipated that LRI-only technology will replace MWI as the primary science instrument to continuously measure intersatellite ranging variations. The LRI team described the work required to take the LRI from technology demo to prime instrument. Laser frequency stability is critical for accurate measurements. The LRI team presented a simple phase modulation scheme that can provide a fractional, absolute, laser frequency stability at the 10 parts-per-billion level at time scales that are likely sufficient to meet the anticipated accuracy requirements of next-generation missions.

[7] For an overview of the 2017 Earth Science Decadal Survey visit *go.nasa.gov/2wXJn2n*. The full report can be accessed in several forms from *www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

Other Future Gravity Mission Concepts

Other presenters in this session examined updated or novel technologies for future missions. One example is the combination of classic satellite-to-satellite tracking—as is done in GGFO—with a Quantum Gravity Gradiometer (QGG) in the cross-track flight direction that could improve the retrieval of *rapid* (i.e., shorter-than-monthly) variations in Earth's gravity field.

A consortium consisting of the University of Florida, Caltech/JPL, Ball Aerospace, and Embry-Riddle Aeronautical University—with funding from the NASA Earth Science Technology Office (ESTO)—reported on their collaborative development of a Simplified Gravitational Reference Sensor (S-GRS). The S-GRS is an ultraprecise inertial sensor—estimated to be at least 40 times more sensitive than the GRACE accelerometers—to measure nongravitational accelerations on the spacecraft with high accuracy. Such an increase in performance allows future missions to take full advantage of the improved sensitivity of the GFO LRI over microwave ranging systems in gravity-recovery analysis.

A final set of presentations assessed more complex satellite constellations, including so-called pendulum orbits and many-pair, small-satellite constellations—which can offer improvements in the gravity field measurements but pose operational and technology challenges that require further study.

Summary

The fully virtual GFO STM 2021 was once again a great success and brought together a record number of international participants. In a post-meeting survey, participants commented that the short, live presentations, in combination with the interactive virtual meeting format and "gathering spaces," made the 2021 GFO STM very effective and "provided a real added-value to the conference." Another participant remarked, "It worked extremely well to have small discussions about various presentations and other science topics. It doesn't replace chats over coffee at a live meeting—but it came close."

The meeting highlighted the broad range of science results and applications that are supported and uniquely enabled by satellite gravimetry-based, mass-change observations. The GFO data—available since June 2018 and now extending over 3.5 years—continue the mass-change data record at a level of performance consistent with that of GRACE.

Data from GFO are extending important climate data records (e.g., the Greenland and Antarctic ice-mass time series; ocean-mass, sea-level data; and TWS over land) and these new results have been validated with independent data sources. In this way, GFO data continue to prove vital to understanding Earth's changing hydrosphere, including sea level, ocean currents, and water distribution over land.

The novel laser-ranging technology provided by LRI on GFO has been a great success. Its increased measurement accuracy is being examined by several groups and shows potential for novel science applications.

Progress has been made in combining gravity data with data from other sensors to achieve improvements in several areas, such as resolving geophysical signals at higher resolution in space and time. And atmospheric sounding profiles from the mission's two GPS-RO receivers are supporting operational weather center forecasts.

Despite the ongoing COVID pandemic, the multinational mission and science operations team—composed of members of the GSOC, GFZ, JPL, and CSR, together with industry support—is efficiently and successfully working to ensure continuity of the long-term data record of gravity and mass change. The next GSTM will be held in October 2022, hosted by GFZ in Potsdam, Germany—hopefully, in person. ■

Summary of the 2021 Precipitation Measurement Mission Science Team Meeting

Andrea Portier, NASA's Goddard Space Flight Center/Science Systems and Applications, Inc., andrea.m.portier@nasa.gov
Dalia Kirschbaum, NASA's Goddard Space Flight Center, dalia.b.kirschbaum@nasa.gov
Scott Braun, NASA's Goddard Space Flight Center, scott.a.braun@nasa.gov

Introduction

The annual Precipitation Measurement Mission (PMM) Science Team Meeting (STM) took place October 18–22, 2021. Although originally planned to be an in-person meeting, due to the ongoing COVID-19 pandemic, the meeting was organized as a virtual event. The PMM program supports scientific research and applications, algorithm development, and ground-based validation activities for the Tropical Rainfall Measuring Mission (TRMM)[1] and Global Precipitation Measurement (GPM) mission—including the GPM Core Observatory.[2]

The meeting included oral presentations, across six video sessions, and poster presentations, which were held across two online sessions, intended to showcase the work of early-career scientists. These sessions were meant to mimic poster presentations at an in-person meeting. In total, 167 participants attended the PMM STM, including representatives from NASA, the Japan Aerospace Exploration Agency (JAXA), the National Oceanic and Atmospheric Administration (NOAA), universities, and other partner agencies, with 20 attendees from 13 countries outside the U.S. Despite the meeting being held virtually, all the online sessions were well attended. The interactive chat capability enabled continued engagement among participants to discuss scientific topics and results, despite the lack of physical proximity.

Meeting Overview

The PMM STM had a mixture of presentations on specific themes related to the PMM program, including algorithm development, use of datasets for scientific research and societal applications, mission status, and ground validation (GV) efforts. The meeting opened on October 18, with a PMM Programmatic session featuring status reports from NASA and JAXA PMM Science Team (ST) leadership, followed by presentations on NASA's Precipitation Processing System (PPS) status, program updates on GV activities, and PMM applications and outreach efforts. In the evening of the first day there was a tribute to Gail Skofronick–Jackson, the former NASA HQ GPM Program Manager, who passed away suddenly in September 2021—see *PMM Science Team Honors Gail Skofronick–Jackson,* on page 28. On the following four days the meeting highlighted scientific updates from current PMM ST principal investigators (PI).

This summary provides updates on the PMM program and status of the GPM instruments, and other science highlights from the online meeting, organized by related science and applications topics. For more information about GPM data products, science team activities, and future updates, visit *gpm.nasa.gov* and *go.nasa.gov/3guNrKK*.

PMM Programmatic Updates: Perspectives from NASA and JAXA

Like its predecessor, TRMM, GPM is a partnership between NASA and JAXA. There is both a U.S. and a Japanese GPM ST. On the first day of the meeting, representatives from both of these agencies gave updates on the status of various components of the mission. Some of the topics summarized in those reports will be expanded upon in subsequent sections of this article.

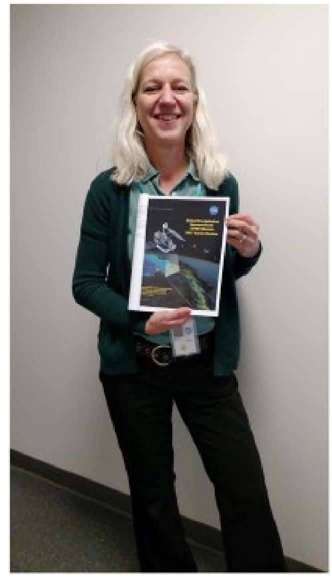
NASA

Scott Braun [NASA's Goddard Space Flight Center (GSFC)—*GPM Project Scientist*] helped welcome participants and then kicked off the meeting with an update on GPM mission status. He highlighted that GPM—now in its extended mission phase—continues to provide valuable near-global precipitation data. He noted that all GPM spacecraft systems are fully functional, and that end-of-fuel predictions for the GPM Core Observatory (CO) should allow it to function nominally until the early 2030s. GPM's two instruments—the Dual-frequency Polarization Radar (DPR) and GPM Microwave Imager (GMI)—are also functioning nominally.

[1] While the TRMM mission was completed in 2015, data reprocessing occurs whenever GPM data products are processed.

[2] TRMM and GPM are partnerships between NASA and the Japan Aerospace Exploration Agency (JAXA), and the Science Team includes more than 20 additional international partners. To learn more about GPM, see "GPM Core Observatory: Advancing Precipitation Measurements and Expanding Coverage" in the November–December 2013 issue of *The Earth Observer* [**Volume 25, Issue 6**, pp. 4-11—*go.nasa.gov/3ryRyvv*] and "The Global Precipitation Measurement (GPM) mission's scientific achievements and societal contributions: reviewing four years of advanced rain and snow observations," at *doi.org/10.1002/qj.3313*.

