Over Thirty Years Reporting on NASA's Earth Science Program

# The Earth Observer

National Aeronautics and Space Administration

July – August 2022. Volume 34, Issue 4

## The Editor's Corner

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The Earth Surface Mineral Dust Source Investigation (EMIT) imaging spectrometer was launched to the International Space Station (ISS) from Launch Pad 39A at NASA's Kennedy Space Center at 8:44 PM Eastern Daylight Time on July 14, 2022, aboard a SpaceX Falcon 9 rocket as part of Commercial Resupply Service (CRS)–25. Over the next two weeks, EMIT was installed on ISS Express Logistics Carrier-1, tested, powered on, and commanded to operational temperatures. The first imaging spectroscopy measurements were acquired on July 28 north of Perth, Australia—see **Figure**. EMIT measures the spectral reflectance from 380–2500 nm for every point in the image with 285 contiguous spectral channels. The image swath is nominally 80 km (~50 mi). Congratulations to **Rob Green** [JPL—*EMIT PI*] and his team on reaching this "first light" milestone.

The measurement performance and area coverage requirements for EMIT are optimized to accurately map the surface mineralogy of Earth's arid land dust source regions and support atmospheric correction and screening for confounding factors such as clouds and heavy aerosol loading. Mineral dust emitted into the atmosphere from arid land regions plays an important role in the Earth system, impacting direct and indirect aerosol radiative forcing, atmospheric chemistry, cryosphere melt, surface hydrology, and the biogeochemistry of ocean and terrestrial ecosystems, as well as posing a hazard to human populations.

Over the course of a year, EMIT will acquire the first comprehensive map of the mineral composition of Earth's arid land dust source regions. These new measurements will be used in conjunction with advanced Earth system models to address specific scientific objectives related to current and future direct radiative forcing. EMIT's measurements, products, and results will be available to other investigators through the NASA Land Processes Data Active Archive Center (LP DAAC). It is hoped these measurements can provide preparatory support for the Surface Biology and Geology mission that is part of NASA's Earth System Observatory (ESO). EMIT was developed through NASA's Earth Venture Instrument-4 (EVI-4) opportunity.

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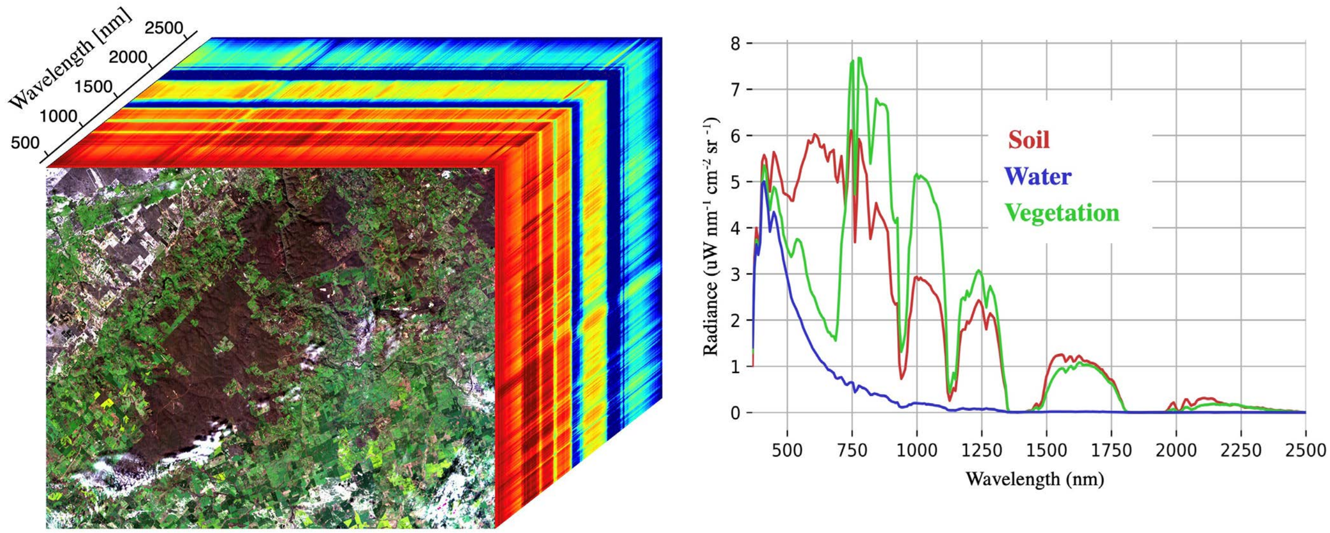


**Figure**. NASA's Earth Surface Mineral Dust Source Investigation, or EMIT, mission launched to the International Space Station (ISS) July 14, 2022, and began collecting an orbital dataset over Western Australia to the north of Perth on July 28 at 2:51 UTC. Following transfer from the ISS to NASA's Marshall Space Flight Center's Huntsville Operational Support Center and then to NASA/Jet Propulsion Laboratory, the raw data were reassembled and passed through the EMIT Science Data System calibration processing algorithms. An image cube of the first spectral light dataset is shown [*left*] along with a set of calibrated radiance spectra that reveal the full set of expected surface and atmospheric features [*right*]. **Image credit**: NASA

## In This Issue



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NASA's Compact Total Irradiance Monitor (CTIM) CubeSat took flight on July 1, 2022, from a runway at the Mojave Air and Space Port in California aboard a Virgin Orbit Boeing 747-400 aircraft. Once airborne, CTIM and the other six payloads that comprised the United States Space Force Space Test Program (STP)-S28A mission were lifted into orbit via an air-launched Virgin Orbit LauncherOne rocket. The launch began at 10:50 PM Pacific Daylight Time (PDT) and concluded with the successful deployment of CTIM (and the other payloads) at approximately 12:55 AM PDT on the morning of July 2.

Spacecraft and instrument commissioning concluded on August 11, 2022. By then, eight detectors had made initial total solar irradiance (TSI) measurements and more than 250 MB of data had been downlinked via the S-band ground station at the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP). The CTIM team is now analyzing these initial measurements and comparing them against the TSI measurements from TSIS-1 TIM on ISS. Congratulations to **David Harber** [LASP—*CTIM PI*] and his team on acquiring these initial measurements.

CTIM is a demonstration of next-generation instrument technology for the measurement of TSI from a CubeSat platform. Typical TSI instruments (e.g., the former SORCE and current TSIS-1 missions) have three or four independent identical detectors, each of which can be used to measure TSI. Because these channels are directly exposed to unfiltered extraterrestrial solar radiation, some ultraviolet-induced degradation of the response of these detectors is unavoidable. This degradation is monitored by comparing the ratio of the measurements performed by primary detector, which is continuously used, to those performed by additional redundant channels, which are only used weekly or monthly. The CTIM instrument employs an entirely new design [developed with the help of researchers at the National Institute of Standards and Technology (NIST)] with eight detectors that use a carbon nanotube optical absorber. CTIM has more detectors than a typical TSI instrument to allow for a more detailed measurement of detector degradation—information that will be useful for future versions of this instrument and other future carbon nanotube detectors. CTIM was supported through NASA's Earth Science Technology Office (ESTO) InVEST opportunity.[1]

The joint U.S. Geological Survey–NASA Landsat program reached a golden milestone recently as it celebrated the fiftieth anniversary of the launch of the first Landsat (then known as the Earth Resources Technology Satellite) on July 23, 2022.[2] On that day, William Pecora's dream—inspired by photos of Earth returned from the Apollo Moon missions—became reality. Continuous observations of Earth's land surface by a series of eight Landsat satellites have continued ever since.[3]

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[1] The ESTO InVEST program provides funds for projects that seek to test instruments in space in order to reduce the risk of incorporating these new technologies into future Earth science missions. For more information visit *esto.nasa.gov/invest*.

[2] To view a "Landsat 50th Consolidated Calendar" that includes a list of publications from USGS, NASA, and other sources, see *docs.google.com/document/d/1rsffUBxKddsMkP496NulKIoQ_H1aE2iOuLWhzz9g0s4/edit*.

[3] There have been nine Landsat missions (with plans underway for a tenth). However, since Landsat 6 failed to reach orbit in 1993, only *eight* missions have contributed to the long-term record of land observations.

As described in a recent anniversary article,[4] "Because Landsat provides freely available, comparable, objective data, many have likened Landsat to a 'time-machine' for looking back at planetary change. Like time-honored indigenous wisdom of place, Landsat gives us knowledge of ecosystem history for the entire planet over the past five decades." For an in-depth Landsat history, see the NASA-funded book, *Landsat's Enduring Legacy*, which can be freely downloaded from *my.asprs.org/landsat*.

The most recent Landsat mission, Landsat 9, continues to do well.[5] On August 11, 2022, NASA transferred the fully-certified Landsat 9 satellite to U.S. Geological Survey (USGS) where it will remain under operational control for the mission duration. **Jeff Masek** [NASA's Goddard Space Flight Center (GSFC)], who served as Landsat 9 Project Scientist (PS) since the mission's inception, retired from NASA on June 30, 2022. **Chris Neigh** [GSFC] has been named Landsat 9 PS, and **Bruce Cook** [GSFC] will serve as Landsat Next PS—which will be the tenth Landsat mission.[6] Best wishes to Jeff on his retirement from NASA and all future endeavors, and congratulations to Chris and Bruce on their new positions.

The first fully integrated powered testing of the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument on Intelsat IS40e at Maxar Technologies' manufacturing facility in Palo Alto, CA, has been completed. This is an important step toward the launch of TEMPO as it clears the mission to move into environmental testing.

TEMPO is currently targeted to launch on a SpaceX Falcon 9 rocket in January 2023 into geostationary orbit, where it will have a continuous view stretching from Puerto Rico and Mexico to northern Canada—and including the entire continental U.S. From this vantage point, TEMPO will be able to obtain hourly daytime air quality observations at an unprecedented spatial resolution.[7] To learn more about plans for TEMPO and the three-member, "virtual" Air Quality Constellation of which it will be a part, see the News story on page 34 of this issue and the TEMPO website at *tempo.si.edu/index.html*.

Continuing with the air quality theme, this issue's feature article summarizes an interagency partnership between NASA and the Department of Interior's Bureau of Ocean Energy Management (BOEM) to monitor and quantify air pollution produced by oil and natural gas (ONG) operations in the Gulf of Mexico (GOM). In 2017 NASA entered into a three-year agreement with BOEM to understand whether NASA and other air quality satellite data can be leveraged to track pollutants, principally nitrogen dioxide ($NO_2$) produced by GOM ONG operations. The agreement culminated in a May 2019 ship cruise called the Satellite Coastal and Oceanic Atmospheric Pollution Experiment (SCOAPE), which collected surface and remotely sensed air quality data to evaluate the accuracy of satellite measurements from OMI on NASA's Aura platform and TROPOMI on the European Space Agency's Copernicus Sentinel 5-Precursor mission. The SCOAPE cruise results indicate that OMI and TROPOMI satellite $NO_2$ data are sufficiently accurate near GOM ONG operations to quantify their effects on air quality.

The success of the initial NASA–BOEM agreement motivated a new five-year agreement (2022-2026) to advance the assessment of GOM air quality, this time incorporating data from the upcoming TEMPO mission and deploying a second SCOAPE cruise.

Also on the subject of air quality, the NASA Southern Hemisphere Additional Ozonesondes (SHADOZ) network is celebrating its twenty-fifth year of operation in 2022.[8] SHADOZ has collected more than 9000 balloon-borne ozone profiles from 14 tropical stations since 1998. Over 20 ozone-measuring satellite instruments have used data from the network for algorithm development and validation.

From its beginning, SHADOZ has led activities that enhance ozonesonde data quality assurance. Working within the World Meteorological Organization/Global Atmospheric Watch (WMO/GAW) framework, SHADOZ operators have participated in laboratory and field tests to build capacity and empower data providers in host nations. SHADOZ participates in the expert panel Assessment of Standard Operating Procedures for Ozonesondes to develop and promulgate best practices throughout the ozonesonde community. Most importantly, SHADOZ profiles have become a staple in studies of ozone chemistry and dynamics.[9]

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[4] See "A Planetary Sage: Landsat at 50," which can be viewed at *go.nasa.gov/3wujlzD*.

[5] To learn more about Landsat 9, see "The Legacy Continues: Landsat 9 Moves Landsat Toward a Golden Milestone" in the July–August 2021 issue of *The Earth Observer* [**Volume 33**, **Issue 4**, pp. 4–12—*go.nasa.gov/3ln3mhE*].

[6] Learn more about Landsat Next at *go.nasa.gov/3wtu0dw*.

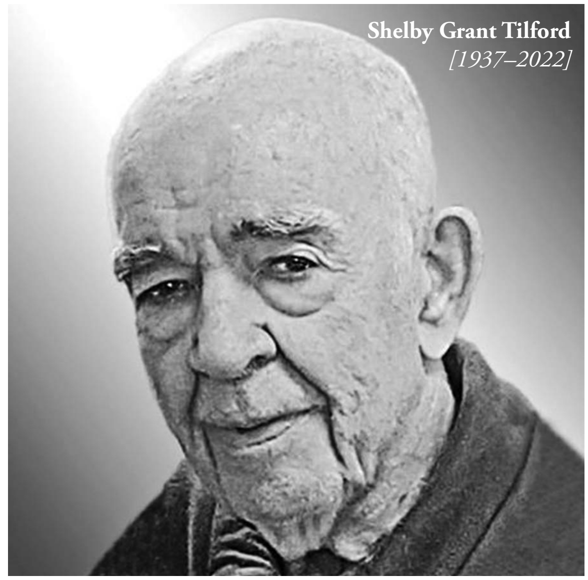
[7] To download a "TEMPO Green Paper" from March 29, 2022, which gives a comprehensive review of the many applications that will benefit from this new source of higher-resolution data, visit *tempo.si.edu/publications.html*.

[8] To read an article marking the twentieth anniversary of SHADOZ see "SHADOZ at 20: Achievements of a Strategic Ozonesonde Network" in the September–October 2019 issue of *The Earth Observer* [**Volume 31**, **Issue 5**, pp. 4–15—*go.nasa.gov/3v0xdht*].

[9] A recent example is a paper published in *Journal of Geophysical Research: Atmospheres* (*doi.org/10.1029/2021JD034691*) describing 22-year ozone trends in the Tropical Tropopause Layer that have established a new reference for satellite and model investigations.

# In Memoriam: Shelby Grant Tilford

*The Earth Observer* is saddened to report the passing of **Dr. Shelby Grant Tilford** on June 10, 2022, at age 85. A key NASA Earth System Science pioneer, Tilford was the Former Acting Associate Administrator of the Office of Mission to Planet Earth (MTPE) and one of the early initiators of NASA's Earth System Science concept—the MTPE program—which represented NASA's contribution to the U.S. Global Change Research Program (USGCRP).



**Shelby Grant Tilford**
*[1937–2022]*

**Thomas Zurbuchen** [NASA Headquarters (HQ)—*Associate Administrator for the Science Mission Directorate*] tweeted: "The entire science community, and especially the @NASAEarth community, mourn the death of one of our most impactful leaders ever in NASA's Science program—Dr. Shelby Tilford." Zurbuchen also shared an obituary for Tilford that can be found at *www.legacy.com/us/obituaries/washingtonpost/name/shelby-tilford-obituary?id=35204597.*

During his career, Tilford was an atmospheric spectroscopist, Earth scientist, and science program administrator. After working at the Naval Research Laboratory, he worked at NASA HQ from 1976–1994, serving in a variety of leadership roles. In 1978, when NASA began consolidating its Earth science components into one office, Tilford was appointed Director of the (then new) Earth Science and Applications Division. In 1983 he established the Earth System Science Committee, which led to the development of a well-formulated science plan for the study of the Earth as a system. That plan resulted in the publication of a landmark document in 1988 that provided an integrated set of recommendations for future research in the Earth sciences and formed the primary basis for the USGCRP and other international climate research programs. Established by presidential initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990, USGCRP was created to "…assist the nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

Later, when NASA created MTPE, Tilford became its acting associate administrator, serving in that role from 1992–1994. Throughout his nearly 20-year tenure with NASA, Tilford led all of the agency's Earth Science programs and activities, including coordination with other U.S. government agencies, NASA field centers, the private and commercial sectors, the university community, and the internatonal space-based Earth observations community.

Zurbuchen's tweet included a quote by **Len Fisk** [retired from NASA—*Former NASA Associate Administrator for Science*] describing the significance of Tilford's impact: "Shelby Tilford led NASA's Earth Science program… when it pioneered the concept that the Earth needs to be studied as an *integrated system*—i.e., that the coupling between the atmosphere, oceans, biosphere, and cryosphere determines the global climate. From this revolutionary concept came the comprehensive Earth Observing System (EOS), which changed forever our approach to studying Earth and understanding and predicting global climate change."

In a 2009 interview as part of the Earth System Science at 20 Oral History Project, Tilford provided his perspective on the activities in which he was involved—including his memories of the inception of EOS and other well-known international Earth Science entities, e.g., the Committee on Earth Observing Satellites (CEOS) and USGCRP. The transcripts of this two-part interview are lengthy, but well worth reading, and may be downloaded from *go.nasa.gov/3cREtbQ,* and *go.nasa.gov/3SlTumG*.

In 2014 the National Council on Science and the Environment (NCSE, now the Global Council on Science and the Environment, or GCSE) presented the John H. Chafee Lifetime Achievement Award to Tilford and to the other four cofounders and early developers of the USGCRP.[1]

Summarizing Tilford's contributions, **Ernest Hilsenrath** [retired from NASA, now at University of Maryland Baltimore County (UMBC)—*Former Aura Deputy Project Scientist*] noted that "the huge amount of satellite data being used for science and applications is a tribute to Shelby's legacy."

[1] In addition to Tilford, award recipients included: **Robert Corell** [then *Assistant Director for Geosciences at NSF*]; **J. Michael Hall** [then *Director of NOAA's Office of Global Programs*]; **Aristides A. N. Patrinos** [then *Director of the Department of Energy's Office of Biological and Environmental Research*]; and **Jack D. Fellows** [then *Branch Chief at Office of Management and Budget*].

# NASA Tracks the SCOAPE of Offshore Oil and Gas Pollution Using Satellite and Ship Cruise Measurements

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**Introduction**

NASA has a long history of partnering with external agencies to acquire and analyze Earth Science data to accomplish their shared scientific goals. One such example is an ongoing collaboration between NASA's Goddard Space Flight Center (GSFC) and the U.S. Department of the Interior's Bureau of Ocean Energy Management (BOEM). The overall goal of this partnership is to quantify offshore air pollution over the sparsely monitored Gulf of Mexico (GOM), where oil and natural gas (ONG) exploration and production are abundant and their impacts on coastal air quality are largely unknown. This article describes the first phase of NASA's partnership with BOEM, representing a multiyear Interagency Agreement (IAA); then it shifts toward a new five-year IAA to advance the work from Phase 1, collecting more sea cruise and potentially new aircraft measurements, and leveraging geostationary data from the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument, an air-quality satellite instrument planned for launch in 2023 (Phase 2).[1] A recent cruise completed during Phase 1, the Satellite Coastal and Oceanic Atmospheric Pollution Experiment, or SCOAPE, is the focus of this article.

*The overall goal of this partnership [between NASA and the Bureau of Ocean Energy Management] is to quantify offshore air pollution over the sparsely monitored Gulf of Mexico (GOM), where oil and natural gas (ONG) exploration and production are abundant and their impacts on coastal air quality are largely unknown.*

**BOEM's Coastal Air Quality Mandate and Partnership with NASA**

The Federal government requires that BOEM monitor air quality impacts from ONG exploration and development in the Outer Continental Shelf (OCS) of the U.S. Specifically, under the Outer Continental Shelf Lands Act (OCSLA),[2] BOEM must ensure that ONG activities do not affect the air quality (AQ) of any state. For example, ONG emissions and transport of nitrogen oxides ($NO_x$)—which are ozone ($O_3$) pollution precursors—toward populated coastal areas produce ozone pollution and can exacerbate or cause a violation of the Environmental Protection Agency's (EPA) National Ambient Air Quality Standard (NAAQS).[3]

One of BOEM's primary regions of interest is the portion of the OCS in GOM waters west of 87° 30' W longitude, where there is a highly developed and dense network of ONG platforms and related exploration and drilling activities. As part of their OCSLA mandate, BOEM assembles inventories of ONG emissions of $NO_x$ [which in this context includes nitric oxide (NO) and nitrogen dioxide ($NO_2$)], the combustion product that is often the major precursor for the formation of ozone pollution, formaldehyde (HCHO), sulfur dioxide ($SO_2$), carbon monoxide (CO), and volatile organic compounds (VOCs). **Figure 1** shows total $NO_x$ emissions for the year 2017 from all platforms in this area, including both shallow gas and deepwater oil platforms, according to BOEM's Emissions Inventory over GOM, which is derived from industry reporting and calculated emissions factors. A key limitation to BOEM's monitoring effort is that no routine *in situ* measurements of AQ exist over GOM, so

[1] For background information on TEMPO see "NASA Ups the TEMPO on Air Quality Monitoring," in the March–April 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 2**, pp. 10–15—*go.nasa.gov/2WGStuX*].
[2] Learn more about this act at *www.boem.gov/oil-gas-energy/leasing/ocs-lands-act-history*.
[3] For a convenient summary of the NAAQS visit *www.epa.gov/criteria-air-pollutants/naaqs-table*.

BOEM uses industry emissions reports and chemical modeling to assess the ONG AQ impact on coastal regions. This limitation motivated the formulation of a three-year IAA (2017–2019) between BOEM and NASA to test the feasibility of using remotely sensed satellite data to monitor air quality over GOM. The NASA/BOEM Phase 1 IAA culminated in the SCOAPE satellite validation air-quality cruise in May 2019, described below.

*Satellite, ground-based, and airborne instruments for remote sensing of $NO_2$ have been employed for decades—but not at the fine scale needed to measure emissions in the target area.*

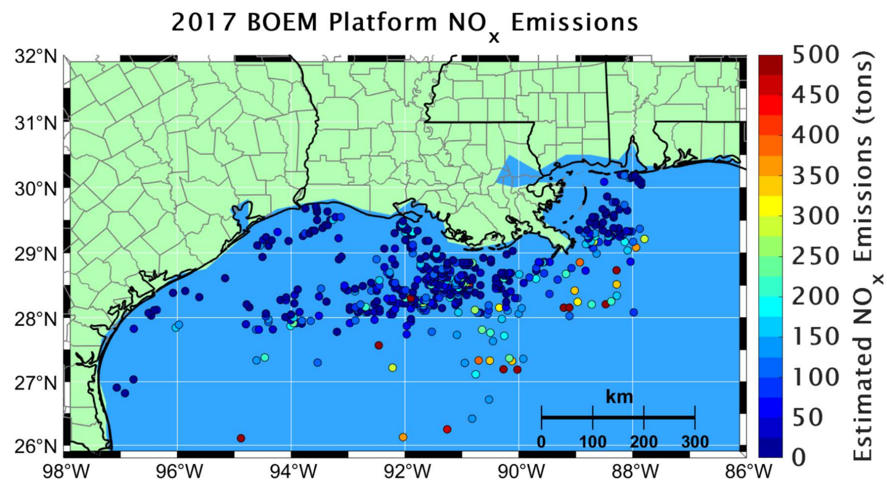


**Figure 1**. The 2017 platform estimated $NO_x$ emissions from U.S. Department of the Interior's Bureau of Ocean Energy Management (BOEM) Gulf of Mexico Emissions Inventory. A total of 457 platforms are shown, with the dots indicating the 2017 total $NO_x$ emissions amount in tons. The individual lower-emitting, shallow-water platforms (darker colors) far outnumber the large, higher-emitting deepwater platforms (lighter colors). **Image credit:** Ryan Stauffer

The Phase 1 scientific results and accomplishments were detailed in several BOEM Technical Reports[4], and a recently submitted journal article to the *Earth and Space Science Open Archive* (ESSOAR).[5] Highlights of the Phase 1 research are presented below, followed by a summary of initial plans for the new, five-year NASA/BOEM Phase 2 IAA.

**Accomplishments from Phase 1**

BOEM chose to focus on $NO_2$ measurements because they serve as a proxy for $NO_x$. In GOM, combustion $NO_2$ originates from both near-shore and outer-shelf ONG platform operations, servicing helicopters and ships for drilling, off-shore port transfers, fishing, and commerce. Satellite, ground-based, and airborne instruments for remote sensing of $NO_2$ have been employed for decades—but not at the fine scale needed to measure emissions in the target area. Furthermore, coastal and oceanic retrievals of $NO_2$ from ultraviolet–visible (UV-Vis)-class satellite sensors are challenging because of varying surface reflectance due to water conditions (e.g., silt and chlorophyll content) especially near coastal regions, and a lack of ground-based validation data. Thus, NASA's research activities for BOEM addressed both technological and scientific issues.

The BOEM study addressed a number of technological questions that are described below, along with the approach taken to answer them.

- *Can satellite measurements be used to detect ONG emissions?*
  To answer this, investigators used measurements of column $NO_2$ data from

[4] The two reports most relevant to this article are: *NASA Resources to Monitor Offshore and Coastal Air Quality* (Bryan Duncan, 2020) which can be found at *espis.boem.gov/final%20 reports/BOEM_2020-046.pdf* and *Evaluation of NASA's Remote Sensing Capabilities in Coastal Environments,* (Anne Thompson, 2020), which can be found at *espis.boem.gov/final%20reports/ BOEM_2020-047.pdf.*

[5] This article can be viewed at *www.essoar.org/doi/10.1002/essoar.10511687.1.*

the Ozone Monitoring Instrument (OMI) on NASA's Aura platform and the European Space Agency's (ESA) TROPOspheric Monitoring Instrument (TROPOMI) on the Copernicus Sentinel-5 Precursor satellite. They also examined other satellite observations related to pollution over GOM, e.g., CO from the Atmospheric Infrared Sounder (AIRS), which flies on NASA's Aqua platform, Aerosol Optical Depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua platforms, and sensing of anthropogenic light and thermal sources with the Visible Infrared Imaging Radiometer Suite's (VIIRS) Day–Night Band (DNB) on NASA's Suomi National Polar-orbiting Partnership (NPP) platform and the NOAA-20 platform.

- *How can satellite and AQ forecasts be used to plan and execute ground- and ship-based sampling over GOM?*
  Investigators used near-real-time (NRT) satellite imagery and assimilation forecasts to design an exploratory, ship-based experiment over GOM and employed these tools to optimize sampling while underway.

- *How accurate are the satellite $NO_2$ measurements?*
  Investigators compared total column $NO_2$ (TC $NO_2$) amounts from OMI and TROPOMI to surface-instrument-based TC $NO_2$ readings over land and GOM. They also evaluated measurements from three Sun-tracking Pandora spectrometer instruments collocated along the Louisiana coast to determine the accuracy of the Pandora instrument prior to deploying one of them on an air-quality cruise for satellite validation.

  The Pandora instrument has been developed by NASA and industry partners over the past 15 years. It uses *differential optical absorption spectroscopy*—i.e., comparing a theoretical solar spectrum with the observed atmospheric spectrum: Differences are due to trace gas concentrations. A collection of Pandora instruments comprises the *Pandonia Global Network* (PGN), with dozens of instruments operating worldwide.

The approaches used to address these basic but all-important questions are discussed below.

***OMI and TROPOMI Satellite $NO_2$ Data Products***

At the start of the study, the best-characterized satellite measurements of coastal TC $NO_2$ over the U.S. were from NASA's Ozone Water-Land Environmental Transition Study (OWLETS) campaigns conducted in the U.S. mid-Atlantic seaboard. Satellite measurements from both OMI and TROPOMI had never been validated before over GOM, where cloud interferences in the UV-Vis satellite retrievals are common. As a result, it took a while for TROPOMI to produce maps displaying clear GOM pollution signals from ONG.

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The locations of two $NO_2$ hotspots observed on January 6, 2019, are shown in **Figure 2** on page 8. The TROPOMI tropospheric $NO_2$ column from a single clear day in January 2019—Figure 2, *left*—reveals two areas of higher $NO_2$ concentration [0.1 Dobson Units (DU) on this scale]. These correspond to the locations of two large, deepwater platform pairs in GOM.

The thermal DNB image from Suomi-NPP VIIRS—see Figure 2**,** *right*—shows that the Mars and/or Olympus platform was/were flaring on January 6, 2019, and was the more likely source of the $NO_2$ "hot spot" than the Brutus/Genesis or A-Allegheny platforms. A detailed trajectory analysis, in which a plume originating within the Mars/Olympus pixels traveled to Brutus, where elevated $NO_2$ was also observed, confirmed this hypothesis. This result provided our first indication that satellite $NO_2$ could be used to monitor GOM air quality near ONG operations.

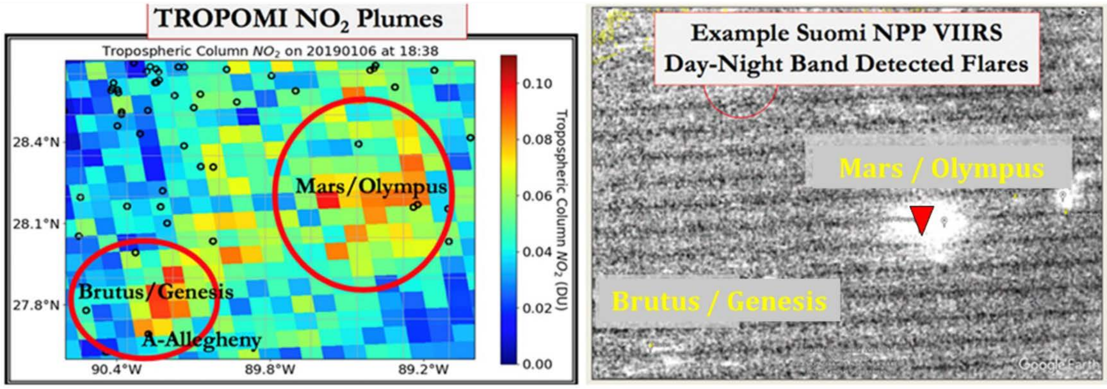


**Figure 2.** TROPOspheric Monitoring Instrument (TROPOMI) tropospheric $NO_2$ observations [in Dobson Units (DU)] from January 6, 2019 [*left*]—before the Satellite Coastal and Oceanic Atmospheric Pollution Experiment (SCOAPE) cruise. Small black circles are overlaid to indicate the locations of the 200 highest $NO_x$-emitting platform operations according to BOEM's 2014 inventory (the version prior to the 2017 inventory). The larger black circles highlight areas of enhanced tropospheric $NO_2$ values, which center on the labeled platforms mentioned in the article. A Visible–Infrared Imaging Radiometer Suite (VIIRS) image from the Suomi-NPP satellite on January 6, 2019 [*right*], helps to decipher the source of the emissions on this day. White regions are elevated thermal anomalies in the thermal infrared. Flares are detected in the Day–Night Band, denoted here by the marker near the Mars/Olympus complex. **Image credit:** Debra Kollonige

### *Satellite and AQ Modeling Tools for Planning a GOM Experiment*

The location of GOM ONG platforms—see **Figure 3** below—was the primary criterion for planning an experiment that would compare satellite and surface $NO_2$ observations along the eastern Louisiana coast and adjacent OCS and collect other trace gas and ancillary data in GOM. However, investigators also used dynamical and radiative data to help them decide when and where to sample. Such sampling is frequently limited or prevented by routine cloud cover over the Louisiana coast, particularly in the latter part of the May–September time frame.

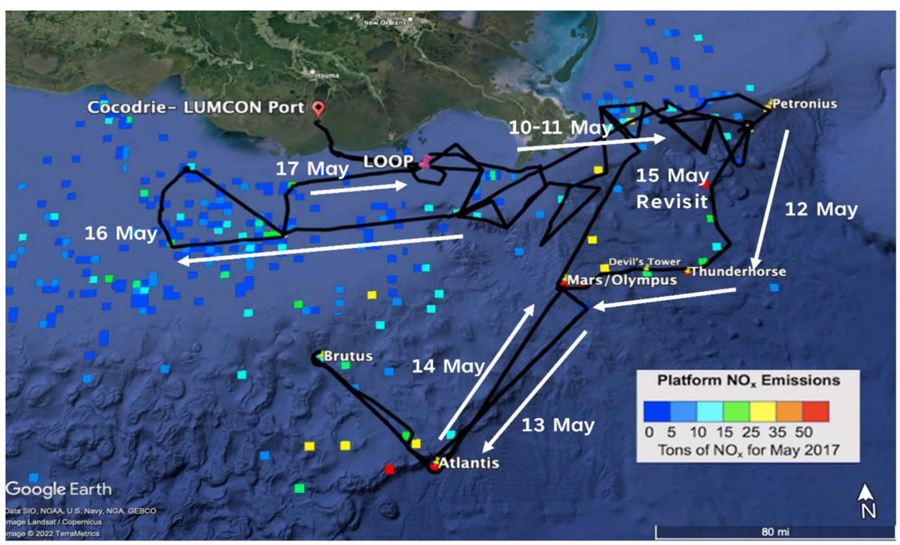


**Figure 3**. BOEM's May 2017 platform emissions inventory estimates (squares) and the SCOAPE cruise track (black lines). Areas of interest (highlighted in text), include the Louisiana Offshore Oil Port (LOOP) and major oil and natural gas platforms, identified by their platform's name. The arrows indicate the direction of sailing through regions that were sampled more than once. The higher emitters are the darker squares. **Image credit:** Debra Kollonige

SCOAPE investigators examined climatological winds using NASA's Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) meteorological reanalysis and cloud cover. The results showed that May would be the best time for an experiment to explore GOM air quality and satellite capabilities with BOEM by way of the SCOAPE campaign, as clouds tend to increase significantly in June and July, which would degrade the quality of satellite $NO_2$ retrievals.

SCOAPE would consist primarily of shipboard measurements of trace gases and relevant meteorological parameters. Because of its convenient access to GOM and our study region of interest, the Louisiana Universities Marine Consortium (LUMCON) in Cocodrie, LA, was selected as the base of operations and port for the research vessel that embarked on the cruise, which lasted from May 10–18, 2019.

Determining course changes during the anticipated cruise would require access to NRT satellite imagery for cloud cover and pollutant-related constituents. Air quality forecasts from GSFC's Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System Composition Forecast (GEOS-CF) products were consulted daily, along with standard meteorological fields (e.g., winds, temperature, cloud cover) from the GEOS Forward Processing (GEOS-FP) products. A list of data products and analytical and visualization tools that helped with mission planning (e.g., weather and air quality conditions and forecasts) appears in **Table 1**.

**Table 1.** Satellite data products, and meteorological and air quality model products used for long-term and near-real-time (NRT) SCOAPE experimental planning.

| Product | Source | Relevant URL(s) |
|---|---|---|
| TROPOMI Tropospheric Column $NO_2$ (NRT and offline) | ESA/Copernicus | *scihub.copernicus.eu* [Open Access Data]<br>*www.tropomi.eu/data-products/nitrogen-dioxide* |
| OMI Tropospheric Column $NO_2$ (during cruise) | GSFC Code 614 | None* |
| OMI Tropospheric Column $NO_2$ (V3 and V4) | GES DISC | *go.nasa.gov/3Q29BUN* |
| VIIRS (Suomi NPP) and MODIS (Aqua/Terra) Flaring and Thermal Anomalies; Aerosol Optical Depth; Cloud Cover | NASA Worldview | *worldview.earthdata.nasa.gov* |
| GEOS Forward Processing (FP) Products: Atmospheric composition maps (e.g. Biomass Burning tracer) | FLUID for SCOAPE Mission (GMAO) | *go.nasa.gov/3zDVNZU*<br>*go.nasa.gov/3JwKRld* |
| GEOS Forward Processing (FP) Products: Weather datagrams and 2D maps | FLUID for SCOAPE Mission (GMAO) | *go.nasa.gov/3P4tvNv*<br>*go.nasa.gov/3Q3Mppe* |
| GEOS Composition Forecast (CF): trace gas datagrams and 2D maps | FLUID for SCOAPE Mission (GMAO) | *go.nasa.gov/3zDVNZU*<br>*go.nasa.gov/3cZmS1H* |

*This was an internal product generated specifically for the SCOAPE Team during the campaign.

**Note on Acronyms:** All but two undefined acronyms in this Table are defined in the article text. The exceptions are *GES DISC*, which stands for Goodard Earth Sciences Data and Info Services Center; and *FLUID*, which is the name of an interactive Python-based framework developed within GMAO for viewing visualizations.

### *Validating Satellite $NO_2$ Columns with the Pandora Spectrometer Instrument*

*An important part of the Phase 1 study was to evaluate satellite $NO_2$ measurements. For this purpose, Tropospheric Column $NO_2$ observations from the ground—collected with the Pandora spectrometer—were compared to corresponding measurements from OMI and TROPOMI.*

An important part of the Phase 1 study was to evaluate satellite $NO_2$ measurements. For this purpose, Total Column (TC) $NO_2$ observations from the ground—collected with the Pandora spectrometer—were compared to corresponding measurements from OMI and TROPOMI. Three new-model Pandoras, numbered P66, P67, and P68, were available for SCOAPE. The instruments were deployed on the roof of the LUMCON building—see **Figure 4**—along with a surface *in situ* $NO_2$ analyzer, and intercompared during a four-week precruise phase of the experiment.