PMM Science Team Honors Gail Skofronick–Jackson



Dr. Gail Skofronick–Jackson was world renowned for her work in snow remote sensing—a passion that led her to leadership positions as chief of the Mesoscale Atmosphere Processes Laboratory at NASA's Goddard Space Flight Center, deputy project scientist—and then project scientist—for the NASA Global Precipitation Measurement (GPM) mission. In 2018 she moved to NASA Headquarters (HQ) to become program manager of the Weather Focus Area within the HQ Earth Science Division.* Gail was passionate about doing good science and making results accessible to diverse communities. In her leadership roles she excelled at building consensus in group deliberations, encouraging new ideas, and mentoring early- and mid-career scientists. Gail's generosity, inclusiveness, and positive spirit were inspirational to all. She epitomized what it meant to be an effective leader, a kind mentor, and a tremendous role model, making connections with people through group runs that she frequently organized at PMM meetings, and taking time to talk and share her observations, activities, visions, and suggestions with her colleagues and friends. They, the PMM, and the larger science communities recognize the tremendous void she leaves, and all with whom she associated will forever miss her.

*To learn more about her accomplishments, see the *In Memoriam* for Gail that was published in the September–October 2021 issue of *The Earth Observer* [**Volume 33**, **Issue 5**, p. 4—*go.nasa.gov/3LdsItb*].

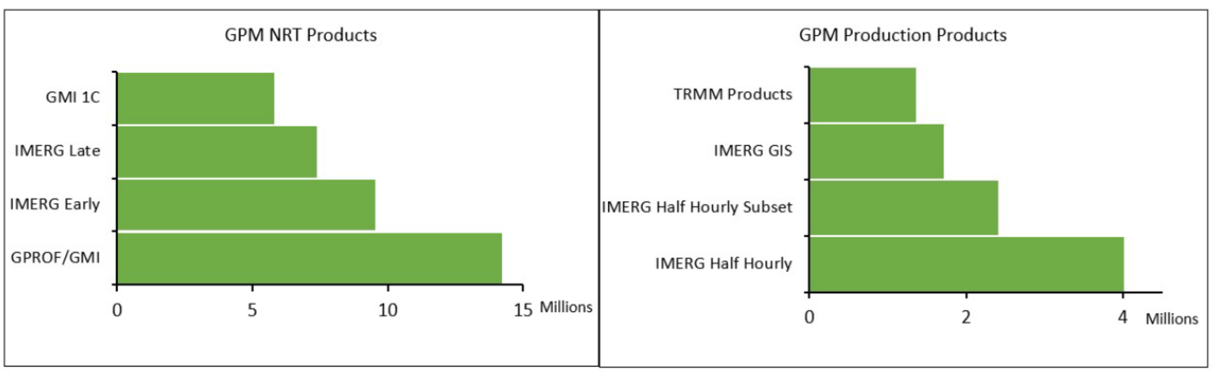


Figure 1. Summary of usage statistics for some of GPM's most popular products from January to September 2021. The numerical values represent the number of "gets," i.e., the number of times the product was accessed from PPS. IMERG and the GMI near-real-time (NRT) product are the most downloaded products from PPS. **Image credit:** Erich Stocker/GSFC

Erich Stocker [GSFC—*GPM Deputy Project Scientist for Data*] discussed the status of GPM data products. The NASA Precipitation Processing System (PPS)[3] currently processes Version 5 (V05) radiometer products and V06 radar, combined radar-radiometer, multisatellite, and latent-heating data products—and is in the process of updating the algorithms for each component to V07. The V07 implementation process will continue into spring 2022. He concluded with an overview of usage statistics of GPM's near-real-time (NRT) and research data products, highlighting that the GPM Goddard Profiling Algorithm (GPROF) for the GMI and the Integrated Multi-Satellite Retrievals for GPM (IMERG) algorithm are the most downloaded products from PPS—see **Figure 1** above and the *GPM Algorithm Updates* section on page 30 for more information.[4]

David Wolff [NASA's Wallops Flight Facility—*GPM Deputy Project Scientist* and *Ground Validation System Manager*] then provided an overview of the GPM GV program. This effort includes a supersite at NASA's Wallops Flight Facility (WFF), analysis of the National

[3] The purpose of the PPS is to process, analyze, and archive data from the GPM mission, partner satellites, and the TRMM mission. See *go.nasa.gov/3ry9giY*.

[4] GPM data products can be divided into two groups (near-real-time and research) depending on how soon they are created after the satellite collects the observations, see *go.nasa.gov/336Yirj*.

Weather Service's (NWS) standard weather surveillance Doppler radars (WSR-88D) around the U.S., and participation in field campaigns such as Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) and the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Tracking Aerosol Convection Interactions Experiment (TRACER),[5] and support for specialized science investigations. To learn more about IMPACTS recent activity, see the News story on page 38 of this issue.

Dalia Kirschbaum [GSFC—*GPM Deputy Project Scientist for Applications*] highlighted current activities related to GPM applications and outreach. The applications and outreach team continues to focus on increasing the use of GPM data and products across communities through user engagement and outreach activities including workshops, trainings (e.g., 2021 GPM–International Precipitation Working Group Applications Training),[6] interviews, visualization tools, and the development of GPM Applications Packages (*go.nasa.gov/3GGiRZ7*). The goal of these efforts is to increase awareness of, and identify data requirements and challenges with, using satellite precipitation data for decision-making. An integral part of GPM outreach is the GPM website, which attracts thousands of visitors and downloads each month and provides resources for team members who are giving their own outreach presentations—see **Figure 2** below.

[5] To learn more about IMPACTS, see *go.nasa.gov/3gvwrUy*; to learn more about TRACER, see *go.nasa.gov/3B7SvhI*.
[6] To learn more about this training, see *go.nasa.gov/3GzVEbi.*

JAXA

Three representatives from Japan summarized the status of the latest activities from the Japanese PMM ST: **Riko Oki** and **Takuji Kubota** [both from JAXA's Earth Observation Research Center (EORC)], and **Nobuhiro Takahashi** [Nagoya University]. They then summarized notable work on version upgrades that have taken place since the last STM to the GPM radar products and to their Global Satellite Mapping of Precipitation (GSMaP) multisatellite products.[7] The radar algorithm upgrades reflect continued work to fully incorporate data from the revised K_a-band radar scan pattern that commenced in 2018, improve assumed vertical profiles of radar background parameters, estimate the occurrence of hail, and improve precipitation estimates near the surface. GSMaP incorporated machine-learning approaches for infrared (IR)-based precipitation estimates to address orographic precipitation and rain-depth modifications for passive microwave estimates. Recent JAXA ST science-related studies include assessing precipitation trends along the Meiyu Front (a.k.a.,

[7] GSMaP is essentially the Japanese PMM ST's version of IMERG.

Figure 2. GPM webpage statistics for users who have accessed and downloaded resources from the GPM website and GPM's Precipitation Education webpage for 2021. The GPM Education page is a helpful resource for K-12 audiences, novice users of satellite data, and educators looking for resources to share. It has received over one million page views in 2021 alone. **Image credit**: Dalia Kirschbaum/GSFC

the Baiu Front),[8] examining the key role of ice-phase hydrometeors in global precipitation, and evaluating cloud microphysics information for the Japan Meteorological Agency's operational numerical model.

JAXA applications and outreach efforts include making observations of tropical storms and contributions to flood monitoring and warning in the Volta River basin in West Africa, developing an augmented-reality globe, and providing monthly GSMaP data fields for the Google Earth Engine—see **Figure 3**. The JAXA ST is also engaged with developing the Advanced Microwave Scanning Radiometer 3 (AMSR3) instrument for the Global Observing Satellite for Greenhouse gases and Water cycle (GOSAT-GW) platform which will be launched in 2023–2024. JAXA is also developing a next-generation precipitation radar.

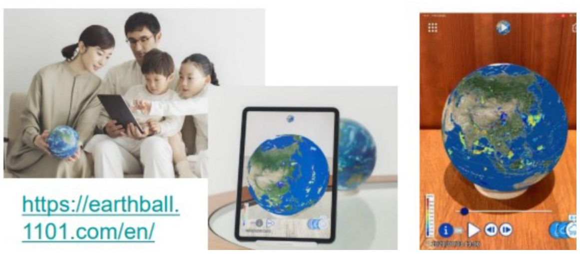


Figure 3. A Japanese private company (Hobonichi) uses GSMaP real-time rainfall images to show Earth's current precipitation status on its augmented-reality globe. When viewing the globe with a smartphone or tablet, a person can see near-real-time global rainfall from GSMaP. **Image credit:** Riko Oki/JAXA EORC

GPM Algorithm Updates

This session provided information and updates on various aspects of the five major algorithms associated with transforming observations of radar reflectivities (Z) from DPR and passive microwave brightness temperatures (T_b) from GMI into precipitation information.

DPR

The latest version (i.e., V07) of the Surface Reference Technique (SRT) and the Level-3 (L3) DPR algorithms were delivered to NASA (PPS) and JAXA in August 2021. The output files from the L3 algorithm have been restructured to facilitate user access to the products. Additionally, the V07 algorithms can process DPR data taken both before and after the K_a-band scan change in May 2018.[9]

GMI

The GPROF algorithm for GMI continues to evolve. Once it is implemented, V07 of the GMI algorithm will not only incorporate the latest intercalibrated brightness temperatures, it will also use the latest radar–radiometer combined product (see next paragraph) to create an *a priori* database (which has typically used the previous radar–radiometer products for the database). Two notable improvements have been made for orographic precipitation measurements, i.e., over mountainous areas, that should bring mountain rainfall measurements derived from GMI into closer alignment with climatologies, where they exist. The first is to correct biases in the *a priori* information regarding snowfall. The second is the addition of ancillary data to estimate orographic precipitation enhancement.

DPR–GMI Combined

An analysis of the GPM Combined Radar–Radiometer Algorithm (CORRA) product showed that critical changes in the way precipitation particle size distributions are constrained—along with greater radar sensitivity to detect light precipitation—result in GPM CORRA V07 estimates of precipitation that are approximately 10% higher, globally, than estimates from the V06 product. The V07 estimates are more consistent with K_a-band radar reflectivity observations from GPM, and they are in better agreement with rain gauge-calibrated radar ground truth over the U.S.

Convective-Stratiform Heating (CSH)

For the CSH algorithm, the cloud-resolving model (CRM) [i.e., the Goddard Cumulus Ensemble (GCE) model] simulations used to build the warm-season look-up tables (LUTs) were changed from two-dimensional to three-dimensional, and new, detailed radiation retrievals were added, resulting in separate longwave and shortwave retrieval products for V07. The CSH algorithm will continue to be improved by adding more representative LUTs and terrain information that could reduce biases over land and high latitudes.

IMERG

V07 of IMERG will include several important upgrades. The infrared (IR)-based precipitation computation will be modernized from the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) Cloud Classification System [PCCS] to the PERSIANN Dynamic Infrared–Rain Rate (PDIR) algorithm. PDIR utilizes a deep neural net that more accurately retrieves precipitation, including from relatively "warm" clouds, than was possible with PCCS. Averaging effects in the Kalman filter will be approximately reversed

[8] Meiyu–Baiu is the major rainy season in Central China and Japan typically from June to mid-July. The Meiyu (or Baiu) Front is a persistent, nearly stationary, weak baroclinic zone that sets up over this region, along which mesoscale convective complexes or mesoscale convective systems tend to form and propagate eastward, leading to intermittent heavy downpours.

[9] As of May 2018 the K_a-band radar swath width was changed from 120 km (~75 mi) to 245 km (~152 mi).

using the Scheme for Histogram Adjustment with Ranked Precipitation Estimates in the Neighborhood (SHARPEN).[10] Numerous smaller improvements have also been made, including climatological calibration of the near-real-time products to *in situ* rain gauge analyses, as well as raising the cap on precipitation rate to 200 mm/hr (~8 in/hr). Starting in December 2021, the NRT products will use a *hybrid* GPM Combined Radar–Radiometer product as input, allowing the calibration to continue until implementation of V07 CORRA at PPS in February 2022 and IMERG moves to V07 in May 2022.

GPM Ground Validation Updates

Ground validation (GV) presentations underscored the importance of ground-based observations and field campaigns (both airborne and ground) for validating results of satellite-based measurements, including (but not limited to) falling snow and precipitation distribution. Observations from GPM (both radar and radiometer) were validated using GPM-sponsored field campaigns, including the Integrated Precipitation and Hydrology Experiment (IPHEx) and Olympic Mountains Ground Validation Experiment (OLYMPEX);[11] the long-term user facility at WFF; and a sea-based complementary-instrument study, the Clouds Aerosols Precipitation Radiation and atmospheric Composition over the Southern Ocean (CAPRICORN) field campaign.[12]

Additional GV science results showed that the spatio-temporal variability of precipitation and its depiction in Level-2 (L2) and Level-3 (L3) products are being compared with NOAA's Multi-Radar Multi-Sensor products, which serve as a high-quality estimate of precipitation near the ground, as well as being modeled using spectral analysis of the error structure and machine learning. Initial research shows that this is a promising approach for representing the distribution of precipitation with these GPM products.

Several PMM international participants highlighted ongoing work in GV. One of the international PMM ST members described a new technique to estimate rain rate by relating signal attenuation among ground communication towers to rainfall intensity. This method has proven helpful over regions with limited observations from radar and ground-based rain gauges. Specifically, this validation approach has been conducted in the Netherlands that, with additional applications over Sri Lanka and Nigeria, demonstrates the value of this new way of estimating precipitation.

[10] To learn more, see SHARPEN: A Scheme to Restore the Distribution of Averaged Precipitation Fields at *doi.org/10.1175/JHM-D-20-0225.1*.

[11] To learn more about IPHEx, see *go.nasa.gov/3HCoN6Z;* to learn more about OLYMPEx, see *go.nasa.gov/34KDI0o*.

[12] To learn more about CAPRICORN, see *doi.org/10.1175/BAMS-D-20-0132.1*.

GPM Science Results

This section included updates on research in four areas: Storm Systems, Weather and Climate Models, Precipitation Microphysics, and Precipitation Retrievals.

Storm Systems

Several presentations highlighted science results that focused on storm-system dynamics from synoptic scale to mesoscale precipitation events. One presentation examined extratropical cyclones using the GPM precipitation feature database maintained at Texas A&M University at Corpus Christi, finding that these extreme events are more prevalent in the Southern Hemisphere than the Northern Hemisphere—which may be a result of there being a greater percentage of the total area that is ocean in the Southern Hemisphere than in the Northern Hemisphere, where there is more land surface.

Another focus of research includes *atmospheric rivers*, with one project finding that these events contribute an increasing amount of the total precipitation observed with GPROF at higher latitudes, with the largest amounts found in the Northwestern Atlantic. Other presentations explored convective processes over the tropics, which play an integral role in transporting energy and moisture in Earth's climate system.

IMERG also is being used to examine tropical cyclone precipitation, validate climate model projections of extreme precipitation, and examine interannual variability of cold-season precipitation in the North Atlantic.

Weather and Climate Models

The presentations in this area discussed approaches for improving weather and climate models with GPM data. For example, one presenter described a model for tropical convective cloud-shield-area time tendencies. This used GPM data to try to improve the simulation of deep convection in the latest version (Edition 3) of NASA's Goddard Institute for Space Studies' (GISS), Global Climate Model (GCM), which currently spreads precipitation (both stratiform and convective) over too large an area.

Other presentations provided updates on data assimilation techniques and improvements in model predictions. For example, ensemble model simulations of Hurricane Harvey (2017) were shown to improve rainfall prediction. This effort involved both simulation and assimilation of passive microwave and geostationary IR radiances.

While the incorporation of both IR and microwave information improved the pattern of precipitation relative to IR only, the formulation of the microphysical properties in the forecast and forward radiative transfer (RT) models can impact forecast accuracy. Future statistical RT operators are being explored with multiple ice-particle scattering databases, such as the OpenSSP Snow Particle and Scattering Property Database.[13]

Another presentation included updates from NASA's Global Modeling and Assimilation Office (GMAO), located at GSFC, which is exploring the assimilation of cloud- and precipitation-affected microwave radiances within the Goddard Earth Observing System (GEOS) analysis and forecast system. GMI has been used in this system since 2018, and all-sky assimilation is being extended to other passive-microwave sensors in preparation for the future NASA Retrospective Analysis for the 21st Century (R21C).[14] Assimilation of passive microwave data can improve both precipitation estimates and model dynamics.