**Figure 4**. [*Left*] The three Pandora spectrometers during the calibration and intercomparison period on the roof of the Louisiana Universities Marine Consortium (LUMCON) building from April 10–May 8, 2019. [*Right*] On May 9 Pandora 66 was moved to the bow of the *R/V Point Sur* to collect measurements from the ship during the SCOAPE cruise. **Photo credits:** Ryan Stauffer

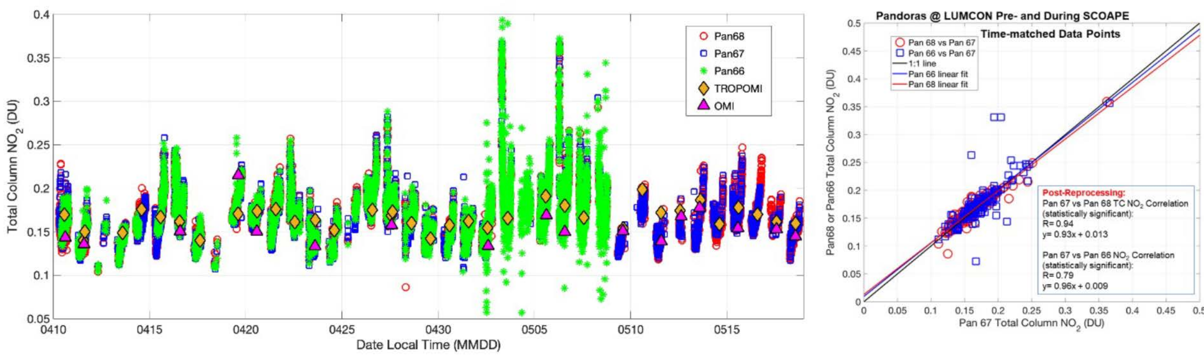


**Figure 5**. [*Left*] TC $NO_2$ (five-minute averages in DU) as measured by Pandoras 66, 67, and 68 prior to the SCOAPE cruise from April 10–May 8, 2019, with coincident TROPOMI TC $NO_2$ readings in yellow diamonds, and Ozone Monitoring Instrument (OMI) v4 TC $NO_2$ in red triangles. After the Pandora 66 was installed on the *R/V Point Sur,* only Pandoras 67 and 68 recorded TC $NO_2$ at LUMCON. [*Right*] Time-matched data from Pandora 66 (blue squares) and 68 (red circles) referenced to Pandora 67 at LUMCON from April 10–May 8, 2019. Linear best-fit lines are blue and red, respectively, with the 1:1 black line shown for reference. **Image credit:** Debra Kollonige

The TC $NO_2$ measurements from the three Pandoras installed on the LUMCON roof, along with coincident OMI and TROPOMI data are found in **Figure 5**. Both the precruise and cruise-period comparisons in April and May 2019 are shown as a time series of all available data. The satellite and Pandora TC $NO_2$ data generally agree well (~2–15% differences) with the largest offsets (spikes on time series graph in Figure 5, *left*) occurring under cloudy conditions. The line graph in Figure 5 illustrates the reproducibility of the three Pandora instruments, with Pandoras 66 and 68 compared to Pandora 67. Agreement in terms of slope and offset of the best-fit lines, as shown in the lower-right box in Figure 5**,** is excellent. The correlation coefficient (R), is lower for Pandora 66 because, as the square symbols show, the latter instrument is slightly noisier than the other two.

*The satellite and Pandora TC $NO_2$ data generally agree well (~2–15% differences) with the largest offsets occurring under cloudy conditions.*

### *SCOAPE Cruise*

There were two reasons for NASA and BOEM to design the SCOAPE oceanographic cruise. First, was to use the shipboard Pandora TC $NO_2$, customized for a moving platform, to evaluate coincident OMI and TROPOMI satellite $NO_2$ columns over the GOM. Second, because there had been almost no prior AQ measurements over the central GOM, exploratory measurements of standard pollutants [e.g., ozone ($O_3$), surface $NO_2$, CO, VOC] were collected, along with TC $NO_2$ from the Pandora. Other measurements were also made on the ship. The complete list of shipboard and coastal instrumentation deployed in SCOAPE is shown in **Table 2** and **Table 3**. Already provided in Figure 3 is the cruise track of the *Research Vessel (R/V) Point Sur* that sampled from May 10, 2019, (0000 hrs, Central Daylight Time; CDT), through the afternoon of May 18, 2019, leaving and returning from the LUMCON port in Cocodrie. Two of the three Pandoras that operated at Cocodrie before the cruise continued to sample during the cruise (Figure 5) along with the surface *in situ* $NO_2$ analyzer. Periodically, $NO_2$ sonde data were also collected along the coast from a mobile vehicular platform. Shipboard meteorological information (e.g., temperature, humidity, wind speed, and direction) was recorded by *Point Sur*-owned instruments. Balloon-borne ozonesondes and radiosondes were launched from the ship on 8 of the 9 days (there were a total of 13 launches). Boundary layer properties were supplied by the balloon soundings and ceilometers at Cocodrie and on the *Point Sur*.

**Table 2.** Offshore instrumentation on the *R/V Point Sur* during the SCOAPE cruise.

| Measurement | Instrument | Collaborator(s) [Affiliation] |
|---|---|---|
| $NO_2$ (and calibration system) | Teledyne API T500U | **Anne Thompson** [GSFC] |
| Column $NO_2$ | Pandora Spectrometer | **Robert Swap** [GSFC] |
| $O_3$ | Balloon-borne Ozonesondes and Thermo 49i (surface) | **Anne Thompson** [GSFC] |
| Temperature, Pressure, Relative Humidity, Winds | Vaisala all-in one meteorological sensor | Sensors on *R/V Point Sur* |
| Aerosol Optical Depth and $O_3$ column amounts | MicroTops II Sunphotometer | **Anne Thompson** [GSFC] |
| VOCs (plus CO and $CH_4$) | Air canister grab samples | **Donald Blake** [University of California Irvine (UCI)] |
| Planetary Boundary Layer (PBL) Height and Aerosol Content | Lufft CHM 8k Ceilometer | **Ruben Delgado** [University of Maryland Baltimore County (UMBC)] |
| Black Carbon Concentration | Magee Scientific RTA10 Aethalometer | **Joseph Conny** [National Institute of Standards and Technology (NIST)] |
| $CH_4$, $CO_2$, $H_2O$ | Picarro G-1301m | **Stephan Kawa** and **Thomas Hanisco** [both at GSFC] |

**Note on Acronyms**: All undefined acronyms in this Table are defined in the article text.

Table 3. Onshore instrumentation during the SCOAPE cruise.

| Measurement | Instrument | Collaborator(s) [Affiliation] |
|---|---|---|
| $NO_2$ | Teledyne API T500U | **John Sullivan** [GSFC] |
| $NO_2$ | $NO_2$ sonde (mobile and *in situ*) | **Deborah Stein-Zweers** and **Mirjam den Hoed** [both at KNMI] * |
| Column $NO_2$ | Pandora Spectrometer | **Robert Swap** [GSFC] |
| VOCs (plus CO and $CH_4$) | Air canister grab samples | **Donald Blake** [UCI] |
| PBL Height and Aerosol Content | Vaisala CL31 Ceilometer | **James Flynn** [University of Houston] |

**Note on Acronyms:** All but one undefined acronym in this Table are defined in the article text. The exception is *KNMI*, which stands for Koninklijk Nederlands Meteorologisch Instituut (KNMI), or in English, the Royal Netherlands Meteorological Institute.

The scientific questions addressed by the cruise and a summary statement of the approaches taken to obtain answers are as follows:

- *What do pollution gradients at the air–sea interface look like? How are they affected by differences in onshore and offshore winds?* SCOAPE investigators examined satellite imagery and surface observations of TC $NO_2$ data under different meteorological conditions encountered during the cruise. Measurements of other chemical constituents that originate from distinct sources (tracers) were used to fingerprint land vs. GOM and anthropogenic vs. natural sources.

- *Stipulating Pandora TC $NO_2$ as a proxy for upcoming geostationary satellite observations (e.g., TEMPO), can the latter be expected to detect short-term var*iations in emissions associated with ONG activity? Pandora and *in situ* $NO_2$ time series were examined in relation to platform locations.

- *Are there differences between $NO_2$ and other trace-gas emissions from ONG activities originating from large, isolated deepwater operations and the small, densely spaced platforms closer to shore?* SCOAPE investigators compared continuous shipboard methane ($CH_4$) readings near the two types of operations and studied tracer-tracer relationships using VOC data collected from flask samples near various sources.

These questions, their answers, and how they were obtained are described below.

***Land-Gulf Gradients and Two Meteorological Regimes***

The satellite images in **Figure 6** show that there is more TC $NO_2$ over land and the near-shore GOM than over the deepwater region of GOM as a whole. The images in the top row of Figure 6, for May 13, 2019, show that the highest TC $NO_2$ values, greater than 0.18 DU, are found over New Orleans and Baton Rouge—the latter an urban region with a large petrochemical industry. Moderately elevated TC $NO_2$ levels in both images appear in pixels throughout the land and near-shore area.

*...there is more TC $NO_2$ over land and the near-shore GOM than over the deepwater region of GOM as a whole.*

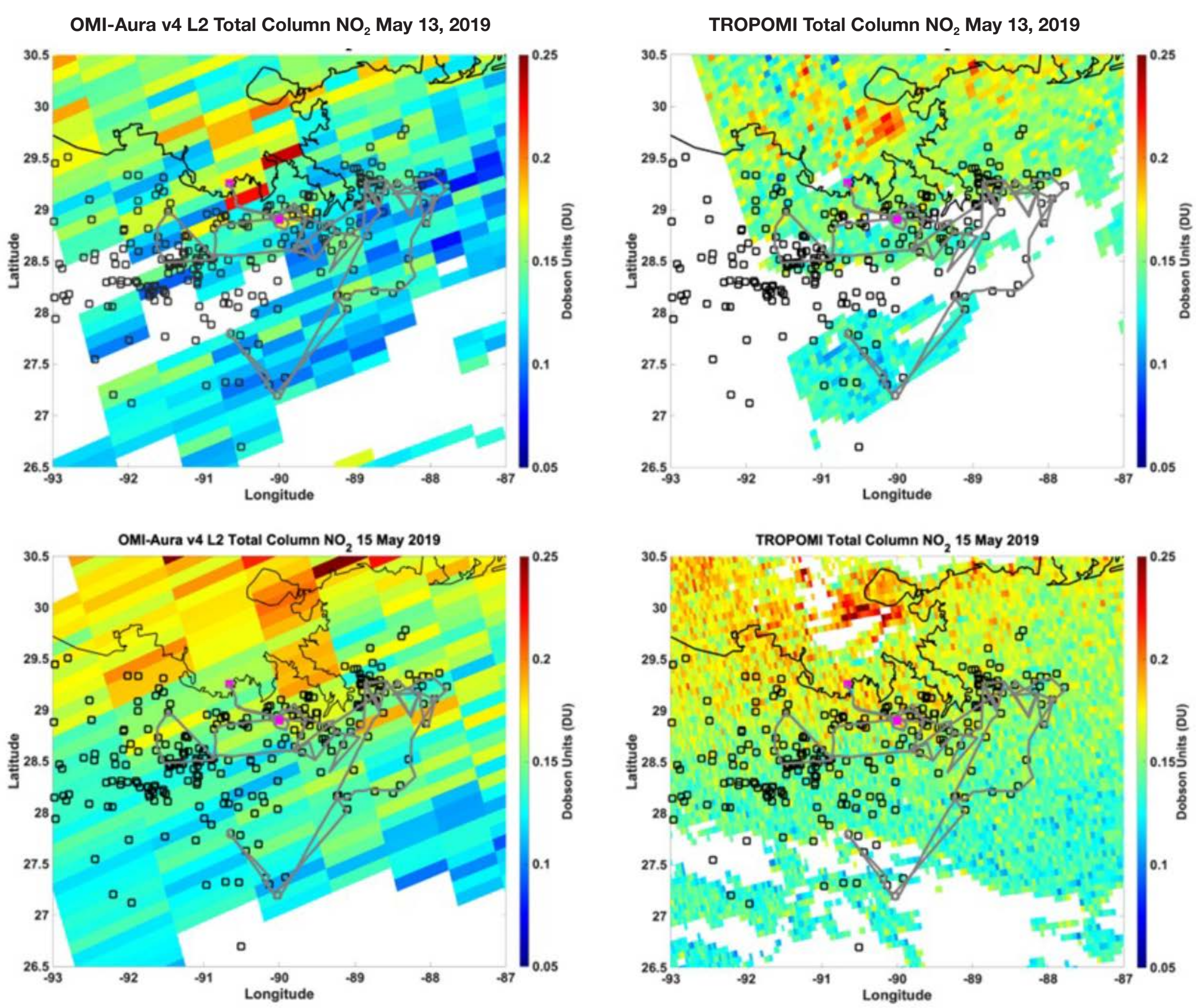


**Figure 6**. Total column $NO_2$ (in DU) over the SCOAPE region on May 13 [*top row*] and May 15, 2019 [*bottom row*] for OMI and TROPOMI observations, respectively. Black open squares are the locations of the top 200 $NO_x$-emitting platforms from BOEM's 2014 inventory. The gray solid line shows the *R/V Point Sur* cruise track. **Image credit:** Debra Kollonige

It is difficult to say whether the moderate pollution at the near-shore locations is from offshore ONG activity or represents remnants in air parcels that originated over land. The maps for May 15, 2019 (bottom row of Figure 6), show a different picture. The TC $NO_2$ over the urban region has increased to more than 0.25 DU, and a fairly uniform distribution of TC $NO_2$ values ranging from 0.15–0.18 DU appears over the rest of the land, stretching south to ~28.5° N latitude. The differences between the May 13 and May 15 TC $NO_2$ distributions are due to a shift in winds from onshore to offshore as a front passed through. Indeed, the SCOAPE study was characterized by two distinct meteorological regimes: primarily onshore flow, or *marine* air mass, and offshore flow, or *continental* air mass, which led to differences in the chemical conditions encountered.

*The SCOAPE study was characterized by two distinct meteorological regimes: primarily onshore flow, or marine air mass, and offshore flow, or continental air mass, which led to differences in the chemical conditions encountered.*

The *in situ* measurements collected on the *R/V Point Sur* during SCOAPE clearly illustrate the effects of the midcruise wind shift and change in air-quality regimes. Beginning May 13 (see Figure 3 for cruise track) there were abrupt changes to wind direction and surface ozone, with much higher (twofold) surface ozone pollution corresponding to offshore winds (i.e., from the continent). The VOC air canister samples collected during the cruise also reflect these changes.

Measurements of $CH_4$ and CO were typically much lower when winds transported air from clean marine sources in the first half of the cruise. When winds blew from continental sources in the second half of the cruise, $CO_2$ amounts dropped below the marine background levels encountered during the first half. This is a result of the early growing season in the Southern U.S., which depletes $CO_2$ through vegetation photosynthesis. Dimethyl sulfide (DMS),[6] which was also measured in the VOC canisters and has primarily marine sources, drops when the winds shift from onshore (marine source region) to offshore (continental source region).

### *Satellite and Pandora Views of TC $NO_2$ Variability*

Assuming that the Pandora instrument is a proxy for the viewing capabilities of a geostationary satellite that will focus on North American $NO_2$ emissions, the remotely sensed $NO_2$ column measurements will be able to detect temporal and regional variability as illustrated in **Figure 7**. The Pandora data from the *Point Sur,* as mapped in the left panel of Figure 7, are consistent with the contrasts observed in the near-shore and open GOM satellite $NO_2$ results of Figure 6. This result shows the potential for satellites to track emissions from individual or appropriately spaced clusters of ONG platforms in a way that can be compared to BOEM's emissions inventories.

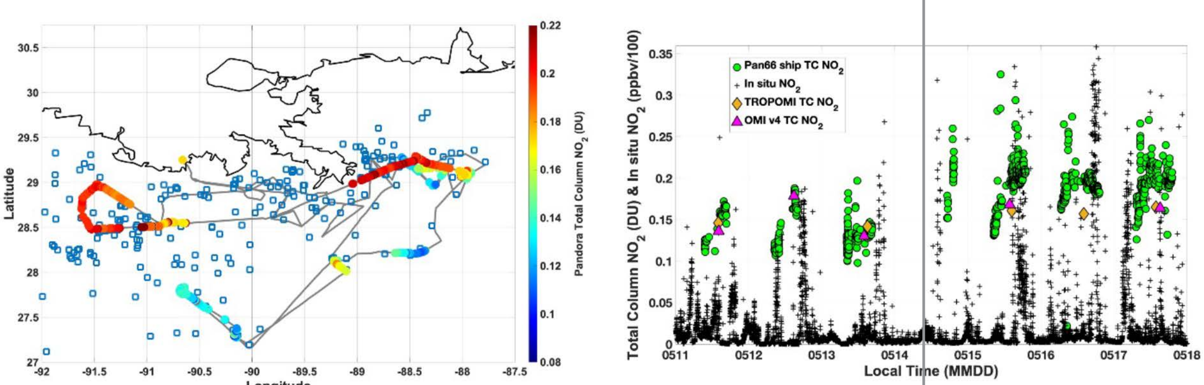


**Figure 7**. SCOAPE investigators sampled cleaner air prior to May 14, 2019, and more polluted air masses after May 14, as verified by cruise and satellite measurements. The plot [*left*] shows Pandora TC $NO_2$ (dots) measured along the SCOAPE cruise ship track (gray lines) from May 10–18, 2019. The open squares mark the locations of the top 200 $NO_x$-emitting platforms according to the 2014 BOEM emissions inventory. The graph [*right*] shows time series of TROPOMI, OMI, and Pandora TC $NO_2$ and *in situ* $NO_2$ during the SCOAPE cruise. Pandora TC $NO_2$ measurements and *in situ* data are five-minute averages. **Image credit:** Debra Kollonige

[6] Dimethyl sulfide (DMS) is a naturally occurring algal metabolite that is the main source of biogenic sulfur aerosol.

However, the right panel of Figure 7 illustrates certain limitations of both the operational satellite measurements and Pandora's observing capabilities over GOM. The satellite observations (diamonds and triangles in the right panel) and Pandora TC $NO_2$ readings (circles) are in very good agreement from May 11–14, 2019, when the air sampled was from relatively unpolluted marine sources. By contrast, after the wind shift to offshore, the TC $NO_2$ amounts measured by the Pandora increased an average of 40–50%, whereas both OMI and TROPOMI satellite TC $NO_2$ measurements increased only ~15%. It is expected, however, that $NO_2$ columns from a geostationary instrument optimized for tropospheric $NO_2$ detection, will be more sensitive to pollution than the current satellites. As described starting on page 15, this focus is part of the plan for Phase 2 of this investigation, taking advantage of the measurements that are expected to be available from TEMPO beginning in 2023.

Overall differences in column $NO_2$ between the marine and continental air were captured well by the Pandora, but the short-term variations in plumes encountered by the *Point Sur* near sources were frequently missed. Displayed in Figure 7 is the relative insensitivity of the remotely sensed data (Pandora and satellite) to observations of elevated *in situ* surface $NO_2$ [at ship height, 10 m (~33 ft) above sea level] while passing nearby platforms. Variable mixing layer heights of trace gases (e.g., shallow boundary layer heights and diurnal changes) are known to complicate TC $NO_2$ observed by both Pandora and satellite—especially over water.

*The NASA/BOEM Phase 1 study marked several milestones in addressing important questions about measuring $NO_2$ emissions in a key coastal environment.*

***Emissions Contrasts Between Near-Shore and Deepwater ONG Platforms***

BOEM's emissions inventory indicates that the large, deepwater ONG platforms are the strongest emitters of $NO_2$. However, the dense network of smaller, shallow water platforms, which generally extract natural gas, far outnumber the deepwater platforms. The shallow-water infrastructure is generally older than the deepwater operations, and is subject to leakage of gas products. As the *Point Sur* sailed to within a few hundred meters of these shallow water platforms, nearly every one of them produced a detectable spike in surface $CH_4$ measurements. Similar spikes in $CH_4$ were not detected near the deepwater ONG platforms.

The most extreme case of this was on May 16, 2019, when $CH_4$ rapidly increased to approximately eight times the typical values encountered during SCOAPE. A VOC canister sample, collected at the exact time the $CH_4$ spike was measured, also indicated increases in natural gas products, including ethane, propane—and even benzene (a carcinogen)—by an order of magnitude or more compared to all other canister samples that were collected. The lack of increase in $CO_2$ or $NO_2$ during the $CH_4$ spike indicated that the source was leaking infrastructure, rather than a combustion process, e.g., from a diesel engine or other power-generating source.