Precipitation Microphysics

Several presentations described different approaches for classifying precipitation using GPM and ground-based observations. There were discussions of identifying precipitation by hydrometeor type as well as by adjacent cloud and thermodynamic properties. A couple of presentations highlighted challenges in interpreting the scattering signal associated with mixed-phase clouds, including the impact of melting ice. The Method of Moments (MoM) Integral-equation Decomposition for Arbitrarily shaped Scatterers [MIDAS] model was shown to be able to properly describe the ice-particle scattering properties with better computational efficiency than other approaches.

Precipitation Retrievals

Presentations in this section showcased efforts to improve falling-snow retrievals and to understand characteristics and changes in ice-phase precipitation and clouds.

One presentation discussed this relationship between large ice hydrometeors, beam filling, and the multiple-scattering signal observed by DPR. The study found that though relatively rare over ocean, the large ice hydrometeors occur frequently over land and can lead to difficulties in DPR retrievals. Another presenter revealed that the DPR precipitation rate retrieval is impacted by uncertainties in the particle size distribution parameterization, scattering model, characterization of fall velocity, and attenuation correction. They noted that the V07 DPR algorithm should be improved by relaxing a range-independent parameter. The snow retrieval can also be improved with a modified rain-rate and mass-weighted mean diameter ($R–D_m$) relationship.

There was discussion of GPM's transformative dataset for investigating falling snow independently and when used with CloudSat data. PMM ST members noted that the dataset shows an overall global decrease in snow with respect to total precipitation, which is latitudinally dependent. The team agreed that machine learning appears to be a powerful tool for estimating falling snow.

GPM Applications

Three presentations provided updates and highlighted new research avenues to using GPM data to improve decision making at local and regional scales. For example, one presenter examined the impact of incorporating IMERG data into the U.S. Army Streamflow Prediction Tool. IMERG was shown to outperform the North American Land Data Assimilation System-based streamflow simulation in the westernmost Missouri river basin. An interactive, map-based, online interface makes these high-resolution streamflow predictions easily accessible for decision making.

Another presentation highlighted the use of the Climate Hazards IMERG with Stations (CHIMES) merged precipitation dataset over East Africa, citing that the precipitation data in this area is widely used within the Famine Early Warning Systems network.[15] The existing Climate Hazards Group InfraRed Precipitation with Station version 2 (CHIRPS2) dataset has a low variance in some (dry) areas, which is the rationale for CHIMES. CHIMES enhances IMERG-Late with high-resolution climatology and gauges.[16] The project showed how the data were used to identify food insecurity and drought in different regions, comparing results with multiple gauge datasets. The presenter showed growing season anomalies for different years. The results indicate that at seasonal scales, CHIMES outperformed other products, such as CHIRPS2 and the Multi-Source Weighted-Ensemble Precipitation dataset, especially in the arid and semi-arid regions.

Another presentation showed the important role satellite precipitation datasets can play in helping to inform hydropower reservoir management decision support

[13] To learn more about this database, visit *go.nasa.gov/3gxKvNw*.

[14] To review plans and updates for the NASA R21C retrospective reanalysis, see *go.nasa.gov/3sqw9E7*.

[15] Learn more about CHIMES at *www.chc.ucsb.edu/data/chimes*.

[16] IMERG has three different data outputs: *Early*: Near-real-time, low-latency, gridded, global, multisatellite, forward-propagation precipitation estimates; *Late*: Near-real-time, low-latency, gridded, global, multisatellite, forward-and-backward propagation precipitation estimates; and *Final*: Research-quality, gridded, global, multisatellite precipitation estimates with quasi-Lagrangian time interpolation, gauge data, and climatological adjustment. To learn more about IMERG data, see *go.nasa.gov/3JguqYH*.

systems in East Africa. Currently, seasonal forecasts cannot be used as they are; however, incorporating IMERG-Early was shown to improve bias correction dependent upon climate region within East Africa.

Conclusion

Despite being virtual, the 2021 PMM STM brought together scientists from around the world to engage on a range of topics that advance understanding of precipitation science, algorithms, and contributions to applications. The STM highlighted ongoing projects and scientific results enabled by the PMM scientific community. During the meeting's final remarks, there was a request for team members to continue to share highlights and publications with the GPM management team.

The meeting closed with a short presentation highlighting one of NASA's future missions, the Atmosphere Observing System (AOS), to highlight its potential to deliver key data for improved forecasts of weather, air quality, and climate.

The next PMM STM will likely be held in October 2022. Check for updates on the PMM website.

Acknowledgements

Each online session of the PMM STM was assigned a session moderator to take minutes. The authors used these notes to help them compose this summary, and would like to thank the following individuals for their important contributions. They include: **George Huffman, William Olson**, **Robert Meneghini**, **Ian Adams**, and **Wei-kuo Tao** [all at NASA's Goddard Space Flight Center], **Joe Turk** [NASA/Jet Propulsion Laboratory (JPL)], **Patrick Gatlin** [NASA's Marshall Space Flight Center], **Christian Kummerow** [Colorado State University], **Chuntao Liu** [Texas A&M Corpus Christi], **Courtney Schumacher** [Texas A&M University], and **Claire Pettersen** [University of Wisconsin–Madison]. ■

The Editor's Corner

continued from page 4

hybrid conference format, the SSO team used the agency-approved virtual event platform to host content. To read about this new—and perhaps new normal—event, turn to page 16 of this issue.

Like so many groups across NASA Earth Science, SSO made tremendous progress in its ability to adapt to the tumultuous past two years. Amid the ongoing pandemic, the doorway to NASA Science remains wide open. ■

List of Undefined Acronyms Used in Editorial and Table of Contents

AGU	American Geophysical Union
CNES	Centre National d'Études Spatiales (CNES) [French Space Agency]
CYGNSS	Cyclone Global Navigation Satellite System
GRACE	Gravity Recovery and Climate Experiment
GSFC	NASA's Goddard Space Flight Center
ISS	International Space Station
NOAA	National Oceanic and Atmospheric Administration

NASA To Launch 4 Earth Science Missions in 2022

Alison Gold, NASA's Earth Science News Team, alison.gold@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*.

NASA will launch four Earth Science missions into low Earth orbit in 2022 to provide scientists with more information about fundamental climate systems and processes including extreme storms, surface water and oceans, and atmospheric dust.

NASA has a unique view of our planet from space. NASA's fleet of Earth-observing satellites provide high-quality data on Earth's interconnected environment, from air quality to sea ice.

These four missions will enhance the ability to monitor our changing planet:

- TROPICS will use six small satellites to provide improved and rapid measurements of tropical cyclones.
- EMIT will trace the origin and composition of mineral dust that can affect climate, ecosystems, air quality, and human health with an imaging spectrometer aboard the International Space Station.
- NOAA's JPSS-2 will help scientists predict extreme weather conditions including floods, wildfires, and volcanoes.
- SWOT will evaluate the world's oceans and their role in climate change, as well as monitor lakes, rivers, and other surface waters.

Measuring Tropical Cyclones

NASA's Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission aims to improve observations of tropical cyclones. Six TROPICS satellites will work in concert to provide microwave observations of a storm's precipitation, temperature, and humidity as quickly as every 50 minutes. Scientists expect the data will help them understand the factors driving tropical cyclone intensification and contribute to weather forecasting models.

In June 2021 the first pathfinder, or proof of concept, satellite of the constellation started collecting data,[1] including from Hurricane Ida in August 2021, which shows the promise of these small satellites. The TROPICS satellites will be deployed in pairs of two over three different launches, expected to be completed by July 31, 2022.

Each satellite is about the size of a loaf of bread and carries a miniaturized microwave radiometer instrument. Traveling in pairs in three different orbits, they will collectively observe Earth's surface more frequently than current weather satellites making similar measurements, greatly increasing the data available for near real-time weather forecasts.

The TROPICS team is led by **William Blackwell** [MIT's Lincoln Laboratory—*TROPICS Principal Investigator*], and includes researchers from NASA, the National Oceanic and Atmospheric Administration (NOAA), and several universities and commercial partners. NASA's Launch Services Program, based at Kennedy Space Center (KSC), will manage the launch service.

"The coolest part of this program is its impact on helping society," Blackwell said. "These storms affect a lot of people. The higher frequency observations provided by TROPICS have the potential to support weather forecasting that may help people get to safety sooner."

Studying Mineral Dust

Winds kick up dust from Earth's arid regions and transport the mineral particles around the world. The dust can influence radiative forcing—or the balance between the energy that comes toward Earth from the Sun, and the energy that Earth reflects back out into space—hence the temperature of the planet's surface and atmosphere. Darker, iron-laden minerals tend to absorb energy, which leads to heating of the environment, while brighter, clay-containing particles scatter light in a way that may lead to cooling. In addition to affecting regional and global warming of the atmosphere, dust can affect air quality and the health of people worldwide and, when deposited in the ocean, can also trigger blooms of microscopic algae.

The goal of the Earth Surface Mineral Dust Source Investigation (EMIT) mission is to map where the dust originates and estimate its composition so that scientists can better understand how it affects the planet. Targeted to launch in 2022, EMIT has a prime mission of one year and will be installed on the International Space Station. EMIT will use an instrument called an imaging spectrometer that measures visible and infrared light reflecting from surfaces below. These data can reveal the distinct light-absorbing signatures of the minerals in the dust that helps to determine its composition.

[1] To clarify, including the Pathfinder satellite, there are a total of seven TROPICS satellites.

"EMIT will close a gap in our knowledge about arid land regions of our planet and answer key questions about how mineral dust interacts with the Earth system," said **Robert Green** [NASA/Jet Propulsion Laboratory (JPL)—*EMIT Principal Investigator*].

Observing Earth's Storms

Forecasting extreme storms many days in advance requires capturing precise measurements of the temperature and moisture in our atmosphere, along with ocean surface temperatures. The NOAA–NASA Joint Polar Satellite System satellites provide these critical data, which are used by forecasters and first responders. The satellites also tell us about floods, wildfires, volcanoes, smog, dust storms, and sea ice.

"JPSS satellites are a vital component of the global backbone of numerical weather prediction," said **Satya Kalluri** [NOAA—*JPSS Program Science Adviser*].

The JPSS satellites circle Earth from the North to the South Pole, collecting data and images as they fly. As Earth rotates under these satellites, they observe every part of the planet at least twice a day.

The Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA-20 satellites are currently in orbit. The JPSS-2 satellite is targeted to launch in 2022 from Vandenberg Space Force Base in California on a United Launch Alliance Atlas V rocket.[2] Two more satellites will launch in coming years, providing data well into the 2030s. NASA's Launch Services Program, based at KSC, will manage the launch service.

Surveying Earth's Surface Waters and Oceans

The Surface Water and Ocean Topography (SWOT) mission will help researchers determine how much water Earth's oceans, lakes, and rivers contain. This will aid scientists in understanding the effects of climate change on freshwater bodies and the ocean's ability to absorb excess heat and greenhouse gases like carbon dioxide.

NASA's Launch Services Program, based at KSC, will manage the launch service, which is targeted for November 2022. SWOT will launch on a SpaceX Falcon 9 rocket from Vandenberg Space Force Base in California.

The SUV-size satellite will measure the height of water using its K_a-band Radar Interferometer, a new instrument that bounces radar pulses off the water's surface and receives the return signals with two different antennas at the same time. This measurement technique allows scientists to precisely calculate the height of the water. The data will help with tasks like tracking regional shifts in sea level, monitoring changes in river flows and how much water lakes store, as well as determining how much freshwater is available to communities around the world.

"SWOT will address the ocean's leading role in our changing weather and climate and the consequences on the availability of freshwater on land," said **Lee-Lueng Fu** [JPL—*SWOT Project Scientist*].

The mission is a collaboration between NASA and the French Space Agency [Center Nationale d'Études Spatiale], with contributions from the Canadian Space Agency and the United Kingdom Space Agency.

Coming Soon to Geostationary Orbit

In addition to these missions close to Earth, NASA is also supporting two missions that will go into geostationary orbit in 2022.

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) will be the first space-based instrument to monitor major air pollutants across the North American continent every daylight hour at high spatial resolution. The mission is the first funded project of NASA's Earth Venture Instrument program, which includes small, targeted science investigations designed to complement NASA's larger research missions. It is part of the agency's Earth System Science Pathfinder program. It consists of the Instrument Project, competitively selected by NASA from the Smithsonian Astrophysical Observatory (SAO) proposal, and the Mission Project, directed to NASA's Langley Research Center.

NASA will also launch NOAA's GOES-T satellite, the third satellite in NOAA's GOES-R series. GOES-T will provide critical data for the U.S. West Coast, Alaska, Hawaii, Mexico, Central America, and the Pacific Ocean, including real-time mapping of lightning activity and advanced monitoring of space weather.

To watch a video that explores the missions launching in 2022, including SWOT, TROPICS, EMIT, and JPSS-2, visit *youtu.be/VPvwwELRNis*. ■

[2] Once established on orbit, JPSS-2 will become known as NOAA-21.

Hunga Tonga–Hunga Ha‘apai Erupts

Adam Voiland, NASA's Goddard Space Flight Center/Science Systems and Applications Inc., adam.p.voiland@nasa.gov
Mike Carlowicz, NASA's Goddard Space Flight Center/Science Systems and Applications, Inc, michael.j.carlowicz@nasa.gov

EDITOR'S NOTE: This article was originally published on the *Earth Matters* blog at NASA's Earth Observatory website on January 18, 2022. The text has been edited for the context of *The Earth Observer*.

On January 15, 2022, a powerful volcanic eruption obliterated a small, uninhabited South Pacific island known as Hunga Tonga–Hunga Ha‘apai (HTHH)—see **Figure 1**. Some communities in the island nation of Tonga have been severely damaged by volcanic ash and significant tsunami waves. As of this writing, the disaster and response continue to unfold—with the added threat of COVID outbreaks on the remote island.[1]

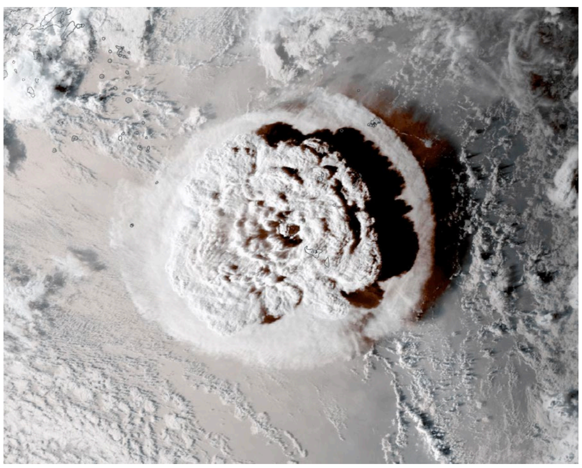


Figure 1. The National Oceanic and Atmospheric Administration (NOAA)'s Geostationary Operational Environmental Satellite 17 (GOES-17) captured this view of a powerful volcanic eruption near Hunga Tonga–Hunga Ha'apai on January 15, 2022, created using data from the satellite's Advanced Baseline Imager. To view an animation of the eruption, see *go.nasa.gov/3smkeZr* or visit *go.nasa.gov/3haelb7*. **Credit:** NASA/NOAA

The volcano had sporadically erupted multiple times since 2009. The most recent activity began in late December 2021 as a series of *Surtseyan eruptions*—explosive eruptions that occur in shallow seas or lakes—that built up and reshaped the island, while sending bursts of *tephra*—rock fragments of all sizes—and volcanic gases spewing from the vent. Relatively powerful blasts shook HTHH on January 13, but it was an even more intense series of explosions early on January 15 that generated atmospheric shock waves, sonic booms, and tsunami waves that traveled the world.

Several Earth-observing satellites collected data during and after the eruption. Scientists affiliated with NASA's Disasters program are now gathering imagery and data,[2] and they are sharing it with colleagues around the world, including disaster response agencies.

[1] To learn more, see *go.nasa.gov/363Cr5j*.
[2] To see a compilation of the NASA imagery that has been collected to date, visit *go.nasa.gov/3Lha03R*.

The sheer power of the eruption was quickly apparent in satellite imagery. As seen in Figure 1, a vast plume of material created what volcanologists call an *umbrella cloud* with crescent-shaped *bow shock waves* and a vast number of lightning strikes.

"The umbrella cloud was about 500 km (300 mi) in diameter at its maximum extent," said **Simon Carn** [Michigan Technological University]. "That is comparable to Pinatubo [1991]—and one of the largest of the satellite era. However, the involvement of water in the Tonga eruption may have increased the explosivity compared to a purely magmatic eruption like Pinatubo."