***Summary of SCOAPE and Phase 1 Findings***

The NASA/BOEM Phase 1 study marked several milestones in addressing important questions about measuring $NO_2$ emissions in a key coastal environment. First, applications of a variety of NASA satellite products were presented to BOEM during the two years leading up to SCOAPE. Second, the measurements obtained during SCOAPE answered in the affirmative BOEM's question about the feasibility of using satellite data to monitor ONG activity over GOM. The measurements showed that TC $NO_2$ data from OMI and TROPOMI are sufficient to create maps that can be compared to BOEM's emissions inventories throughout GOM and over time. Third, from NASA's viewpoint, SCOAPE was the first experiment to establish the reliability and precision of a new generation of Pandora spectrometers. Finally, comparisons of OMI and TROPOMI TC $NO_2$ with data from Pandoras confirmed previous studies at the land–water interface that suggest limitations in satellite $NO_2$ retrievals under varying meteorological conditions in coastal regions.

**A New Agreement to Continue Satellite Pollution Monitoring Over GOM**

The success of the NASA/BOEM Project Phase 1 and SCOAPE cruise motivated a renewal of the collaboration between the two agencies with a new five-year IAA beginning in mid-2022. The Phase 2 project will be a continuation of the Phase 1 effort, with several key additions that will provide BOEM with a wealth of new data and information for GOM air-pollution monitoring.

***Geostationary Data from the TEMPO Instrument***

Sometime in early 2023, a new satellite air quality instrument, called the Tropospheric Emissions: Monitoring of Pollution (TEMPO; *tempo.si.edu/index.html*), will be launched into geostationary orbit. This high vantage point allows for the satellite to constantly monitor the same area—a crucial distinction from the polar-orbiting satellite instruments OMI and TROPOMI that generally provide only one midday measurement at a location per day. With its sensors permanently fixed on North America, TEMPO will provide *hourly* measurements of pollutants such as $NO_2$, $O_3$, and HCHO during the daytime. TEMPO is the first of its kind for North America, with its measurement domain spanning from most of Mexico to Southern Canada—covering all of the SCOAPE and GOM region. The spatial resolution of the measurements is expected to be slightly better than TROPOMI, yielding unprecedented diurnal information on air quality.

*The success of the NASA/BOEM Project Phase 1 and SCOAPE cruise motivated a renewal of the collaboration between the two agencies with a new five-year IAA beginning in mid-2022.*

A similar instrument, the Geostationary Environment Monitoring Spectrometer (GEMS) was launched in February 2020, and is currently in orbit above the Korean Peninsula. Sentinel-4, scheduled for launch in the 2023 timeframe, is to be stationed above Europe and will complete a virtual AQ constellation of three geostationary air-quality sensors focused on heavily populated continents, mostly in the Northern Hemisphere. This constellation is depicted in the News story on page 34 of this issue.

***Empowering BOEM to Monitor the Gulf of Mexico***

TEMPO will produce an order of magnitude more data for BOEM to monitor oil and gas emissions and air quality over GOM. A primary goal of Phase 2 will be to provide BOEM with information on how satellite $NO_2$ products over GOM vary temporally and regionally, and how such variability is related to oil and gas production. TEMPO data will be invaluable for comparisons with BOEM's emissions inventory. Given a history of well-characterized satellite $NO_2$ data, one approach for initial analysis is shown in **Figure 8** on page 16. It displays OMI tropospheric $NO_2$ for the month of May averaged for all years from 2005–2021 (May was chosen because the SCOAPE cruise occurred in May 2019). The top 150 $NO_x$ emitters in BOEM's 2017 emissions inventory are indicated by the white dots on the GOM map. The time series of all May-averaged OMI tropospheric column $NO_2$ is shown on the bottom panel, which represents the area bound by the box on the top panel, covering many of the top $NO_x$-emitting platforms.

Using data from OMI, TROPOMI, and eventually TEMPO, NASA, and BOEM will explore methods to detect any appreciable $NO_2$ signals or changing $NO_2$ concentrations near GOM's ONG platforms. Because $NO_2$ amounts over the water are much lower than over land (note the color scale and land/water contrast on Figure 8), finding a signal or relationships among satellite $NO_2$ and BOEM's emissions inventory will require long averaging periods. The hourly data from TEMPO should provide the best opportunity to quantify the emissions from ONG platforms over GOM, which will aid BOEM in validating their future inventories.

feature article

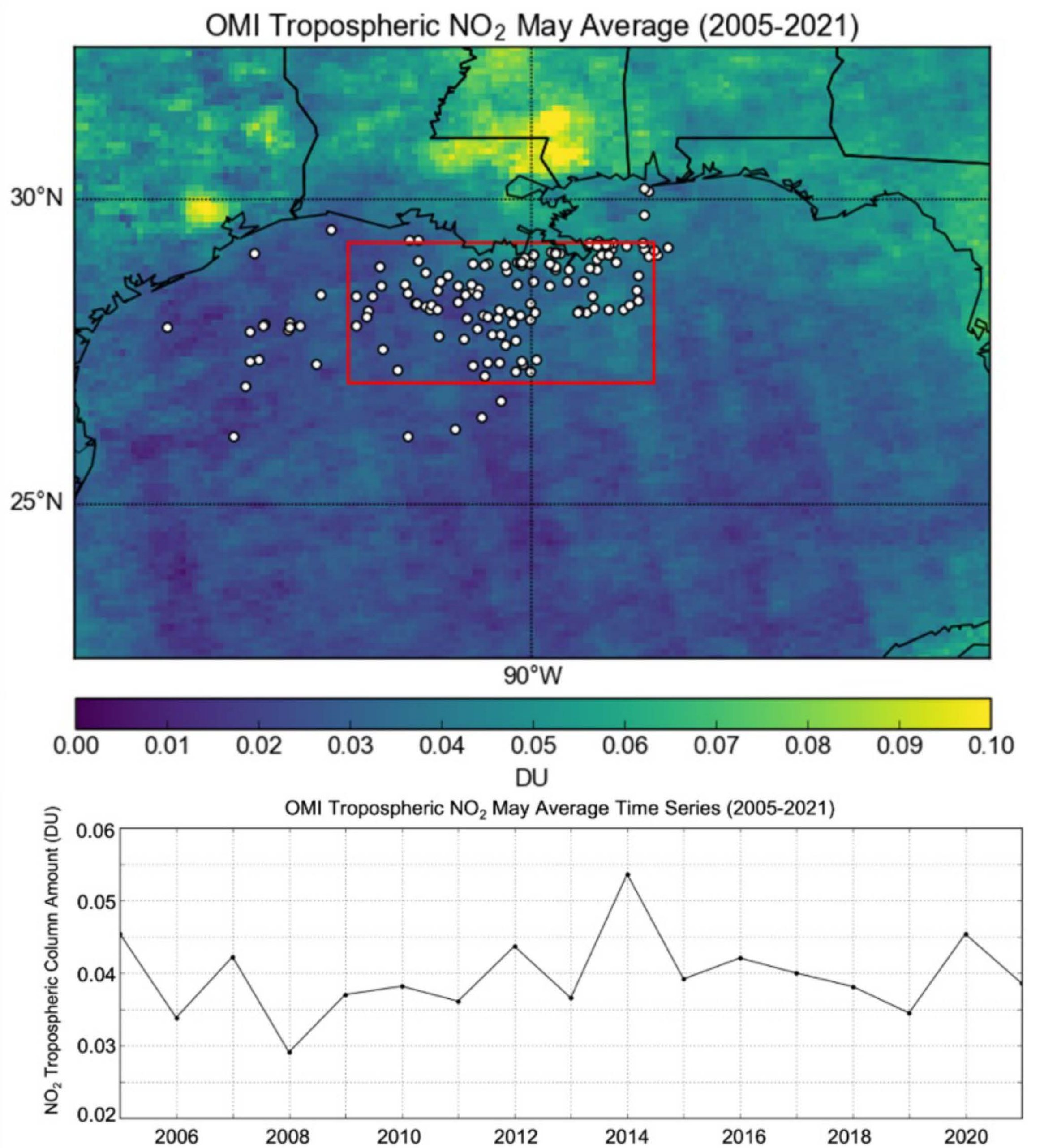


**Figure 8**. [*Top*] OMI tropospheric column $NO_2$ averaged for the month of May for all years from 2005–2021 (in DU). The white dots represent the top 150 $NO_x$ emitters in BOEM's 2017 emissions inven-tory. The red box is the area considered for average values shown in the time series on the bottom panel. [*Bottom*] The time series of May average OMI tropospheric $NO_2$ for each year from 2005–2021. **Image credit:** Niko Fedkin

***TEMPO Validation: SCOAPE-II and Potential Aircraft Measurement Coordination***

Because TEMPO will be a new satellite instrument that BOEM will use to assist its air quality monitoring over GOM, validating the TEMPO measurements will be essential. Therefore, Phase 2 also includes plans for a GOM revisit in a SCOAPE-II cruise in spring 2023 or 2024. Similar to SCOAPE, a research vessel will be outfitted with surface *in situ* air quality instrumentation, an aerosol backscatter ceilometer, and Pandora spectrometers (both coastal and ship based).

The SCOAPE-II cruise measurements are being coordinated to potentially coincide with NASA aircraft measurements from the GEOstationary Coastal and Air Pollution Events (GEO-CAPE) Airborne Simulator [GCAS] onboard NASA's Gulfstream-V. The GCAS measures below-aircraft column amounts of $NO_2$ and HCHO, measurements similar to those provided by OMI, TROPOMI, and—eventually—TEMPO. Given BOEM's new focus on greenhouse gas emissions in their jurisdiction, the aircraft measurements during SCOAPE-II may include remotely-sensed $CH_4$ and $CO_2$ measurements at an accuracy and spatial resolution much better than any operational satellite instrument. The planned coordination of ship-based *in situ* and Pandora measurements, aircraft measurements of $NO_2$ and greenhouse gases, and satellite measurements will give NASA and BOEM an unprecedented view of GOM air quality and the emissions produced by ONG operations.

**Conclusion**

The unique satellite and field data collected during Phase 1 and those planned for Phase 2 of the NASA–BOEM partnership will yield numerous scientific and technical benefits. The 2019 SCOAPE cruise results confirmed that continental sources of air pollution typically outweigh those from ONG operations over GOM, with background pollution amounts highly dependent on wind direction, i.e., more polluted when originating from continental sources. SCOAPE investigators validated OMI and TROPOMI satellite $NO_2$ measurements with Pandora instruments in a complex coastal region and over the open GOM for the first time, an exciting finding that clearly demonstrates that satellite measurements are sufficiently accurate to monitor GOM air quality and pinpoint $NO_2$ sources under good viewing conditions. They also tested the capabilities of three newer Pandora spectrometers by siting them side by side on the coast for a four-week, precruise period, finding that the agreement among the three instruments was excellent. Further, the Sun-tracking and measurement performance of the ship-based Pandora during the cruise was also a success.

*SCOAPE investigators validated OMI and TROPOMI satellite $NO_2$ measurements with Pandora instruments in a complex coastal region and over the open GOM for the first time, an exciting finding that clearly demonstrates that satellite measurements are sufficiently accurate to monitor GOM air quality and pinpoint $NO_2$ sources under good viewing conditions.*

The measurements and lessons learned from Phase 1 will serve as a guide for Phase 2 of the project, which will incorporate new and exciting measurement platforms and satellite data. Adding in geostationary measurements from the TEMPO instrument will be a game changer by providing hourly views of GOM air quality—as opposed to the approximately once-per-day measurements from OMI and TROPOMI. A second SCOAPE cruise, which potentially will be coordinated with NASA aircraft measurements, will both validate the new TEMPO measurements and provide BOEM with additional data and capabilities to inform the Bureau's air quality monitoring strategy and development of emissions inventories.

**Acknowledgments**

The two lead authors express their appreciation to **Captain Nicholas Allen, First Mate Jeffery Ellington** and the entire crew of the *R/V Point Sur* LUMCON for their extraordinary support and hospitality; and **Natasha Daçic** [GSFC/SSAI] and **Virgilio Maisonet-Montañez** [BOEM] for on-board measurement assistance. The authors are also grateful for the support and expertise of the GSFC Pandora group and, in particular, to **Nader Abuhassan,** for Pandora 66 operation during the SCOAPE cruise. NRT satellite data transmittal was from **Debra Kollonige** and **Alex Kaltenbaugh** [both from GSFC] and **Lok Lamsal** [GSFC/UMBC]. This study was partially funded by BOEM through Interagency Agreement M17PG00026 with **Bryan Duncan** [GSFC—*Principal Investigator*]. NASA's Earth Sciences Application Health and Air Quality Science Team supplied additional funding. ■

# Winnie Humberson Retires and Receives NASA Distinguished Public Service Medal

*Alan Ward, NASA's Goddard Space Flight Center/Global Science & Technology, Inc., alan.b.ward@nasa.gov*
*Jarrett Cohen, NASA's Goddard Space Flight Center/Global Science & Technology, Inc., jarrett.s.cohen@nasa.gov*

After a nearly 40-year career working as a NASA contractor—including the past decade leading NASA's Science Support Office (SSO)—**Winnie Humberson** retired on June 30, 2022. Under Winnie's leadership the 14-person SSO team (organizationally within the Earth Observing System Project Science Office) has had success upon success in organizing NASA science outreach activities at domestic and international scientific conferences and public events, such as the American Geophysical Union (AGU) Fall Meeting, NASA Earth Day (at Union Station in Washington, DC), and the United Nations Climate Change Conference of the Parties (COP). Winnie was a tireless advocate for her team and the agency. Her energy and passion were contagious to all who worked with her.

NASA and Global Science & Technology (GST) management hosted a farewell party for Winnie at NASA's Goddard Space Flight Center (GSFC) on June 30, at which her family (see **Photo 1**), friends, and colleagues (see **Photo 2**) celebrated her long and distinguished career. The celebration was held in the lobby of Building 33 where the NASA Hyperwall is prominently featured. This was only fitting, since Winnie's SSO team played a pivotal role in turning the nine-screen videowall into the centerpiece of many NASA conference exhibits, attracting thousands of people to the exhibit to be educated and inspired while watching NASA's high-resolution science data visualizations.

**Photo 2**. Members of NASA's Science Support Office with Winnie. [*Back row, left to right*] **Kevin Miller**, **Debbi McLean**, **Steve Graham**, **Doug Bennett**, **Mark Malanoski**, and **Kevin Durham**. [*Front row, left to right*] **Amy Moran**, **Heather Hanson**, **Winnie Humberson** (the Guest of Honor), and **Cindy Trapp**. [*Not pictured*] **Ryan Barker**, **Marit Jentoft–Nilsen**, **Nathan Marder**, and **Alan Ward. Photo credit:** NASA

**Photo 1**. **Winnie Humberson** [*middle*] with her son **Karl** and daughter **Brenda**. **Photo credit**: NASA

At the celebration, **Steve Graham** [NASA/GST—*SSO Manager*] and **Heather Hanson** [NASA/GST—*SSO Deputy Manager*] gave opening remarks, followed by NASA Headquarters leadership presentations from **Jack Kaye** [NASA HQ—*Associate Director for Research, Earth Science Division*], **Kristen Erickson** [NASA HQ—*Director, Science Engagement and Partnerships Division, Science Mission Directorate (SMD)*], and **Thomas Zurbuchen** [NASA HQ—*Associate Administrator, SMD*], who gave his remarks remotely via the Hyperwall (see **Photo 3**). Zurbuchen presented Winnie with the *NASA Distinguished Public Service Medal,* signed by **NASA Administrator Sen. Bill Nelson**. The citation recognizes her "…*decades of outstanding service in sharing the Nation's science in innovative ways at scientific conferences and public events in the U.S. and around the world"* (see **Photo 4).**


**Photo 3. Winnie Humberson** [*middle*], with her medal and citation proudly on display, with NASA management. [*Left to right*]: **Steve Platnick**, **Kristen Erickson**, **Jack Kaye**, and **Thomas Zurbuchen** (virtually presented via the NASA Hyperwall). **Photo credit**: NASA


**Photo 4**. Winnie's *Distinguished Public Service Medal* plaque, which **Thomas Zurbuchen** presented during her retirement celebration. **Photo credit**: NASA

Speaking on behalf of GSFC, **Dalia Kirschbaum** [GSFC—*Director, Earth Sciences Division (ESD)*] and **Steve Platnick** [GSFC—*Deputy Director for Atmospheres, ESD*] both gave remarks. Kirschbaum presented Winnie with a plaque that will be installed next to the Building 33 Hyperwall, honoring Winnie for her many years of sharing science with a broad community.

In recognition of the impact Winnie has had—not just within NASA, but in the larger science outreach community—both **Michèle Jacobs** [Union Station—*Former Managing Director for Special Events*] and **Tracy LaMondue** [American Geophysical Union (AGU)—*Vice President for Development*] reflected on their experiences working with Winnie over the years while planning Earth Day events and NASA exhibits at AGU meetings.

**Larry Roelofs** [*Former GST Vice President*] spoke on behalf of Winnie's most recent employer—GST. He shared his fond recollections of working with Winnie in various roles over more than three decades at GSFC.

Last, but certainly not least, the guest of honor thanked everyone in attendance and extended her deep gratitude for having had the opportunity to work with a talented team and for receiving the NASA Distinguished Public Service Medal.

The staff of *The Earth Observer* and the SSO team offer their congratulations and best wishes for a wonderful retirement. You've certainly earned it, Winnie!

***Editor's Corner coninued from page 3***

I'm saddened to report that **Shelby Tilford**, a tremendously influential figure in the early history of the Earth Observing System (EOS), passed away recently, at age 85. An *In Memoriam* for Shelby on page 4 of this issue provides more details on his extraordinary career and accomplishments. I extend my condolences to Shelby's family and friends.

After more than 40 years working with NASA as a contractor, **Winnie Humberson** retired from Global Sciences & Technology, Inc (GST) on June 30. Over the past several decades, Winnie played an active and prominent role in the success of many NASA Science Mission Directorate and Earth Science Division exhibit activities (most recently as lead for the Science Support Office, or SSO), in addition to agency-wide exhibits. Winnie's legacy also includes a host of EOS Project Science Office activities that she led and/or managed. She generously devoted her time, energy, and passion to her work. Turn to page 18 of this issue to read about a NASA/GST-hosted event held on June 30 at which Winnie received the NASA Distinguished Public Service Medal. On a personal note, it was a pleasure to know Winnie and to work closely with her over many years; she will be sorely missed. My congratulations to Winnie on her retirement and the best of wishes as she embarks on the next chapter of her life.

Winnie has left the SSO Task in good hands, with **Steve Graham** and **Heather Hanson** [both at NASA/GST] becoming Task Manager and Deputy Task Manager, respectively. I congratulate Steve and Heather on their new leadership roles and look forward to continued interaction with them and the other members of the SSO Team.

***List of Undefined Acronyms Used in the Editorial and/or Table of Contents***

| | |
|---|---|
| ASPRS | American Society for Photogrammetry and Remote Sensing |
| CLARREO | Climate Absolute Radiance and Reflectivity Observatory |
| GEDI | Global Ecosystems Dynamic Investigation |
| GLOBE | Global Learning and Observations to Benefit the Environment |
| InVEST | In-Space Validation of Earth Science Technology |
| OMI | Ozone Monitoring Instrument |
| SCOAPE | Satellite Coastal and Oceanic Atmospheric Pollution Experiment |
| SORCE | Solar Radiation and Climate Experiment |
| TSIS-1 | Total and Spectral Solar Irradiance Sensor–1 |
| TROPOMI | TROPOspheric Monitoring Instrument |

# Summary of the GEDI Science Team Meeting

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## Introduction

The Global Ecosystem Dynamics Investigation (GEDI) Science Team (ST) meeting was held May 17–18, 2022, at the University of Maryland, College Park (UMD). Due to the ongoing global pandemic, virtual and in-person, masked options were offered, resulting in a successful hybrid meeting with over 80 participants from around the globe—some of whom are shown in the **Photo** below. The GEDI ST is a collaborative body comprised of the mission science team and the competed science team. While these groups often work independently, this meeting provided a venue for all GEDI-related researchers to receive updates and discuss research collaborations.

The main objectives of this meeting were to discuss mission status, data products, competed science team projects, and data calibration, validation, distribution, and applications. Given that the GEDI instrument is set to be de-orbited in January 2023, the meeting heavily emphasized the prioritization of activities within the next seven months. More information on the GEDI mission, including recent news articles, is available at *gedi.umd.edu*.[1]

[1] For an overview of the GEDI mission, use of LiDAR technology, and associated data products, see "Summary of the Second GEDI Science Team Meeting" in the November–December 2016 issue of *The Earth Observer* [**Volume 26**, **Issue 2**, pp. 31–36—*go.nasa.gov/3diph88*].

## DAY ONE

The first day of the meeting began with an overview of GEDI mission operations and instrument status, followed by science presentations from ST members to showcase the variety of ways GEDI data is being used or improved. Breakout sessions followed, giving participants a collaborative space to discuss biomass- and plant-cover-related topics.

### GEDI Mission Operations and Instrument Status

**Ralph Dubayah** [UMD—*GEDI Principal Investigator (PI)*] opened the meeting with an overview of the mission status. GEDI, which is situated on the Japanese Experiment Module-Exposed Facility (JEM-EF) on the International Space Station (ISS), officially reached three years of data collection as of April 2022. Version 2 data products have been released, with 33 months of Level-1 (L1), L2A and L2B, L3, and L4A data available, and 28 months of L4B data available. GEDI ST members are continuing to assess data quality, improve Aboveground Biomass Density (AGBD) models, estimate uncertainty, and fill coverage gaps. Dubayah also emphasized strong international support for extending GEDI's lifespan, highlighting articles on the instrument's impending removal from the ISS in *The Guardian* and *Eos* (a science news magazine published by the American Geophysical Union), as well as letters of support from the European Space Agency's (ESA) BIOMASS mission and NASA–Indian Space Research Organisation (ISRO) Synthetic

**Photo**. Participants of the second day of the hybrid GEDI Science Team meeting. **Photo credit**: Tali Schwelling/UMD

Aperture Radar [NISAR] mission. The NBC Network has also published a piece on GEDI featuring supporters of the mission, including **Rebecca Shaw** [World Wildlife Fund—*Chief Scientist*].

Following the mission status update, participants heard a detailed report on mission operations, instrument status, data processing, and data-level-specific updates from members of the mission science team. **Tony Scaffardi** [NASA's Goddard Space Flight Center (GSFC)—*GEDI Mission Director*] began with a Science and Mission Operations Center (SMOC) Overview, reporting that GEDI has persevered through altitude shifts, visiting vehicles, and power outages on the ISS. **Bryan Blair** [GSFC—*GEDI Deputy PI* and *Instrument Scientist*] relayed that all systems are performing at essentially the same level they were at the start of the mission 3.5 years ago, with no major changes to the power or precision of the three lasers on the instrument.

**Scott Luthcke** [GSFC] kicked off the data processing discussion and provided an update on the Science Operations Center (SOC). The SOC oversees mission operations and data processing in addition to assisting with the selection of Reference Ground Tracks (RGTs) that GEDI targets to optimize operations and sampling. While the mission is exceeding its RGT-targeting pointing control requirements, a change in the ISS altitude has shifted GEDI out of its desired randomly precessing orbit—which allows for varied orbit tracks that cover more ground—into a four-day repeat cycle orbit, which results in oversaturation of data in some areas and undersaturation in others. This has led to additional RGT sampling being required and large gaps in coverage that limit the ability of GEDI to meet its Level-1 Science Requirements. The ISS controllers agreed to change its orbit in January 2022, which should enable GEDI to observe areas for which no data currently exist. Regardless, the SOC is currently working on Version 3 data products for release in 2023 in addition to a new advanced L3 topography product.

L2A and L2B data products are continuously improving due to the work of **Michelle Hofton** [UMD], **John Armston** [UMD], and other collaborators. The team is performing six different algorithm-setting runs on each *GEDI waveform*[2] to account for the wide range of conditions that GEDI sees during each orbit. Crossovers (paired footprints) of GEDI and NASA's Land, Vegetation, and Ice Sensor (LVIS) are being used for calibration and validation efforts, with almost 700,000 high-quality footprints collected so far. GEDI-to-Airborne Laser Scanning (ALS) and GEDI-to-GEDI crossovers are also being analyzed to help assess and improve data quality and algorithm selection for L2A and L2B products. The GEDI L2B Version 2 product—which estimates biophysical metrics including canopy cover fraction (CCF), plant area index (PAI), and foliage height diversity (FHD)—has been released and provisional gridded estimates of mean canopy cover and uncertainty have been made available to the ST. The forthcoming Version 3 product will include estimates of the canopy-to-ground reflectance ratio, increased ability for quality filtering over dense forests, and flagging of shots impacted by atmosphere (e.g., fog, low clouds).

### Science Presentations

Following presentations on the status of the mission and its data products, some ST members shared the ways in which they are applying GEDI data to their projects. **Ovidiu Csillik** [NASA/Jet Propulsion Laboratory (JPL)] shared an overview of his group's work on pantropical forest structure and the factors that impact model accuracy using ALS. **Allie Shenkin** [Northern Arizona University] is investigating variables that impact maximum tree height globally, including wind, topography, and aridity. Future work by Shenkin and his colleagues will incorporate GEDI sampling in Google Earth Engine (GEE), new soil layers, and ongoing studies looking at biomass and carbon fluxes in tropical forests. **Qiuyan Yu** [New Mexico State University] and her group are working to understand a similar and relevant concept: global drivers of canopy height and biomass in water-limited environments. Yu and her colleagues have hypothesized that climate and phylogeny may determine canopy height on the macroscale and used GEDI L2A products to assess maximum canopy heights in relation to water availability. In an excellent example of cooperation, the Yu and Shenkin project teams have been communicating about how to complement each other's projects.

GEDI data can be used to investigate a wide array of topics besides forest-structure metrics. **Patrick Burns** [Northern Arizona University] demonstrated the use of GEDI L2 and L3 products—with analysis using satellite image data combined with machine learning, camera traps, and simulated species analysis—to create spatially continuous GEDI habitat structure maps. This project demonstrates the potential for GEDI data fusion with multispectral imagery as it incorporates images from the European Space Agency's Copernicus Sentinel-1 and -2 missions, and from NASA–U.S. Geological Survey Landsat missions within the GEE platform. Machine-learning algorithms are also being used by **Jim Kellner** [Brown University], who presented on his work to further develop and improve

[2] The GEDI instrument includes three identical laser transmitters that create five beams. Each beam illuminates a 25-m footprint on the Earth's surface, which results in a waveform that contains information about the vegetation canopy and the topography underneath. The waveform represents return energy from topography, the ground, and the forest canopy. The GEDI waveforms are described in more detail in the article referenced in Footnote 1.

L4A and GEDI waveform models. As GEDI accumulates more data, there are many opportunities to fill gaps and optimize the AGBD models, including understanding how to directly use waveforms to estimate aboveground biomass. The current multistep approach consists of translating waveform data (return energy of laser beams, as described in footnote 2) to canopy height and then translating canopy height to aboveground biomass measurements. **Wenge Ni-Meister** [Hunter College] is working to develop general allometric relationship models between AGBD and waveforms to avoid error when using a multistep approach to estimate biomass (i.e., comparing waveform to height and height to AGBD).

### Breakout Sessions

The first day of breakout sessions provided time for participants to share ideas about biomass models, forest cover, and waveform processing.

**Laura Duncanson** [UMD] led the biomass breakout session, which focused on improving existing models by expanding or limiting the geographical scope of certain variables (e.g., plant functional types), adjusting models to address different ecosystem types (e.g., mangroves), and reducing bias. Assessing where GEDI is performing well, as in Mediterranean forests, can be used to identify next steps in improving areas where GEDI is under-performing.

**Hao Tang** [National University of Singapore (NUS)] led a session on plant cover, plant area index (PAI), and waveform processing. He discussed how steep slopes, urban areas, and seasonality are all factors that can introduce uncertainty or bias.

## DAY TWO

The second day of the meeting provided participants with in-depth updates on data products and data calibration and validation efforts. Six more ST members presented on their ongoing work and future plans, followed by two breakout sessions on Google Earth Engine and an upcoming field campaign in SE Asia. Representatives from the Land Processes (LP) and Oak Ridge National Laboratory (ORNL) Distributed Active Archive Centers (DAACs) and the Open Altimetry online platform closed out the meeting.

### Data Products and Validation

**Jim Kellner** provided a thorough update on the L4A footprint biomass data product and algorithm performance. Planned updates to the product included increasing the amount of field data available to build the GEDI models, improving geolocation issues with existing datasets, updating the GEDI waveform simulator, refining prediction strata, and evaluating new predictor variables. Training data from over 8000 waveforms from 21 countries are currently being used. End users can expect regular updates to L4A Version 2 and an L4A Version 3 release to the DAAC in 2023.

**Sean Healey** [U.S. Forest Service] reported that GEDI is on track to achieving its L1 science requirements, and while more observations are collected, the estimated data precision will increase and uncertainty will decrease. The L4B product is projected to make approximately 40 million statistical estimates of aboveground biomass in 1-km (~0.6-mi) gridded cells. The highly anticipated and now-released Version 2 GEDI L4B gridded biomass product builds on this progress and is available through the ORNL DAAC and Google Earth Engine. With features by NASA Earthdata[3] and GSFC[4] along with excitement from online user communities, L4B provides the first estimates of global aboveground forest biomass density (AGBD)—see **Figure 1**. In addition, based on a paper in review (with Ralph Dubayah as lead author) which compares GEDI estimates of biomass to the Forest Inventory Analysis (FIA) estimates, GEDI is performing with high levels of

[3] Learn more at *go.nasa.gov/3dd5uqx*.
[4] Learn more at *go.nasa.gov/3A3DqyE*.

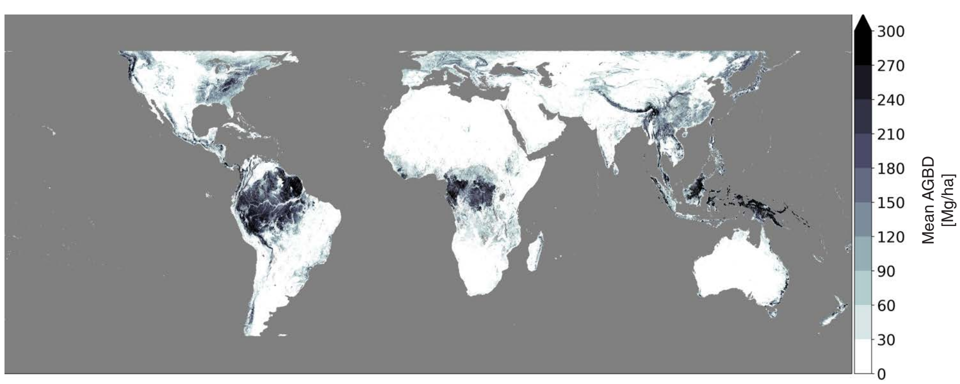


**Figure 1**. This preliminary map shows mean aboveground biomass density (AGBD) for 1 km (~0.6 mi) cells derived from 25-m (~82-ft) GEDI footprint estimates, visualized here at 6 km (~3.7 mi) resolution, using GEDI data collected between April 2019 and March 2022. This map was presented at the GEDI Science Team Meeting in May 2022 and is an update to the public release version of the Level 4B product, which used GEDI data collected between April 2019 and August 2021. **Credit**: John Armston/UMD

precision and collecting large amounts of biomass data that could be underreported by FIA.

Calibration and validation efforts of GEDI data are ongoing. **John Armston** reported on updates to the GEDI Forest Structure and Biomass Database (FSBD) since the last Science Team Meeting (November 2021), highlighting new datasets from Europe, North America, and Australia, and a greater than 50% increase in the amount of colocated GEDI–ALS crossovers. Key priorities for the next six to seven months include validating the GEDI simulator for Level-2B metrics, filling geographic gaps using LVIS data from the GEDI airborne campaigns in 2021, and improving quality assurance and quality control (QA/QC) for the GEDI FSBD. The next calibration and validation campaign will prioritize Southern Asia, where there is a paucity of high-quality colocated field and ALS data available for assessing L2 product performance and calibrating L4A biomass models.

**Science Presentations**

Using ALS data for calibration and validation is a crucial component of the GEDI mission. **Andrew Finley** [Michigan State University] and collaborators have been working to identify, characterize, and correct GEDI geolocation error, which can especially impact canopy metrics in heterogeneous forest structure. **Laura Duncanson** discussed collaborative efforts between the GEDI/UMD team and colleagues at other academic institutions and non-government organizations (NGOs) to investigate the relationship of Global Protected Areas (GPAs) to preserving forest structure, biomass, and forest conservation. The ST also heard from **Shaoqing Liu** and **Liling Chang** [both at Harvard University] about their work regarding carbon dynamics and carbon and water fluxes in Southeast Asian tropical forests and the California Sierra Nevada, respectively. **Keith Krause** [Battelle] presented an overview of a project using LVIS and National Ecological Observatory Network (NEON) data to evaluate how GEDI can be used to scale ecosystem structure and structural variability over broader spatial ranges. **Hao Tang** closed out the applied science session with a presentation on work being done to identify and mitigate the impact of geolocation error on footprint-level products and work to provide the SOC with feedback. The Version 2 data release begins to address this error, as there are already far fewer impacts from geolocation compared to Version 1.

**Breakout Sessions**

Day two of the meeting also had two breakout sessions: one on the use of GEE assets and the second on the Southeast Asia LVIS calibration and validation campaign.

**Sean Healey** led the GEE breakout session, during which he noted that only one algorithm is available on GEE—but that this will be updated soon.

**John Armston** led the Southeast Asia LVIS breakout session, which focused on identifying ground target locations for the flight campaign, targeting use of a terrestrial laser scanner (TLS) instrument in the field, and sampling areas where there is existing ALS data. This field and airborne campaign will be executed in 2023.

**DAAC and Other Perspectives**

Users can access GEDI datasets through the Oak Ridge National Laboratory (ORNL) DAAC (*daac.ornl.gov/gedi*) and the Land Processes (LP) DAAC (*lpdaac.usgs.gov*). GEDI L3 and L4 datasets can be accessed through the ORNL DAAC, which serves to provide data services for a comprehensive archive in support of NASA's Earth Science activities. **Rupesh Shrestha** [ORNL DAAC] reported that all L3 and L4 Version 2 datasets have been published, with L4A Version 2.1 released as well. The ORNL DAAC also offers a variety of data tools and services for L3, L4A, and L4B products, such as NASA Earthdata Search interface, NASA Worldview, and tools developed to process data from the Moderate Resolution Imaging Spectroradiometer (MODIS).[5] Learning resources can be found at *github.com/ornldaac/gedi_tutorials* (e.g., tutorials, Jupyter notebooks,[6] and scripts). Shrestha also shared GEDI data usage metrics as of April 2022: GEDI L3 products have been downloaded 41,745 times by almost 5000 unique users, L4A has been downloaded 932,293 times by almost 2000 unique users, and L4B, which was only just released this April, has already been downloaded almost 2000 times by just under 500 unique users. User support can be found on the Earthdata forum, Github, and the ORNL DAAC's User Services Office (USO).

The LP DAAC, which has a user base of about 70,000, has 718 terabytes (TB) of GEDI data in its archive as of April 2022. **Tom Maiersperger** [LP DAAC] shared that 2.2 petabytes (PB) of data have been distributed to date, making GEDI data extremely prominent in the user community. Cumulative GEDI use continues to increase considerably—about three- or fourfold between December 2020 and April 2022. The LP DAAC is looking forward to releasing Version 3 products on a new cloud interface called the NASA Earthdata Cloud.[7] Migration from a traditional on-premises archive to a cloud-based environment will help address growing demands for new science and maintain free and open data access.

**Siri Jodha Khalsa** [University of Colorado] gave the last presentation of the meeting on OpenAltimetry

[5] A MODIS instrument flies on NASA's Terra and Aqua platforms.

[6] The Jupyter Notebook is a web-based, interactive computing platform.

[7] Read more about the migration of NASA's Earth Observing System Data and Information System (EOSDIS) data into the Earthdata Cloud at *go.nasa.gov/3JzhY81* and *go.nasa.gov/3P89F4f*.

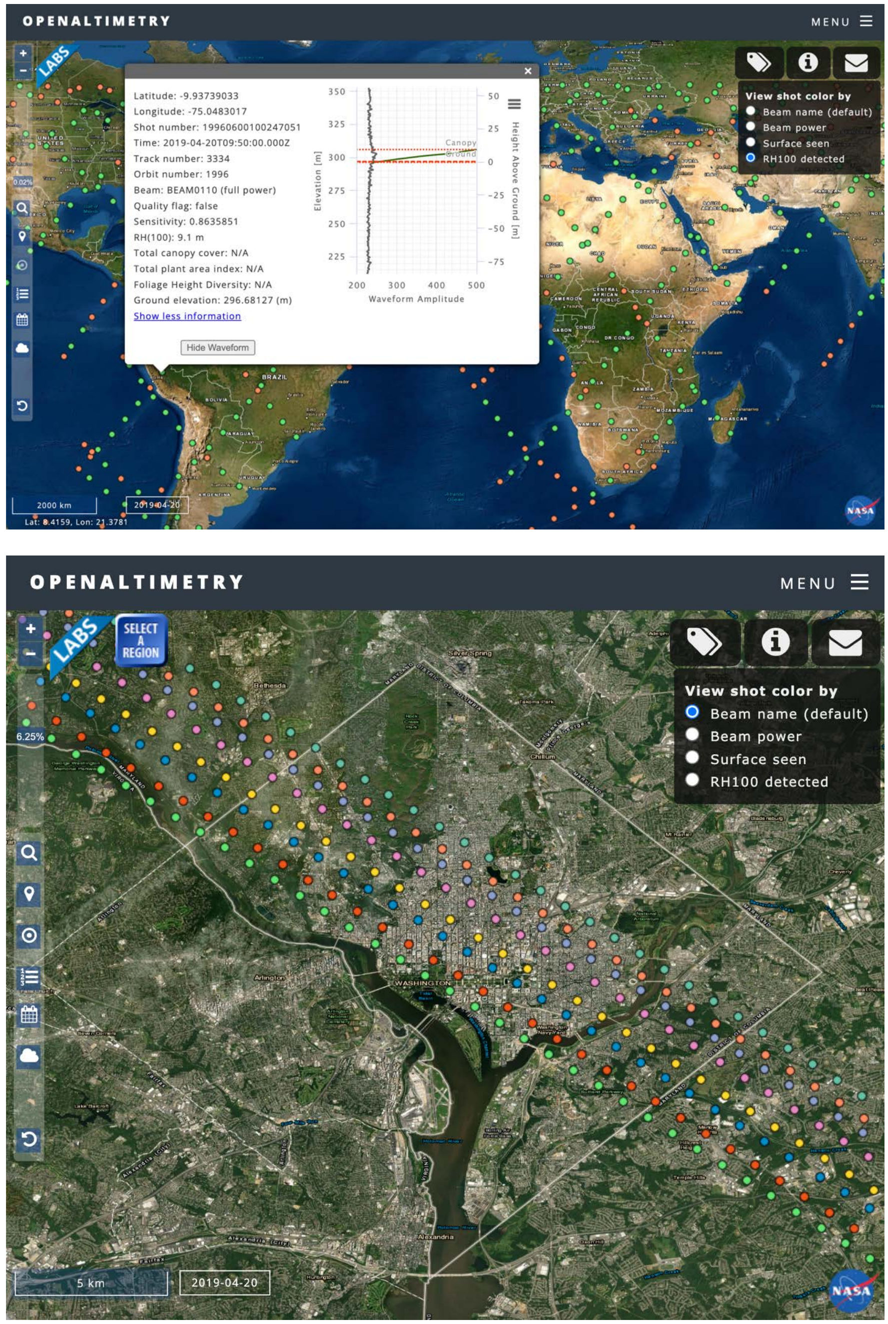


**Figure 2**. GEDI ground tracks and a GEDI footprint in Peru with its associated waveform from April 20, 2019 [*top*] and ground tracks over Washington, D.C. from April 20, 2019 [*bottom*] viewed on the OpenAltimetry platform. **Image credit**: Tali Schwelling/UMD

(OA), an online platform that supports data services and visualization related to the Ice, Clouds, and land Elevation Satellite (ICESat) and ICESat-2 missions (*openaltimetry.org/data/gedi*). To highlight the capabilities of the OA platform for a broader audience, the programmers incorporated ten days of GEDI data into the platform. Khalsa demonstrated some of the features, which include sorting by beam name, beam power, if Earth's surface is seen, or when canopy relative height (RH100)[8] metrics are detected. Users can also search by location, view by date, and overlay MODIS imagery on the map—see **Figure 2**.