The joint NASA–French Space Agency [Center Nationale d'Études Spatiale] Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission passed over the eruption on January 16, and scanned the area with its lidar—see **Figure 2**. These data indicate that material from the HTHH eruption rose to an altitude of 31 km (19 mi). Other CALIPSO data (collected on January 15, *not shown*) indicates that a small amount of ash and gas may have reached as high as 39.7 km (24.7 mi).

"This is by far the highest volcanic plume we've ever measured with CALIPSO," said **Jason Tackett** [NASA's Langley Research Center]. CALIPSO has been in orbit since 2006.

The eruption was powerful enough to inject volcanic material into the stratosphere, which generally begins above 15 km (9 mi) in this part of the world. Scientists watch closely when volcanic materials reach this relatively dry layer of the atmosphere because particles linger much longer and travel much farther than if they remain in the lower, wetter troposphere. If enough volcanic material reaches the stratosphere, it can start to exert a cooling influence on global temperatures.

Despite the extreme height of the January 15 plume, scientists do not expect it to have much impact on climate. Satellite observations indicate the eruption injected about 0.4 Tg of sulfur dioxide into the upper atmosphere—but the threshold for climate impacts is about 5 Tg.[3] "It is not unlike a dozen other eruptions that have occurred in the past 20 years in terms of likely impacts on climate," explained **Brian Toon** [University

[3] By comparison, Pinutubo—which did have a significant cooling impact on global climate—injected approximately 20 Tg of sulfur dioxide into the atmosphere.

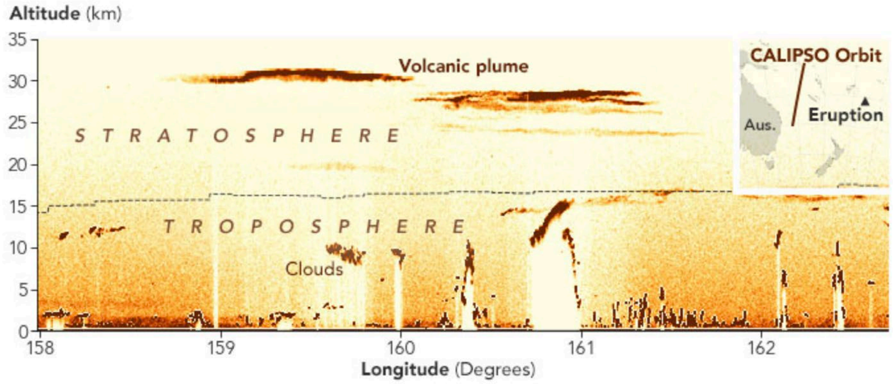


Figure 2. Data from the Cloud–Aerosol Lidar with Orthogonal Projection (CALIOP) instrument on CALIPSO collected on January 16, 2022, show material from the Hunga Tonga–Hunga Ha'apai volcanic plume rising as high as 31 km (19 mi) into the atmosphere. The inset image [*top right*] shows the path of CALIPSO (line) and its distance from the eruption (triangle), indicating that the volcanic plume expanded upward and outward over the South Pacific. **Image credit**: Joshua Stevens and Lauren Dauphin/NASA Earth Observatory.

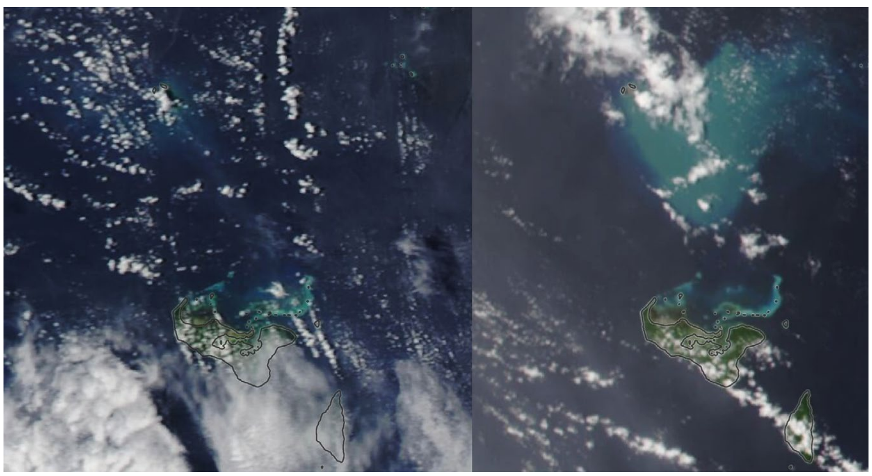


Figure 3. A series of images obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite from January 7 [*left*], January 15 [*center*], and January 17 [*right*] of the area around Hunga Tonga–Hunga Ha'apai show sediment, ash, pumice, and possibly continuing emissions from the volcano discoloring the water in the days after the event. **Image credit**: Joshua Stevens and Lauren Dauphin/NASA Earth Observatory

of Colorado]. "It is possible the impacts will be observable in very closely studied data (when the effects of La Niña and El Niño are removed), but the impacts will be too small to be felt by the average person."

Why this eruption was so violent is not clear yet. "With something this explosive, it is typically a consequence of a large volume of seawater coming into contact with a large reservoir of magma in a confined geologic setting," explained **Daniel Slayback** [NASA's Goddard Space Flight Center/Science Systems and Applications, Inc.], who visited HTHH in 2019 to study how erosion was affecting the youngest parts of the island.[4] Understanding erosion processes around volcanic features on Earth provides insights into how related processes may have played out in other parts of the solar system, including Mars.

Signs of the island's recent demise were easy for satellites to spot in the seas. As an example, a trio of natural-color images from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite shows how the eruption discolored the water in the days after the event—see **Figure 3**. Other imagery from commercial satellites and European and Canadian radar imagers suggest that little of HTHH still stands above the water line.[5]

The geologic record suggests HTHH may have produced large explosive eruptions like this in the past. "I just didn't expect to see one happen quite so soon," said Slayback. "It was a beautiful little island with a thriving ecosystem of grasses, tropical birds, and other wildlife." ■

[4] To read Daniel Slayback's account of his experience, visit *go.nasa.gov/3gxFxjR*.

[5] To learn more, see *go.nasa.gov/3rBmMm0*.

NASA Planes Fly into Snowstorms to Study Snowfall

Sofie Bates, NASA's Earth Science News Team, sofie.bates@nasa.gov

EDITOR'S NOTE: This article was originally published on the *Earth Matters* blog at NASA's Earth Observatory website on January 18, 2022. The text has been edited for the context of *The Earth Observer*.

Scientists repeatedly checked the weather forecasts as they prepared aircraft for flight and performed last-minute checks on science instruments—so they'd be ready. The team had been tracking storms across the Midwestern and Eastern U.S. since early January 2022 using two NASA planes equipped with scientific instruments to help understand the inner workings of winter storms as they form and develop. In late January 2022, they saw a disturbance moving in from the southwest, and the forecasts told them that the atmosphere was primed to create the storm they'd been waiting for—a *Nor'easter*. The initial (or *parent*) low "sacrificed itself" to feed the formation of a large area of low pressure off the Mid-Atlantic coast. The storm moved up the Eastern Seaboard, intensifying rapidly, drawing in an abundant supply of moisture from the Atlantic Ocean along with ample cold air from Canada to produce snow over a large area. Some places along the Mid-Atlantic coast and especially along the New England coast were measuring in feet—not inches.

The experiments conducted on these flights are part of the second deployment of NASA's Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Storms (IMPACTS) mission, which began in January and is planned to wrap up at the end of February.[1] As they have done with other storms that have occurred during their investigation, the IMPACTS team conducted coordinated flights of the two NASA aircraft to investigate the Nor'easter—one above the storm and one within the clouds. Each aircraft was equipped with a different suite of scientific instruments to collect data about snow particles and the conditions in which they form (see details below).

The data collected during the IMPACTS flights helps the team relate properties of the snow particles and their environment to large-scale processes—such as the structure of clouds and precipitation patterns—that can be seen with remote sensing instruments on aircraft and satellites. Ultimately, what the IMPACTS team learns about snowstorms will improve meteorological models and our ability to use satellite data to predict how much snow will fall and where.

[1] IMPACTS is run out of NASA's Wallops Flight Facility, which is managed by NASA's Goddard Space Flight Center. To learn more about the mission, visit *espo.nasa.gov/impacts/content/IMPACTS*.