[8] RH100 is the hundredth percentile of waveform energy relative to ground elevation of the canopy.

## Conclusion

The GEDI ST meeting concluded with a summary of the sessions and emphasis on accelerating calibration and validation efforts as the instrument's planned removal from the ISS looms. Activities to be prioritized for ST members over the coming months include publishing results, highlighting the importance of GEDI in many domains, and developing and supporting applications for end users—including other missions, e.g., the upcoming NISAR and BIOMASS missions. The next GEDI ST meeting is scheduled for November 2022. ■

# Summary of the 2021 CLARREO Pathfinder Science Workshop

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## Introduction

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder [CPF] team organized a two-day virtual science workshop on November 2–3, 2021. The elevated number of COVID-19 cases at the time of the meeting necessitated the exclusively virtual format. Nevertheless, over 70 attendees (some of which are shown in the **Photo** below) participated in the workshop between the two days. There were two main purposes for this informal workshop: to educate those external to the CPF Team about the mission, payload capabilities, and science objectives; and to engage the science community on their interest in using CPF measurements to support their research and intercalibration/validation activities. To encourage discussion among participants, each session had a small number of invited formal presentations followed by discussion periods that included five-minute lightning talks—which are described in shaded boxes in the summary that follows.

In addition to the meeting platform, the CPF Workshop hosts created virtual bulletin boards organized to match the workshop schedule, that enabled an interactive chat capability. The boards enabled lively interaction among the participants regardless of whether there was time for questions after each presentation. Attendees could revisit topics at any time if thoughts, ideas, or questions came up at another time during the workshop. Although it is impossible to recreate the interpersonal interactions that organically occur during an in-person workshop, the virtual bulletin boards increased the amount of interaction among participants compared to what a virtual meeting typically allows.

This report presents the highlights from the two-day meeting. The full agenda and presentation slides from the workshop are archived and accessible from *go.nasa.gov/3JCgtpu*.

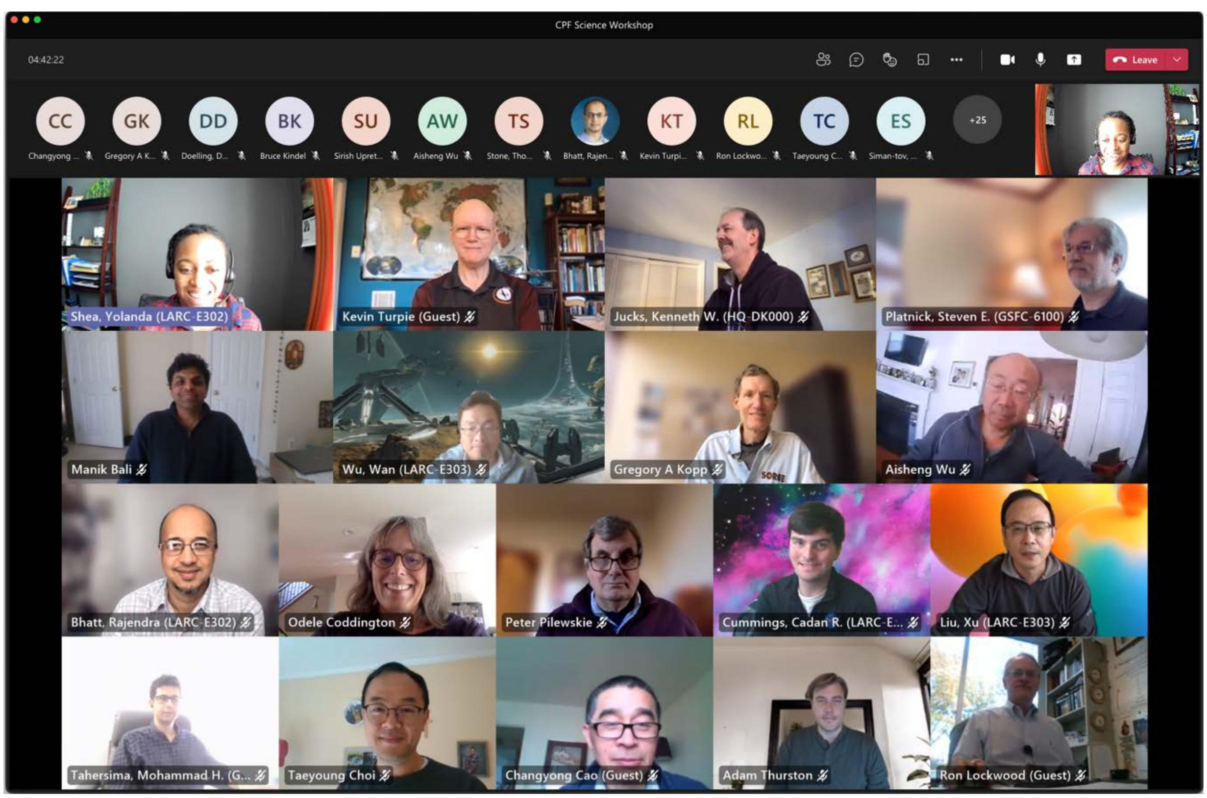


**Photo.** This photo shows a cross section of the CPF science workshop attendees. Altogether, more than 70 people participated over the course of the two-day virtual meeting. **Image credit:** Yolanda Shea/LaRC

## DAY ONE

The first day of the workshop focused on educating the scientific community about the CLARREO Pathfinder mission and investigative science studies that could be conducted by leveraging the information in CPF hyperspectral measurements. The meeting opened with each of the meeting organizers making brief remarks and welcoming the participants. These included: **Yolanda Shea** [NASA's Langley Research Center (LaRC)—*CPF Project Scientist (PS)*]; **Peter Pilewskie** [University of Colorado Boulder/Laboratory for Atmospheric and Space Physics (CU/LASP)—*CPF LASP Science Principal Investigator*]; **Steve Platnick** [NASA's Goddard Space Flight Center (GSFC)—*CPF Collaborator*]; and **Rajendra "Raj" Bhatt** [LaRC—*CPF Deputy PS for Intercalibration]*.

After the welcoming remarks, two guest speakers from NASA Headquarters (HQ) gave presentations: **Jack Kaye** [NASA HQ—*Associate Director of Research for the Earth Science Division*] and **Ken Jucks** [NASA HQ—*CPF Program Scientist*]. **Kaye** thanked the attendees for the continued work they have done as part of the NASA Earth Science research community. **Jucks**, who has been Program Scientist of the CPF mission since its inception in 2016, and who before then served as the CLARREO Pre-formulation Mission program scientist for several years, provided his perspective on the current status of CPF.

### CLARREO Pathfinder Mission Overview and Status

After the opening remarks, the workshop began with three presentations that provided an overview of the project's scope, status, and technical details. First, **Yolanda Shea** gave an overview of the CPF mission, which will fly a reflected solar (RS) spectrometer on the International Space Station (ISS). CPF is planned for launch in December 2023; its instrument, the Hyperspectral Imager for Climate Science (HySICS), will measure Earth-reflected solar radiation from space over a spectral range spanning 350 nm to 2300 nm, with a low absolute radiometric uncertainty of 0.3% at k=1.[1] With its spatial (0.5-km) and spectral (3-nm) resolution, along with the unprecedented radiometric accuracy, the CPF measurements will also provide an in-orbit, Système Internationale (SI)-traceable reference for intercalibrating other satellite imagers. The CPF mission will implement a state-of-the-art intercalibration approach. As part of its core objectives, both the shortwave channel (0.3–5.0 mm) of the Clouds and the Earth's Radiance Energy System (CERES)[2] and the reflective solar channels of the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the National Oceanic and Atmospheric Administration's (NOAA)-20 satellite platform will be intercalibrated, with a targeted methodology uncertainty of 0.3% (k=1).

CPF will take high-accuracy measurement of Earth's reflectance, which will be distributed publicly in Level-1A (L1A) and L1B data products[3] at the Atmospheric Science Data Center at LaRC. Additionally, CPF will schedule time-, space-, and angle-matched intercalibration measurements with CERES and VIIRS on NOAA-20, and at least one geostationary (GEO) sensor still to be determined.

The CPF project will also distribute two L4 fused data products that will include the CPF, target (i.e., CERES or VIIRS), and auxiliary data needed to conduct the intercalibration data analysis. The L4 data files will also include the output from each of the CPF-developed intercalibration algorithms.

Day Two of the meeting was dedicated to a discussion of the plans and approaches to be taken for CPF intercalibration—see page 29 to read about them.

**Peter Pilewskie** then discussed science capabilities of CPF—i.e., beyond its core science objectives. He discussed additional studies that could be supported by CPF's unique measurements, and noted that CPF will have the most advanced combination of spectral coverage, spectral resolution, spatial resolution, and radiometric accuracy of any Earth-observing instrument to date.

Pilewskie gave several examples of how the combination of these qualities can support a wide variety of science applications including CPF's role as a predecessor to the 2017 Earth Science Decadal Survey's[4] *designated observable* shortwave spectrometers (e.g., the Atmospheric Observing System, or AOS),[5] in enabling the development of vertically resolved retrievals of cloud droplet effective sizes, and in support of hyperspectral retrievals of aerosol properties. He also invited the workshop attendees to begin thinking about

[1] This is equivalent to one standard deviation for a Gaussian distribution.

[2] There are currently six CERES instruments in orbit. There are two CERES instruments on NASA's Terra and two on NASA's Aqua platform. There is a CERES Instrument on the Suomi National Polar-orbiting Partnership (NPP) platform, as well as one on the NOAA-20 satellite.

[3] Level-1A includes geolocated, calibrated spectral measurements, including on-orbit calibration data; Level-1B includes spectral measurements sampled to consistent spatial and spectral scales.

[4] The 2017 Earth Science Decadal Survey report, formally named "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space," defines five *designated observables* as foundational observations to be implemented as cost-capped medium- and large-size missions directed or competed at the discretion of NASA. These are: Aerosols, Clouds, Convection, and Precipitation, Mass Change, Surface Biology and Geology, Surface Deformation and Change. The full report can be viewed at or downloaded from *nap.nationalacademies.org/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

[5] AOS combines the Aerosols and Clouds, Convection, and Precipitation Designated Observables into a single mission that is now part of the Earth System Observatory.

their science applications in preparation for the data product release and science team solicitation, expected in 2024-2025.

**Paul Smith** [LASP—*CPF Calibration Engineer*] concluded the CPF Introduction session with a presentation on the HySICS instrument, including the measurement approach and in-orbit calibration approach. The two-axis gimbal that is part of the HySICS Pointing System [HPS] allows the instrument to take direct measurements of the Sun and Earth using nearly the same optical path and without the use of a reflective diffuser. Input aperture area and detector integration time changes are used to achieve approximately five orders of magnitude attenuation needed between solar and Earth views. Smith also gave an overview of the more than 80 uncertainty contributors and the expectation that about 84% of the uncertainty budget contributors will be partially or fully validated in orbit. The remaining uncertainty contributors that will not be validated in orbit will have full instrument proxies that will serve to provide information about their in-orbit performance. Referencing Earth views to the Sun, which is a stable source, using nearly the same optical path will result in measurements with 5 to 10 times less uncertainty than any current satellite sensor measuring in this spectral range. Smith concluded the presentation with an overview of the CPF L1 data products that will be publicly distributed.

Prior to the first discussion session, **Greg Kopp** [LASP—*Instrument PI*] summarized key outcomes from the SI-Traceable Space-based Climate Observing System (SITSCOS) workshop held September 9–11, 2019, in London, U.K. The SITSCOS workshop report included recommendations to CPF to intercalibrate additional sensors and characterize additional pseudo-invariant surface sites. The report also recommended that NASA consider extending the CPF mission lifetime to five years to increase the likelihood that CPF could overlap with other upcoming SI-Traceable Satellite Instruments (SITSats), e.g., Traceable Radiometry Underpinning Terrestrial and Helio-Studies (TRUTHS).[6]

**Additional Remote Sensing and Climate Science Studies**

As discussed earlier, the novelty of CPF measurements provides a multitude of possibilities for a wide variety of science studies beyond CPF's core mission objectives. Therefore, the next session included presentations that showcased some of the research topics that CPF measurements could support.

The session started with three presentations that provided key examples of additional science studies, and ended with a round of lightning talks. The presentations gave strong endorsements for the value of the wealth of information in hyperspectral reflectance measurements. Several presentations in this session highlighted the many ways in which the redundancy of information in CPF's hyperspectral measurements can be leveraged for cloud, aerosol, water vapor, as well as surface remote sensing studies and retrieval algorithm advancement. The information in hyperspectral measurements, such as those from CPF, can be leveraged to augment information in existing multispectral cloud and aerosol retrievals.

As illustrated in **Figure 1** below, CPF will be preceding several upcoming missions that may also include shortwave spectrometers, e.g., AOS or the Surface Biology and Geology (SBG) mission. CPF measurements can be used to test hyperspectral analysis and retrieval methods that are being developed for those future missions. Additionally, CPF's prime mission operational timeframe means that it will likely overlap with missions that include instruments with similar measurement characteristics, e.g., the Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) mission. The

[6] TRUTHS is an instrument that will be launched in the late 2020s or early 2030s by the European Space Agency. It will provide SI-traceable shortwave measurements.

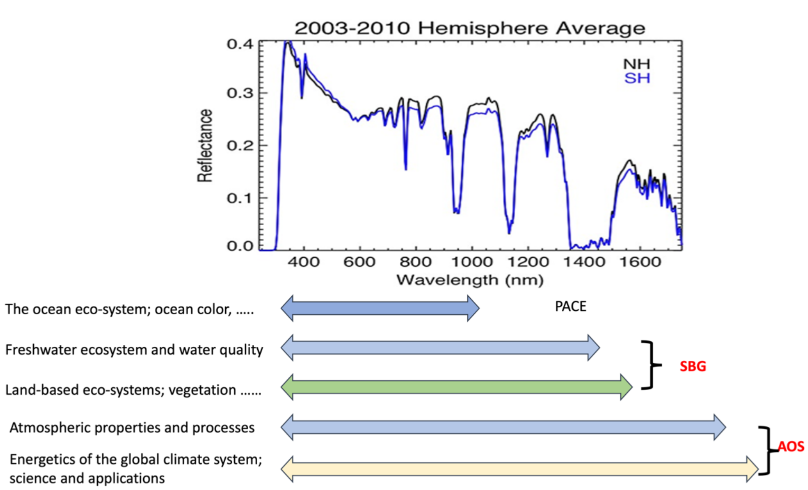


**Figure 1.** The spectral range of CPF is comparable to several other missions that will overlap with CPF in time or for which CPF will serve as a predecessor. The graph [*top*] shows two sample spectra that have similar spectral range to CPF, averaged over the Northern Hemisphere (NH) and Southern Hemisphere (SH). The arrows [*bottom*] show estimated spectral range of similar upcoming missions, and some of the science research areas that will benefit from hyperspectral measurements in the indicated ranges [text, *bottom left*]. The future mission acronyms [text, *bottom right*] are defined in the text. **Image credit**: Graeme Stephens/ NASA/Jet Propulsion Laboratory

PACE Ocean Cloud Instrument (OCI) and CPF will have comparable spectral coverage—although CPF has contiguous spectral band coverage and higher spectral sampling across its entire spectral range.

Metrics have been used to quantify how much information content is increased in optical cloud retrievals by adding spectral bands and increasing the radiometric accuracy of the measurements used in the retrieval. CPF measurements will be able to build on the foundation provided by this work, supporting future development of hyperspectral optical cloud-retrieval algorithms. Shortwave reflectance spectra have also been shown to contain information about anthropogenic aerosol sizes and loading. The spectral signatures of anthropogenic aerosols and surface reflectance can be used in concert to constrain emissions of fine particles, which can be used as a benchmark for climate model simulations. CPF measurements could therefore provide constraints on emissions and aerosol radiative forcing at regional scales.

**Lightning Talks**

A round of lightning talks closed out the first session. Several groups are using measurements from multiple instruments and platforms to develop multidecadal climate data records of retrieved cloud and aerosol properties. However, calibration poses a challenge to reliable, unambiguous trend detection, and several lightning talks acknowledged the benefit that the high-accuracy spectral measurements from CPF are expected to contribute to their efforts. MODIS[7] and VIIRS measurements are being used to develop continuity cloud and aerosol retrieval algorithms. These imager cloud and aerosol retrieval algorithms are also being ported to geostationary (GEO) imagers to expand the diurnal coverage of the data records. Differences in calibration among multiple instruments have become apparent in the time series of the retrieved geophysical properties. To give an example, the Dark Target[8] Aerosol Optical Depth (AOD) retrieval algorithm applied to MODIS Terra and Aqua data and Suomi National Polar-Orbiting Partnership (NPP) VIIRS measurements returns three different answers for similar scenes. After accounting for differences—which can be attributed to sampling—the Dark Target team estimates that a 2% difference in reflectance corresponds to approximately a 10% difference in retrieved AOD. CPF measurements can support cloud and aerosol retrieval algorithm development efforts, all of which use multispectral bands spanning the CPF spectral range, by providing a reliable reference to the multiple instruments used to construct climate data records. CPF measurements will also be complementary to Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) measurements in the development of novel aerosol PACE retrievals, which will span the capabilities provided by the Ozone Monitoring Instrument (OMI), Deep Blue,[9] and Dark Target aerosol retrieval algorithms.

**Climate Science Studies**

The first day of the workshop concluded with a session on climate science studies that can be enabled by CPF measurements. One presentation discussed the value of climate benchmarking and climate change attribution. *Climate benchmark measurements* are direct observables with sufficient accuracy to provide a reliable long-term record, information content for climate change attribution, and sampling to interpret the impact of observed changes. The abundance of information content in hyperspectral measurements lends itself well to climate change attribution methods, e.g., separation of sources contribution to the observed signal, multivariance analysis, and climate fingerprinting. *Climate fingerprinting* uses spectrally-resolved climate benchmark measurements to tie observed spectral signals to their geophysical drivers. CPF measurements will have many of the qualities of climate benchmark measurements, paving the way toward a climate benchmark prototype.

The CPF team solicited feedback from the climate model community to facilitate discussion on the observational needs of the climate community. Despite decades of sustained work, a variety of metrics continue to show that climate model projections of near-term climate change still diverge. Because observations of changes in geophysical quantities are valuable climate model constraints, measurements such as those from CPF would be especially valuable to the climate modeling community. CPF's high accuracy, its ability to maintain that high accuracy in orbit throughout its lifetime, and its intercalibration capabilities will improve satellite retrievals of geophysical variable changes, all of which are expected to be valuable for constraining climate model projections.

[7] MODIS stands for Moderate Resolution Imaging Spectroradiometer, which flies on NASA's Terra and Aqua platforms.

[8] The MODIS Dark Target algorithms retrieve aerosol properties over dark land (e.g. vegetated and dark-soiled) and ocean surfaces.

[9] The Deep Blue retrieval algorithms complement the Dark Target algorithms by also retrieving aerosol properties over bright land surfaces, such as deserts.

**Lightning Talks**

The second session closed with two lightning talks that highlighted additional climate study applications for CPF measurements. The CERES top-of-atmosphere shortwave broadband irradiance record—which spans over 20 years—shows a decrease in top-of-atmosphere (TOA) reflected shortwave irradiance over the past five or six years. This decrease has been attributed to a likely decrease in low cloud cover. As a result, there is community interest in how the shortwave spectral reflectance has changed in the more than 20 years that will have elapsed between the hyperspectral measurements from the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY)[10] instrument and CPF as well as how the spectral variability observed will complement broadband observations. CPF measurements can also be used for climate change attribution by developing spectral clusters and assigning measured spectra of identified scenes to various clusters, an approach that has been demonstrated with SCIAMACHY data over West Africa as a use case.

The last talk showcased research activities that could be performed in partnership with the Libera mission.[11] CPF spectra can be used to verify the processes that drive observed broadband variability and complement Libera's broadband split shortwave channel to characterize the spectral variability in that range. This could help to answer the question of what spectral variability underlies observed broadband, near infrared, and visible changes.

**DAY TWO**

The focus of the second day of the workshop was on the CPF intercalibration plans and capabilities. **Raj Bhatt** presented an overview of the state-of-the-art direct intercalibration approach that the CPF intercalibration team (CPF ICT) has been developing for transferring high radiometric accuracy (CPF uncertainty of 0.3% at k=1) from CPF to a target reflective solar instrument. During the first year of the mission, the CERES and VIIRS instruments aboard NOAA-20 will be the prime targets for demonstrating the intercalibration capability. With its two-axis pointing capability, CPF can closely match its boresight line of sight to that of a target sensor. To mitigate the impact of residual angular sampling differences between CPF and the target sensor, the CPF ICT has developed an angular adjustment algorithm that aims to limit the uncertainty contribution from angular mismatches to less than 0.1%. For CPF–CERES intercalibration, the CPF ICT has developed a spectral extension method to fill in the gaps between the spectral domains of CPF and the CERES shortwave channel. Both the angular adjustment and spectral extension algorithm use spectral correlations from CPF.

The CPF instrument will have low polarization sensitivity by design and may assist in characterizing any polarization sensitivity changes of the VIIRS instrument on orbit. The CPF ICT will implement both PARASOL-based and radiative transfer model-based polarization distribution models to identify intercalibration samples over low-polarized scenes to intercalibrate the VIIRS reflective solar bands against the CPF measurements.[12]

CPF will also take lunar measurements that will contribute to improving lunar models for sensor calibration. If additional time in orbit beyond the first year of operations is granted, the CPF ICT will explore more intercalibration opportunities, including cross-comparison with TRUTHS, intercalibration of more reflective solar imagers (e.g., GEO, Landsat), and radiometric characterization of deep convective clouds and pseudo-invariant calibration sites (PICS).

**Kurt Thome** [GSFC—*CPF Independent Calibration Lead*] discussed the role of instrumented Earth targets and PICS in postlaunch radiometric calibration and validation of satellite optical sensors. The high-accuracy hyperspectral CPF measurements over Earth reference sites will improve their radiometric and spectral characterizations. This presentation affirmed that the CPF observations over the calibration sites will assist in decoupling atmospheric effects from sensor noise and surface bidirectional effects and will ultimately reduce associated uncertainties.

Several presentations highlighted new research avenues incorporating collaborative use of the CPF high-accuracy benchmark Earth observations. **David Doelling** [LaRC] discussed the expected benefits of CPF to the Global Space-based Inter-Calibration System (GSICS) community. GSICS is currently using NOAA-20 VIIRS as a reference sensor for intercalibrating global GEO imagers. The outcome of the CPF–VIIRS

[10] SCIAMACHY was a hyperspectral instrument that flew on ESA's Envisat mission, which was operational from 2002 to 2012.

[11] Libera was chosen as the first Earth Venture Continuity mission (EVC-1). It will contribute to the multidecadal climate data record from CERES. In Roman mythology, Libera was the daughter of Ceres; hence the name. EVC was another category established by the 2017 Earth Science Decadal Survey to maintain continuity of existing climate datasets such as the energy balance data that CERES has collected for more than two decades.

[12] PARASOL stands for Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL), which was part of the Afternoon Constellation, or "A-Train," from 2004 until 2009. To learn more about the A-Train visit *atrain.nasa.gov*.

intercalibration will allow GSICS to extend the SI-traceable absolute reference across GEO imagers and enable robust and harmonized data records from those instruments. The VIIRS Characterization and Support Team (VCST) emphasized that the intercalibration of NOAA-20 VIIRS with CPF will enhance the understanding of an existing systematic radiometric bias between the two VIIRS instruments (i.e., aboard NOAA-20 and Suomi NPP) and provide correction factors for improving their absolute calibration. The VCST also expressed interest in improving in-orbit radiometric calibration of more than 40 years of collective data from MODIS on Terra and Aqua by tying the MODIS measurements to the CPF reference.

Select members from the CERES project presented desirable and expected outcomes of the CPF–CERES intercalibration. **Mohan Shankar** [LaRC—*CERES Deputy Project Scientist*] demonstrated that the intercalibration of CERES against CPF over radiometrically and spectrally diverse scene types will allow the CERES Instrument Working Group to evaluate the instrument performance at various wavelengths and dynamic ranges. A highlight was that CPF could provide an independent validation for direct comparison of the radiometric differences between the CERES instruments onboard NOAA-20 and Suomi NPP satellites, whose orbits do not intersect.

**Kerry Meyer** [GSFC—*MODIS/VIIRS Cloud Retrieval Team*] discussed the importance of sensor intercalibration for multisensor data processing, to derive consistent cloud and aerosol retrievals that are essential for generating multidecadal climate data records. Developing a reliable continuity algorithm to obtain consistent cloud property retrievals from MODIS and VIIRS has been challenging due to significant radiometric and spectral differences between the two instruments. The hyperspectral Earth observations from CPF will support the data continuity mission by eliminating the issue of spectral band differences with predecessor imagers. Meanwhile, using the direct intercalibration capability of CPF will also facilitate an independent pathway to assess the MODIS/VIIRS Cloud Retrieval Team's approach for establishing radiometric and spectral harmonization between imagers.

**Cody Andersen** [USGS—*Landsat Calibration/Validation Manager*] discussed the Landsat 8 Operational Land Imager (OLI) onboard calibration methodology and uncertainty budget. The OLI radiance and reflectance data products are independently calibrated. This presentation emphasized that the presence of a highly accurate, in-orbit, absolute calibration reference like CPF would assist in further improving the radiometric quality of Landsat products via intercalibration.

The exceptionally stable surface reflectance of the Moon makes it an attractive natural invariant target for radiometric calibration. Satellite operators across the globe have demonstrated the use of lunar observations as an effective means for monitoring the temporal stability of sensors in reflective solar bands.

**Tom Stone** [U.S. Geological Survey—*CPF Collaborator*] discussed the need for a high-accuracy characterization of the spatially integrated lunar irradiance at different geometries to perform sensor intercalibration, or using the Moon as an absolute calibration reference. CPF will have daily opportunities to observe the Moon and will do so as a secondary mission objective. The lunar images from CPF, however, will encompass concatenated scan lines composed of non-uniform, oversampled lunar pixels that can introduce additional uncertainty in the lunar measurements. While CPF's achievable radiometric accuracy for lunar irradiances is yet to be determined, with a proper characterization of the oversampling factors, the CPF lunar observations are likely to improve our knowledge of absolute lunar irradiance and assist in developing advanced lunar models for calibration.

**Lightning Talks**

The second day also included two lightning talk discussion sessions to explore CPF intercalibration capabilities beyond the primary mission objectives. The community foresees CPF as a promising instrument for in-orbit radiometric adjustment of other contemporary satellite instruments—including geostationary imagers (e.g., Geosationary Operational Environmental Satellite–R (GOES-R) series-Advanced Baseline Imager (ABI)), Suomi NPP-VIIRS, and Terra/Aqua-MODIS—to an SI-traceable reference via direct intercalibration against CPF or with NOAA-20 VIIRS scaled to CPF—see **Figure 2**. The coincident

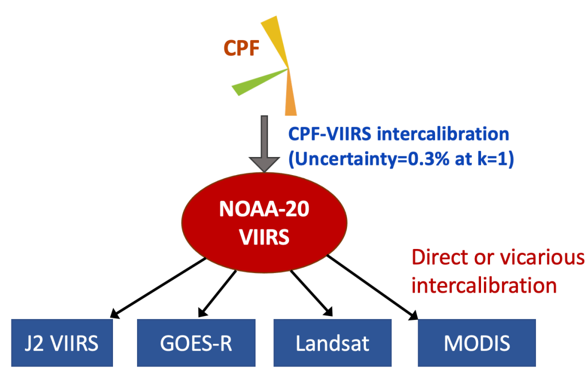


**Figure 2**. NOAA-20 VIIRS scaled to CPF calibration can be used as an intermediate transfer radiometer for in-orbit radiometric adjustment of other contemporary satellite instruments to CPF reference. Note that with one exception, all acronyms used in the Figure are for mission and instrument names defined in the text. The exception is *J2*, or Joint Polar Satellite System (JPSS)–2, which after checkout will become NOAA–21. **Image credit**: Rajendra Bhatt

and collocated CPF measurements may also be used to characterize the polarization sensitivity of the instruments' shorter wavelength channels. Discussion included utilizing the CPF measurements to evaluate the robustness of current intercalibration methods and splitting the associated methodology uncertainty into individual sources.

Two of the lightning talks focused on characterizing the Moon as a stable calibration target. The ARCSTONE mission will fly a compact and high-accuracy spectrometer on a 6U CubeSat[13] for radiometric characterization of the Moon for in-orbit sensor intercalibration. Similarly, the Airborne Lunar Spectral Irradiance (air-LUSI) mission[14] will provide SI-traceable measurements of lunar spectral irradiances between 380 and 1100 nm from above 95% of the Earth's atmosphere, with a targeted uncertainty of <0.5% at k=1. The air-LUSI data sets will be valuable in improving current lunar irradiance models and validating the in-orbit calibration of hyperspectral instruments (like CPF and TRUTHS) at select wavelengths.

Other interesting ideas presented during the discussion included characterizing upper-atmosphere limb scattering as a visible calibration target for shorter wavelengths using CPF measurements. Another was to develop an *in situ* satellite sensor calibration system by illuminating a satellite sensor with a broadly tunable narrow-band laser from the ground. Recent advancements made by the National Institute of Standards and Technology (NIST) team in developing a high-accuracy irradiance responsivity calibration method for shortwave infrared wavelengths using pyroelectric detectors were also discussed.

[13] The dimensions of the standard cube used for CubeSat construction is 10 x 10 x 10 cm (or 3.9 x 3.9 x 3.9 in), which is defined as 1 Unit (U). To learn more, see "CubeSats and Their Role 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*].

[14] This mission falls under the jurisdiction of NASA's Airborne Science Program. For more details see *go.nasa.gov/3bzsWOn*.

**Summary**

The fully virtual 2021 CPF Science Workshop was a success. There was a great turnout with over 70 attendees, whose consensus was that the workshop was productive and that it achieved its goals of informing multiple communities about CPF mission objectives, gathering the various communities' needs and interests in CPF measurements, and promoting future collaborations with them. The CPF team is planning one additional science workshop in 2023— prior to launch. Watch for details on the CPF website. ■

in the news

# Great Air Quality for the Great Lakes Region

*Lia Poteet, NASA Headquarters, Applied Sciences Program, lia.n.poteet@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*.

Air quality planning agencies in the U.S. Great Lakes region now include high-resolution NASA satellite data in their ozone pollution assessments. Creating models that accurately predict the complex lake and land breezes along Lake Michigan's shoreline is very difficult, but it's also vital to understanding how ozone pollution circulates in the region.

The unique weather of the Lake Michigan shoreline can create pockets of high levels of ground-level ozone. This air pollutant is created by emissions from cars, trucks, fossil-fuel power plants, and other sources. It is also monitored by local and federal regulators, which require states to *attain*, or meet, federal air quality standards.

"Our member states are facing several non-attainment areas in this region that are violating federal ozone standards," said **Zac Adelman** [Lake Michigan Air Directors Consortium (LADCO)]. "This system is operational and we're using it from a policy standpoint now—we're actively deploying the modeling systems developed through this project to simulate mitigation efforts and inform the states' attainment strategies."

To make sure the right data was getting into the right hands and in the right format, the project, which is formally known as "A Satellite Constrained Meteorological Modeling Platform for LADCO States: State Implementation Plan (SIP) Development," worked with LADCO and the Wisconsin Department of Natural Resources (WDNR) to create a modeling tool that incorporates satellite data into ozone monitoring efforts.[1] Adelman said this is important to improve confidence in policy decisions for lowering ozone pollution. Data comes from sources such as NASA and the National Oceanic and Atmospheric Administration (NOAA).

"We tested many different surface data sets from NASA and NOAA to figure out how we can combine them to produce the most accurate estimate of meteorological conditions that influence these ozone concentrations," said **Jason Otkin** [University of Wisconsin-Madison, Space Science and Engineering Center—*Principal Investigator*].

[1] This project is also reported on the NASA Applied Sciences website at *go.nasa.gov/3cPlz5A*

**Figure 1**. On July 1, 2020, the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Terra satellite acquired this true-color image of the Great Lakes. **Credit**: NASA's Goddard Space Flight Center MODIS Land Rapid Response Team

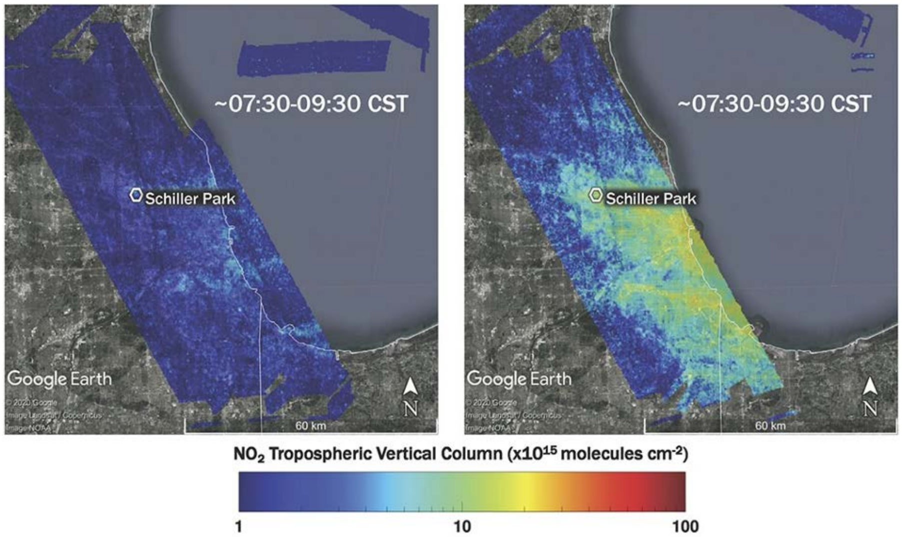


**Figure 2**. These two images show how a pocket of increased nitrogen dioxide ($NO_2$) concentration appeared within 24 hours in the Schiller Park area along Lake Michigan's shoreline in June 2017 resulting from the transition from the weekend to a weekday: Sunday, June 18 [*left*] to Monday, June 19 {*right*]. These data were acquired via ground observations and NASA's Geostationary Trace gas and Aerosol Sensor Optimization (GeoTASO) aircraft instrument, which measures nadir backscattered light in the ultraviolet and visible in two channels at wavelengths 290–400 nm (UV) and 415–695 nm (VIS) and maps the atmosphere in two dimensions under the aircraft's flight track. **Image credit**: NASA/National Science Foundation

"It's really exciting to see how LADCO has run with these resources, and how they've been so engaged throughout the process," Otkin said.

LADCO's Adelman agreed, noting that: "This project really helped us add value to the meteorological and air quality models we use to support the decisions in the states, making it easier for us to help our member states assess ozone levels and meet federal pollution standards."

In addition to wind and weather, NASA provides other Earth observations that affect the complex environment around the Great Lakes. Those include high-resolution data on soil moisture and temperature from NASA's Land Information System and Short-term Prediction Research and Transition Center (SPoRT), which incorporates data from NASA's Soil Moisture Active Passive (SMAP) mission and NOAA sources such as the Geostationary Operational Environment Satellite (GOES) series of satellites. The team also incorporates lake surface temperature and vegetation data from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on board the joint NASA-NOAA Suomi National Polar-orbiting Partnership (Suomi NPP), and the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra—see **Figure 1**—and Aqua satellites.

To evaluate the effectiveness of these complex computer models of the Great Lakes regions, NASA's Health and Air Quality project team built on previous work in the area, including the 2017 Lake Michigan Ozone Study, which focused on local ozone air quality near Lake Michigan, and mapping ozone hotspots around the Great Lakes—e.g., see **Figure 2**.

Using this view from above, the project team also worked with local air quality partners at LADCO to run their model to improve the accuracy of simulations—therefore allowing more precise action measurements.

"Previously, LADCO was doing air quality simulations with the Environmental Protection Agency at 12-km (~7.5-mi) resolution," said **Brad Pierce** [Project Team Member]. "We were able to improve that resolution, bringing it up to 1.3 km (0.8 mi) and increasing the accuracy of the simulations by more than 30%."

By working directly with the end users, the team has been able to actively refine the modeling process as LADCO tries out these improvements. Otkin and his team have monthly technical calls with LADCO and quarterly calls with WDNR to make further adjustments to the system now that it's in operation.

"The most effective partnerships are those where you're not just throwing something over the fence," Pierce said, "but you work with the user, incorporate their feedback, and actually give them a fully operational tool that's really customized for their needs. That's what we were able to do here—LADCO has been as active of a participant as we have in terms of the research, a real partner."

The results mean LADCO's member states can more confidently plan strategies to comply with federal ozone standards for years to come, Adelman said. He added that LADCO's member states are counting on the more accurate estimates from NASA Earth observations for when their formal plans to tackle ozone and meet state-specific air quality goals are due to the Environmental Protection Agency in 2023. ■

# NASA Air Pollution Instrument Completes Satellite Integration

*Joe Atkinson, NASA's Langley Research Center, joseph.s.atkinson@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*. It has also been augmented with the addition of Figure 2.

On June 30, 2022, crews successfully completed the first fully integrated powered testing of the Tropospheric Emissions: Monitoring of Pollution (TEMPO), instrument on Intelsat IS40e at Maxar Technologies' satellite manufacturing facility in Palo Alto, CA—see **Photo**. This testing marks the completion of the TEMPO Instrument integration with the IS40e satellite.