Surveying a Variety of Storms

Storms often form narrow structures called snow bands, said **Lynn McMurdie** [University of Washington, Seattle—*IMPACTS Principal Investigator*]. One of the main goals of IMPACTS is to understand how these structures form, why some storms don't have snow bands, and how snow bands can be used to predict snowfall. To do this, the team hopes to sample a wide variety of storms throughout the three-year IMPACTS campaign.

During the 2020 IMPACTS campaign, the team sampled a variety of storms in the Midwest and East Coast, including warmer rainstorms and storms with strong cold fronts and convection. But McMurdie said the team hadn't yet seen a Nor'easter. Nor'easters come up the East Coast and can dump several feet of snow, effectively shutting down cities, said **John Yorks** [NASA's Goddard Space Flight Center (GSFC)—*IMPACTS Deputy Principal Investigator*]. Being better able to predict where these storms will bring snow and how much could help cities—and the millions of people living in them—better prepare for severe winter weather.

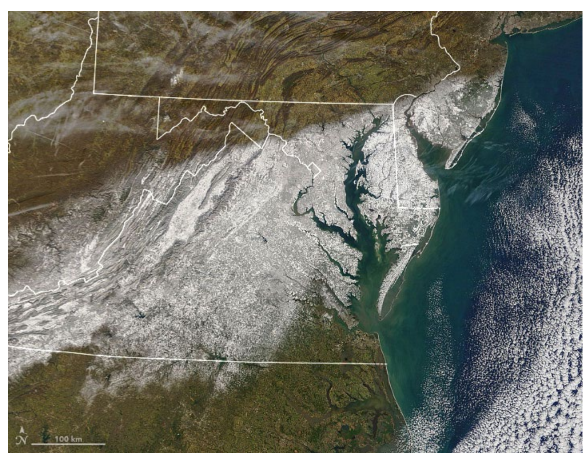


Photo 1. On Jan. 4, 2022, the MODIS instrument aboard NASA's Terra satellite captured this image of snowfall after a large storm dumped wet, heavy snow across the Mid-Atlantic region of the United States. Some areas accumulated over 14 inches, shutting down businesses, schools, and interstate highways. **Credit:** NASA

Photo 2. NASA's ER-2, a high-altitude jet equipped with a suite of science instruments, takes off. **Credit:** NASA's Armstrong Flight Research Center

Above, Below, and Into the Clouds

NASA and its partners have several satellites that measure precipitation from space, such as the Global Precipitation Measurement mission that observes rain and snow around most of the world every three hours. "But satellites can't tell us a lot about the particles—the actual snowflakes—and where they form within the clouds," said **Gerry Heymsfield** [GSFC—*IMPACTS Deputy Principal Investigator*].

The NASA Armstrong Flight Research Center's ER-2, a high-altitude jet flying out of the Pope Army Airfield near Fayetteville, NC, will fly at about 65,000 ft (~19,800 m) to get a top-down view from above the clouds—see **Photo 2**. The instruments aboard the ER-2 are similar to those on satellites but with higher spatial resolution, additional measurement capabilities, and more frequent sampling. Scientists on the ground are also measuring cloud properties from below using ground-based radars.

"A project like IMPACTS can really complement those spacecraft measurements with aircraft measurements that are higher resolution, higher accuracy, sample an event more frequently, and provide additional parameters such as Doppler measurements," said Yorks.

Meanwhile flying below the ER-2 is the P-3 Orion based out of NASA's Wallops Flight Facility, which flies at altitudes up to 26,000 ft (~7900 m). Probes hanging off the P-3's wings measure the size, shape, and distribution of precipitation particles. Flying the P-3 at different altitudes allows the team to measure snow particles throughout the cloud, and the temperature, water vapor, and other conditions in which they form.

The P-3 also drops small instruments, called *dropsondes*, over the ocean. These instruments work like weather balloons in reverse, measuring temperature, wind, and humidity in the atmosphere as they fall. The team is also launching weather balloons every few hours as the storm passes overhead from several sites that move depending on which storm the team is studying. The data collected by the dropsondes and weather balloons provide information about the atmospheric conditions before, during, and after the storm.

"Snowstorms are really complicated storms, and we need every piece of data—models, aircraft instruments, meteorological soundings—to really figure out what's going on within these storms," said Heymsfield.

The multiyear IMPACTS campaign is the first comprehensive study of snowstorms across the Eastern U.S. in 30 years. The science team includes researchers from NASA, several universities across the country, the National Center for Atmospheric Research, and the National Oceanic and Atmospheric Administration, including partners at the National Weather Service. ■

Northrop Grumman Names Cygnus ISS Resupply Spacecraft After Piers Sellers

This text was originally published as an email from **Dennis J. Andrucyk** [NASA's Goddard Space Flight Center (GSFC)—*Director*] to the GSFC community. It has been modified for the broader audience of *The Earth Observer*.

Northrop Grumman has named the Cygnus spacecraft used for its most recent resupply mission (CRS-17) to the International Space Station (ISS) the *S.S. Piers Sellers*. The spacecraft launched from NASA's Wallops Flight Facility aboard an Antares rocket on Saturday, February 19, at 12:39 PM EDT. It is now installed on the Unity module's Earth-facing port.

In many ways and in many incarnations, **Piers Sellers** embodied the very best of NASA. He began his career at GSFC in the 1980s as a bright-eyed scientist from his native U.K., and it wasn't long before he would make a name for himself as a leading modeler of Earth's biosphere and other systems. He fulfilled a childhood dream in 1996 by joining the astronaut corps. He flew to the ISS as part of three space shuttle missions and participated in several spacewalks—effectively becoming a "human satellite." In addition to helping build the orbiting laboratory into the incredible research platform it is today, he credited his spaceflights with augmenting his appreciation for Earth, as leaving it to see it from above allowed him to better see the interconnections among people, spaces, and climate systems.

Piers Sellers joined the NASA astronaut corps in 1996 and flew to the International Space Station in 2002, 2006 and 2010, performing six spacewalks and various space station assembly tasks. As STS-112 mission specialist, Sellers is pictured above on the aft flight deck of the Space Shuttle Atlantis in 2002. **Credits:** NASA

Following his retirement as an astronaut in 2011—and despite other offers across the agency—he returned to GSFC. He became the Director of the Goddard Earth Sciences Division and Deputy of Sciences and Exploration, and in that role he would help lead our center's cadre of scientists dedicated to advancing our knowledge of Earth and everything beyond. In part, he was ensuring that others carried on the work he helped pioneer.

Undeterred by his diagnosis of terminal pancreatic cancer, Piers insisted on carrying on and unwittingly elevated himself from what was an already distinguished career to a global spokesperson for the climate crisis, encouraging all players to come together to use NASA's tools and other advancements to tackle one of the largest collective challenges we have known. It was his "last mission" of sorts, and few could have undertaken it in equal parts dignity and enthusiasm as Piers did.

In receiving this honor, Piers joins the likes of such NASA legends as John Glenn, Katherine Johnson, Deke Slayton, Alan Bean, Gene Cernan, and Ellison Onizuka. It seems somehow fitting that the Cygnus spacecraft bearing his name will carry more than 8000 pounds of supplies to the current occupants of the station—a place he himself once called home.

"His countless achievements notwithstanding, I am just as proud to have called Piers my friend, as so many of us did. His career speaks for itself, but I'll always remember the conversations and passion for all things in life that he brought every time he passed through our gates. As the *S.S. Piers Sellers* flies into space as its namesake once did, let us continually find ways to carry on Piers' work and—like he did throughout his professional life—advance NASA's work on behalf of humanity," **Dennis J. Andrucyk** [NASA's Goddard Space Flight Center (GSFC)—*Director*] said in an email to GSFC employees, announcing the news.

NASA Earth Science in the News

Ellen Gray, NASA's Goddard Space Flight Center, Earth Science News Team, ellen.t.gray@nasa.gov

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 Heat Stays On: Earth Hits Sixth Warmest Year on Record, January 13, *apnews.com*. Data from NASA and the National Oceanic and Atmospheric Administration (NOAA) agree: The last eight years have been the eight hottest on record. And Earth simmered to the sixth hottest year on record in 2021, according to several newly released temperature measurements. And scientists say the exceptionally hot year is part of a long-term warming trend that shows hints of accelerating. Two U.S. science agencies—NASA and NOAA—and a private measuring group, released their calculations for last year's global temperature, and all said it wasn't far behind ultra-hot 2016 and 2020.[1] Six different calculations found 2021 was between the fifth and seventh hottest year since the late 1800s. NASA said 2021 tied with 2018 for sixth warmest, while NOAA puts last year in sixth place by itself. Scientists say a *La Niña*—natural cooling of parts of the central Pacific that changes weather patterns globally and brings chilly deep ocean water to the surface—dampened global temperatures the opposite of the way *El Niño* boosted them in 2016. Still, they said 2021 was the hottest La Niña year on record and that the year did not represent a cooling off of human-caused climate change, but is part of the warming trend. **Gavin Schmidt** [NASA's Goddard Institute for Space Studies—*Director*], the climate scientist who heads NASA's temperature team, said "the long-term trend is very, very clear. And it's because of us. And it's not going to go away until we stop increasing the amount of carbon dioxide in the atmosphere."