**Photo**. Crews recently completed the first fully integrated powered testing of the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument on Intelsat IS40e at Maxar Technologies' satellite manufacturing facility in Palo Alto, CA. **Image credit**: Maxar Technologies

From its *geostationary orbit*—a high Earth orbit that allows satellites to match Earth's rotation—TEMPO will take hourly daytime air quality observations at an unprecedented spatial resolution. Its measurements will reach from Puerto Rico and Mexico to northern Canada, and from the Atlantic to the Pacific, encompassing the entire continental U.S.

"The completion of TEMPO Instrument integration with its host satellite will allow Intelsat IS40e to transition into environmental testing, which brings us one significant and exciting step closer to launch," said **Kevin Daugherty**, TEMPO project manager at NASA's Langley Research Center in Hampton, VA.

Environmental testing will include thermal vacuum, dynamics, and electromagnetic interference and compatibility. These tests ensure the spacecraft will successfully endure conditions it will be exposed to during launch and in the harsh environment of space. TEMPO is currently targeted to launch aboard a SpaceX Falcon-9 rocket in January 2023.

From its geostationary orbit TEMPO will also form part of an air quality satellite "virtual constellation" that will track pollution around the Northern Hemisphere. In addition to TEMPO, the other members of this air quality constellation are the Geostationary Environment Monitoring Spectrometer (GEMS) instrument aboard the Korean Aerospace Research Institute GEO-KOMPSAT-2B satellite and the Ultraviolet–Visible–Near Infrared Spectrometer on the European Space Agency's Copernicus Sentinel-4 mission—see **Figure**.[1]

[1] To learn more about this constellation see *go.nasa.gov/2V5j5EJ*

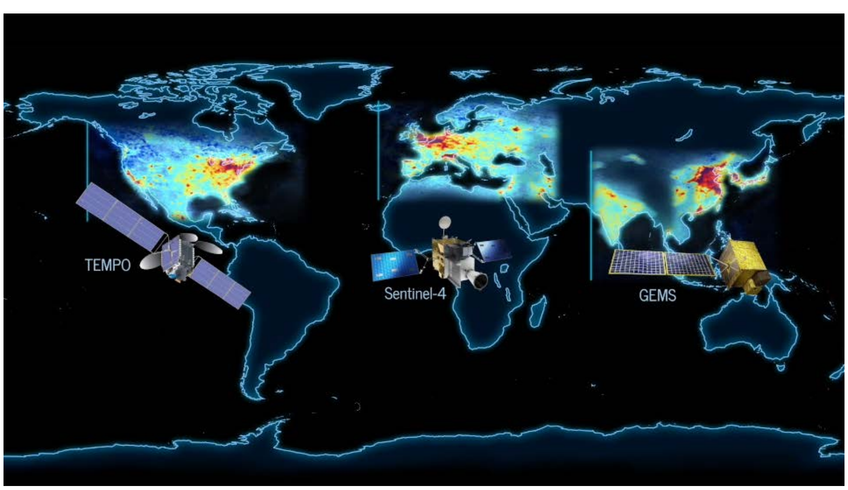


**Figure**. Once all missions are deployed, TEMPO, GEMS, and UVN will form an air quality constellation that will track pollution around the Northern Hemisphere.

# Skygazing for Science: GLOBE Surpasses One Million Cloud Measurements

*Sara Pratt, NASA's Goddard Space Flight Center, sara.e.pratt@nasa.gov*

**EDITOR'S NOTE:** The following has been adapted from a post on the NASA Earth Matters blog. The original appears at *go.nasa.gov/3Q7kMvE*.

For the past 27 years, millions of students (now in more than 120 countries) have collected and entered more than 200 million environmental measurements into the Global Learning and Observations to Benefit the Environment (GLOBE) database. Those observations include surface temperatures, rainfall amounts, tree heights, land cover, mosquito habitats, and a variety of other environmental observations—including cloud type and coverage.[1]

Clouds are an important part of the climate system.[2] They affect how much sunlight reaches the ground and how much heat returns to space, which in turn affects Earth's temperature and rainfall patterns. Scientists are working to better understand the role that clouds play in the global climate system, but that requires significant amounts of data.

"No single cloud observation method or system… is able to provide a complete and accurate depiction of cloud properties across the Earth under the many conditions that naturally occur," said **Bill Smith** [NASA's Langley Research Center (LaRC)]. Cloud observations are gathered by active and passive satellites, ground-based sensors, and, by humans.

The citizen scientists of the GLOBE Program have played a vital role in data collection by observing clouds around the globe, especially at times that "match" a satellite flyover—see **Photo 1**. When that happens, the observations from the citizen scientists on the ground are matched with satellite observations that were made near the same time and place. By combining the ground-up view of GLOBE citizen scientists with the top-down view of satellites, scientists get a more complete view of the atmosphere.[3]

The NASA GLOBE Clouds team had been conducting a campaign this summer to reach one million matches by the time of the GLOBE annual meeting that took place in late July. The campaign was calledd *Matched to a Million*.[4] Just after the meeting—on July 31, 2022—that impressive milestone was surpassed.[5]

[1] Learn more about GLOBE's founding and the first 20 years of its history at *https://www.earthmagazine.org/article/benchmarks-april-22-1995-globe-launched*.
[2] Learn more about clouds see *go.nasa.gov/3d5dSs2*.
[3] Learn more about the value of GLOBE cloud observations at *observer.globe.gov/do-globe-observer/clouds/science#satellitematching*.
[4] Learn more about this campaign at *go.nasa.gov/3QovPk2*.
[5] Learn more at *go.nasa.gov/3dCFKnP*.

**Photo 1**. GLOBE participants taking cloud observations. **Image credit**: GLOBE Program

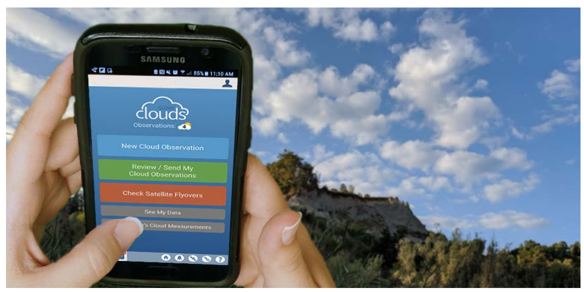


**Photo 2**. GLOBE deploys citizen scientists who can use the Globe Observer app to classify clouds using their phone. **Image credit**: GLOBE Program

When a GLOBE cloud observation is taken within 15 minutes of a satellite observation, both points of view are coupled, creating a match. Some satellites are geostationary satellites, e.g., the Geostationary Operational Environmental Satellites (GOES—National Oceanic and Atmospheric Administration), Himawari (Japan), and Meteosat (Europe) series. Others are polar-orbiting satellites, such as Aqua, Terra, and CALIPSO. The satellite-matched data provides an augmented dataset for research. When a match is made, the NASA GLOBE Clouds team sends a personalized email to participants with the matching satellite data. Approximately 4000 emails are sent to participants each month.

Participants can photograph clouds, then upload the photographs and classify the clouds using the GLOBE Observer app—see **Photo 2**.[6]

They can also follow GLOBE on Twitter (*twitter.com/NASAGO*) and share what they're doing to help GLOBE match to a million by using the hashtag *#GLOBE1M*. ■

[6] Learn more about the Globe Observer app and how you can help NASA learn about Earth's atmosphere at *observer.globe.gov*.

# Participate in the GLOBE Land Cover Challenge: Land Cover in a Changing Climate

Citizens are invited to join scientists—from NASA and elsewhere—in documenting land cover phenomena and land use change as part of the GLOBE Land Cover Challenge.

As noted at the Challenge's site:[1] "Nearly every aspect of our lives is fundamentally tied to the land on which we live. Documenting what is on the land (land cover) is important for many areas of critical science studied by NASA scientists and others, including hazard analysis for floods, fires and landslides, mapping wildlife habitat, and tracking the impacts of climate change. The Global Learning and Observations to Benefit the Environment (GLOBE) Program invites you to take part in its Land Cover Challenge: *Land Cover in a Changing Climate*."

Photos taken by "citizen scientists" using The GLOBE Program's *GLOBE Observer App* can document the current state of land cover and may also show evidence of land cover or land use change in the area. While participants are encouraged to look for places where change is known to have occurred recently (or where it is known to be imminent)—observations from any location are valuable. The App contains a "Field Notes" section where users can enter notes about their perception or understanding of the reason for and/or the timing of the change. Such detailed information is an extremely useful complement to existing land cover databases (e.g., the 50-year Landsat record), which can show *where* change is happening—but not necessarily *why* it is happening.

The data collecting during the GLOBE Land Cover Challenge will be used to narrow that gap in understanding between where land cover and land use change is happening and why it is occurring.

**Weekly Themes**

GLOBE is collaborating with the Landsat Communications and Outreach Team and their Camp Landsat summer programs to provide a theme (or focus area) for each week of the challenge:

| Week | Theme/Focus Area |
|---|---|
| 1 | People & Places |
| 2 | Plants & Habitats |
| 3 | Food & Farms |
| 4 | Water & Wellness |
| 5 | Ice & Climate |

Each week, GLOBE will release one or more videos on social media, and the Camp Landsat website (*go.nasa.gov/3zYQghG*) will have a variety of connected resources and activities. The full schedule of speakers, their affiliation, and the topics they will discuss in their video can be found at the Challenge's website (see footnote). This same link also contains links to additional land cover resources.

**How to Participate**

Getting involved is easy:

1. Download the *Globe Observer app* from *observer.globe.gov/about/get-the-app*.
2. Take photos of the changing landscape around you using the app's "Land Cover Tool," following the directions at *observer.globe.gov/do-globe-observer/land-cover/taking-observations*.
3. [*If applicable*] Comment in the Field Notes about any changes you know have occurred in the area you photographed, or changes you know are planned.
4. Submit your photos.

Participants who submit 50 or more observations during the challenge will receive Landsat commemorative material. (Those who met an earlier August 26 deadline received a digital Landsat image of one of their observations.)

Experience the joy and wonder of being a "citizen scientist" by downloading the app today and embarking on the Land Cover Challenge. The GLOBE Program looks forward to your participation!

[1] For more on the NASA GLOBE Land Cover Challenge 2022: Land Cover in a Changing Climate, please visit *observer.globe.gov/do-globe-observer/challenges/land-cover-challenge-2022*.

# 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*.

**Unique Subpopulation of Greenland Polar Bears Discovered by NASA-Funded Researchers**, June 28, *scitechdaily.com*. A NASA-funded research study, reported on in the journal *Science*, found that Greenland's fjords harbor a unique group of polar bears that rely on glacial ice—in addition to sea ice—as a platform for hunting seals. In Southeast Greenland scientists discovered bears survive for most of the year in fjords by relying on ice *melanges,* a mix of sea ice and pieces of glacial ice carved off marine-terminating glaciers (see **Figure)**. Physically isolated for several hundred years, this population of bears was found to be genetically distinct from the larger population. Combining new data and genetic analysis with three decades of data from Greenland's east coast, the international team of scientists also used the Moderate Resolution Imagine Spectroradiometer instruments (MODIS) aboard NASA's Terra and Aqua satellites and National Snow and Ice Data Center (NSIDC) data to document the fjord and offshore sea ice environment. This small, genetically distinct group of polar bears uses strategies that could help the species survive in a warming world. But the authors caution that glacier ice can't provide habitat for many bears, because relatively few places drop large quantities of glacier ice into the ocean. Polar bear numbers will likely decrease in most of the Arctic where they rely solely on sea ice. This collaborative research was funded in part by NASA's Biological Diversity and Ecological Forecasting and Cryospheric Sciences programs.


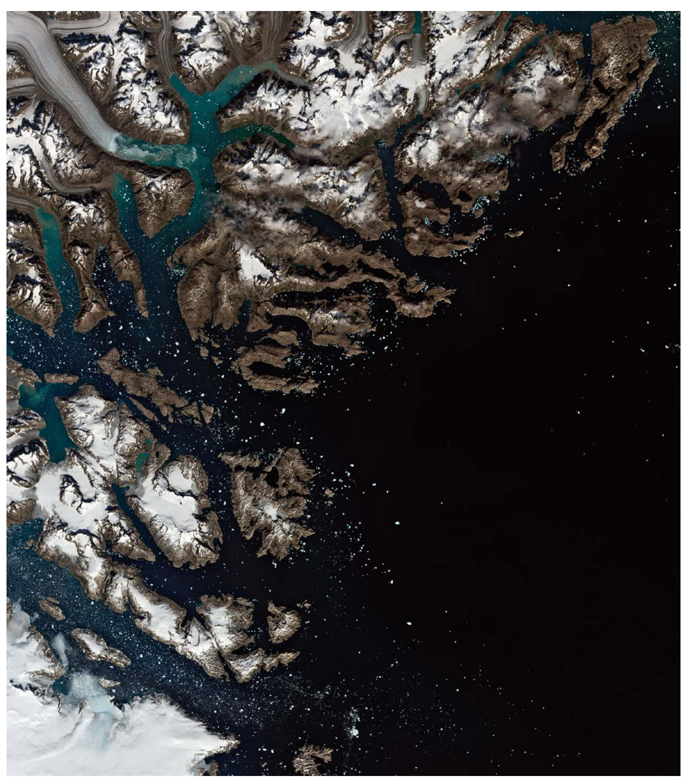

**Figure**: Satellite tracking [*above*] shows that the Southeast and Northeast polar bear populations are distinct and have different behaviors. The area outlined in light gray shows that Northeast Greenland polar bears travel across extensive sea ice to hunt. The area outlined in black line shows that Southeast Greenland polar bears have more limited movements inside their home fjords or neighboring fjords.

Shown [*right*] is the Tingmiarmiut fjord in summer. The white dots are floating glacial ice that has broken off the central Heimdal glacier and other glaciers in the fjord, which the bears use instead of sea ice to hunt. This image was collected by the Operational Land Imager on Landsat 8 on August 8, 2021. **Credit:** NASA's Earth Observatory

**NASA Project Gathers Data on Climate-Influencing Thunderstorms**, June 7, *aviationweek.com*. If the threat of severe thunderstorms materializes over Eastern New Mexico and the Texas Panhandle this summer, the staff of a NASA project and its heavily instrumented high-altitude ER-2 jet aircraft plan to be there to gather data on how intense summer thunderstorms over the Central U.S. influence Earth's atmosphere and contribute to climate change. The five-year study was initiated in 2020 by NASA's Earth Science Division and a NASA Earth Venture Suborbital research project called Dynamics and Chemistry of the Summer Stratosphere (DCOTSS). Due to the COVID pandemic, however, deployments didn't begin until the summer of 2021. The project seeks to better understand the effects of *overshooting* storms that boost air particles and chemicals in thunderstorms over the Midwest from the troposphere into the stratosphere—which most thunderstorms do not usually reach. "Approximately 50,000 storms occur over the U.S. during a typical summer. So almost every day, somewhere in the U.S., overshooting storms are happening," said **Kenneth Bowman** [Texas A&M University—*DCOTSS Principal Investigator*]. He noted that DCOTSS data will characterize stratospheric constituent levels such as ozone-depleting chemicals and aerosols. The DCOTSS airborne data-gathering team all gathered at the Salina Regional Airport in Kansas—the operating base for the Lockheed ER-2 high-altitude flying laboratory provided by NASA's Armstrong Research Center.[1] Earlier data from satellites and radar revealed that the overshooting phenomenon occurs more often than presumed, with impacts that can affect Earth's protective high-altitude ozone layer and the ejection of water vapor into the stratosphere—which then becomes a potent greenhouse gas. "We have been observing [the] Earth for decades. So, we can both see the state of the planet today, and also how it has changed over time," said **Kate Calvin** [NASA HQ—*Chief Scientist*], noting that the last eight years have been the warmest since modern weather recordkeeping began.

[1] The DCOTSS team includes scientists from eight academic institutions, four NASA centers, the National Oceanic and Atmospheric Administration (NOAA), and the National Center for Atmospheric Research (NCAR).

**Satellite to Find Hidden Reservoirs of Freshwater from Space**, July 25, *indiatoday.in*. A joint satellite mission developed by NASA and the European Space Agency will conduct a global freshwater survey to find hidden reservoirs of water. The Surface Water and Ocean Topography (SWOT) satellite will map the planet's surface water to increase understanding of Earth's water cycle, aid in water-resource management, and expand knowledge of climate change effects on lakes, rivers, and reservoirs. SWOT will measure the height and surface area of water bodies on Earth's surface to further explore water sources and sinks on Earth. It will also observe features like eddies less than 100 km (~62 mi) across in the ocean. NASA said that SWOT will measure more than 95% of Earth's lakes larger than 15 acres and rivers wider than 330 ft (100 m) across. "Current databases may have information on a couple of thousand lakes around the world. SWOT will push that number to between 2–6 million," said **Tamlin Pavelsky** [University of North Carolina—*NASA SWOT Mission Freshwater Science Lead*]. Such crucial information will enable scientists to calculate how much water moves through freshwater bodies, as scientists have long speculated that climate change is accelerating Earth's water cycle. The change could lead to major consequences for global agriculture and food production. "As Earth's water cycle intensifies, predicting future extreme events like floods and droughts requires monitoring both changes in water supply from the ocean and water demand and usage on land. SWOT's global look at all surface water on Earth will give us exactly that," said **Nadya Vinogradova-Shiffer**, [NASA HQ—*SWOT Program Scientist*]. The spacecraft will use a $K_a$-band Radar Interferometer (KaRIn) that will be able to gather information along a roughly 120-km (~75-mi) area of the planet at once. The SWOT mission is scheduled to launch in November from Vandenberg Space Force Base in California. ■

# Earth Science Meeting and Workshop Calendar

## NASA Community

**September 14–15, 2022**
PACE Applications Workshop, *virtual*
*www.eventbrite.com/e/pace-applications-workshop-2022-tickets-321347487987?aff=newsletter*

**October 18–20, 2022**
Land Cover and Land Use Change Science Team Meeting and Silver Jubilee, Bethesda, MD
*lcluc.umd.edu/meetings/2021-22-nasa-lcluc-science-team-meeting-silver-jubilee-celebration?page=*

**October 31–November 4, 2022**
Ocean Surface Topography Science Team Meeting, Venice, Italy
*ostst-altimetry-2022.com*

## Global Science Community

**September 29–30, 2022**
History of NASA and the Environment Symposium, *hybrid*
Washington, DC
*go.nasa.gov/3Ne8lMg*

**October 23–27, 2022**
22nd William T. Pecora Memorial Remote Sensing Symposium
Denver, CO
*pecora22.org*

**November 7–18, 2022**
Conference of the Parties 27 (COP 27)
Sharm El-Sheikh, Egypt
*www.cop27.eg/#/*

**December 12–16, 2022**
American Geophysical Union Fall Meeting
Chicago, IL
*www.agu.org/Events/Meetings/Fall-Meeting-2022*

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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. Also indicate if the meeting is *hybrid* (combining online and in person participation) or *virtual* (online only). Newsletter content is due on the weekday closest to the fifteenth of the month preceding the publication—e.g., December 15 for the January–February issue; February 15 for March–April, and so on.

Please email **Doug Bennett** (*doug.bennett@nasa.gov*) to subscribe to The Earth Observer newsletter or to update your address info. If you're an existing subscriber who would like to stop receiving hard copies and, instead, receive an email notification when the next issue is available for download, please include **Go Green** in the subject field of your message. Finally, please note that print copies of *The Earth Observer* are no longer sent to addresses at GSFC; they will be emailed to the addresses we have in our database. If you are located at GSFC and still wish to receive a print copy, you may provide a home (or alternative) address to Doug Bennett.

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NP-2022-8-841-GSFC