***'Rocked': NASA Scientist Brave Bumpy Flights into Winter Storms**, February 3, *nbcnews.com*. In late January 2022, a Nor'easter dumped more than 30 in (72 cm) of snow over some New England towns in the U.S. From the cockpit, **Brian Bernth** [NASA's Goddard Space Flight Center—*Chief of Flight Operations*], a former Marine corporal, spent more than nine hours darting in and out of the storm in a Lockheed P-3 Orion. In the cabin, nine scientists were strapped into their seats, measuring the storm with various instruments—see **Photo 1**. No one had expected a smooth ride, but the journey got surprisingly sporty. "We got rocked," Bernth said, comparing the G-forces and the bumps the passengers and crew experienced to riding a roller coaster while blindfolded. "Did we have a few people get sick? Yeah." The flight was one of more than a dozen piloted for the Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS), a NASA project to collect data below, above, and in the center of damaging snowstorms. This January 2022 storm was the hammering storm researchers had been waiting for. "We want the whole gamut, but we really want something like we got over the weekend," said **Lynn McMurdie** [University of Washington—*IMPACTS Principal Investigator*]. The larger effort involves dozens of scientists who will collect three seasons of data from winter storms, and aims to untangle the complex forces behind snowfall, improve weather models, and help researchers better measure snow from satellites in space.

Photo 1. A flight safety briefing aboard the P-3 aircraft at NASA's Wallops Flight Facility. **Credit:** NASA

NASA Welcomes Chief Scientist, Senior Climate Adviser in New Dual Role, January 11, *thehill.com*. Connecting NASA's numerous problem-solvers across many fields with the common thread of climate science will be critical to the mission of the agency's new chief scientist and senior climate adviser, **Katherine Calvin**. "Like many people, my introduction to NASA was through movies," Calvin told reporters in a teleconference. "I remember watching *Apollo 13* years ago and

[1] To read the NASA article on this topic, visit *go.nasa.gov/3hbBc6g*.

being amazed at how NASA scientists work together. As someone with a background in math, computer science, and engineering, I was inspired by seeing women in science, technology, engineering, and math (STEM) help launch a man into orbit in *Hidden Figures,*" she continued. "NASA shows us what happens when you bring together a team of really smart people to explore the universe and solve problems. I'm excited to be a part of that." Calvin assumed the dual roles of NASA chief scientist and senior climate adviser on January 10—serving as principal adviser to the administrator and other NASA leaders, while representing the agency's strategic science objectives to the national and international space communities. Her main interest involves "trying to connect the climate science research with the rest of the research in NASA." **NASA Administrator Sen. Bill Nelson** stated that, "We have created this new position of a dual role of chief scientist and senior climate advisor. We've chosen to elevate this senior climate adviser position," noting that the position will help "harmonize and coordinate" science activity among mission directorates.

*__NASA Says Tonga Eruption Was More Powerful than an Atomic Bomb__, January 25, *smithsonianmag.com*. The volcanic eruption that rocked the South Pacific kingdom of Tonga earlier this month was hundreds of times more powerful than the atomic bomb the U.S. dropped on Hiroshima during World War II, according to an analysis by NASA scientists. "This is a preliminary estimate, but we think the amount of energy released by the eruption was equivalent to somewhere between 4 to 18 megatons of TNT," **Jim Garvin** [NASA's Goddard Space Flight Center—*Chief Scientist*] said in a NASA Earth Observatory blog.[2] The eruption of the Hunga Tonga–Hunga Ha'apai volcano sent a dramatic plume of ash and water vapor 25 mi (~40 km) into the atmosphere and generated nearly 50-ft (~15-m) tsunami waves that hit parts of Tonga's main island and sent swells across the Pacific. The blast also severed the nation's internet cable, cutting off communication to the remote archipelago for days. To calculate the power of the event, scientists used a combination of satellite images and on-the-ground surveys.

Students Get Ride on Flying Space Lab, January 10, *avpress.com*. It may have taken longer to take off than originally planned, but 53 college students flew on NASA's DC-8 airborne science laboratory as part of NASA's Student Airborne Research Project (SARP) in December 2021.[3] The student researchers took part in a series of low-level flights over the Inland Empire, Imperial, and San Joaquin Valleys, in early December to collect data on air pollution. The flights originated from the DC-8's home base at NASA's Armstrong Flight Research Center's (AFRC) facility in Palmdale—see **Photo 2**. The students' participation in the research flights was delayed from last year due to the COVID-19 pandemic, according to a NASA release on the program. SARP allows university students in science, math, and engineering fields to take part in NASA research campaigns. Participants gain hands-on experience in all aspects of the campaign, from planning through presenting the results. During the December flights, the students aided researchers in operating the airborne instruments to measure air pollution and greenhouse gases, to better understand their sources and how they react in the atmosphere. The data collected during the flights will be compared to air-quality forecasts and satellite observations. "For many of these students, it is their first time being able to conduct scientific research," said **Brenna Biggs** [AFRC—*SARP Program Manager*]. "SARP is a great opportunity to train the next generation of scientists, especially those who are interested in atmospheric sciences."

*See News Story in this issue.

[2] To read more, visit *go.nasa.gov/3JIu8dm*.

[3] To read the NASA feature, visit *go.nasa.gov/3LUiNZP.*

Photo 2. NASA Student Airborne Research Program (SARP) students, mentors, and faculty pose in front of NASA's DC-8 on December 7, 2021, at NASA's Armstrong Flight Research Center. **Credit:** NASA/ Carla Thomas

Earth Science Meeting and Workshop Calendar

NASA Community

March 21–25, 2022
Ocean Surface Topography Science Team Meeting, Venice, Italy.
ostst-altimetry-2022.com

April 18, 2022
Land Cover Land Use Change Science Team Meeting, Bethesda, MD

May 9–13, 2022
AIRS Science Team Meeting, Pasadena, CA
go.nasa.gov/3LTJvSa

May 16–20, 2022, *tentative*
2022 Sun–Climate Symposium, Madison, WI
lasp.colorado.edu/home/meetings/2022-sun-climate-symposium

Global Science Community

April 22, 2022
NASA's Hybrid Earth Day Event,
Washington, DC and Online Everywhere, *virtual*

May 22–27, 2022
Japan Geoscience Union Meeting, *hybrid*
Makuhari, Chiba, Japan
www.jpgu.org/meeting_e2022

May 23–27, 2022
EGU General Assembly, *virtual*
www.egu21.eu

July 16–24, 2022
COSPAR 2022,
Athens, Greece
www.cosparathens2022.org

July 17–22, 2022
IGARSS 2022,
Kuala Lumpur, Malaysia
www.classic.grss-ieee.org/conferences/future-igarss

August 1–5, 2022
AOGS 18th Annual Meeting, *virtual*
www.asiaoceania.org/aogs2021/public.asp?page=home.html

June 21–24, 2022
Global Council for Science and the Environment, *virtual*
www.gcseconference.org

Erratum

The title of the News story on **page 32** of the November–December 2021 issue should have included a footnote that read: "While this is the *nasa.gov* title for this article, this is not meant to suggest that climate impacts are not already occurring. As explained in the text, it is 'discernible impacts' that are projected to occur by 2030." The number appears after the title but the footnote text was left out of the print version of the issue. The online version has been corrected.

Code 610
National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, MD 20771

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National Aeronautics and Space Administration
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The Earth Observer

The Earth Observer is published by the Science Support Office, Code 610, NASA's Goddard Space Flight Center (GSFC), Greenbelt, Maryland 20771, and is available in color at *eospso.nasa.gov/earth-observer-archive*.

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.

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NP-2022-2-738-GSFC