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Editor's Corner

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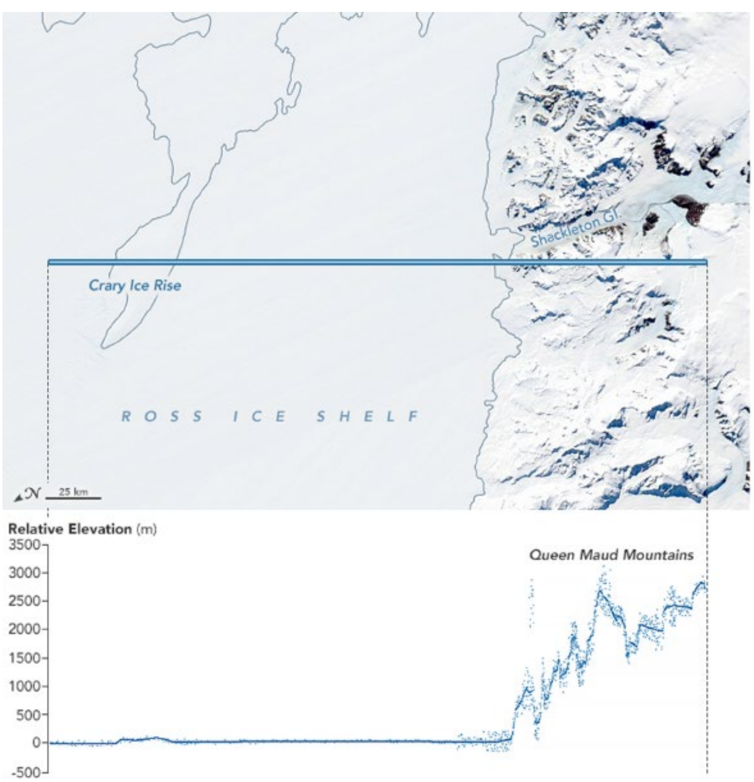
The NASA Earth Science Division capped off a busy year of successful launches with the Global Ecosystem Dynamics Investigation (GEDI) instrument on SpaceX's Commercial Resupply Mission 16. The Falcon 9 rocket carrying GEDI into orbit launched on December 5, 2018 from Cape Canaveral in Florida—see photo on page 34. Once deployed, the Dragon capsule orbited Earth for a little over 66 hours before it caught up with the International Space Station (ISS) on December 8, when Alexander Gerst, the station commander, captured the Dragon capsule using the Station's robotic arm.

The GEDI instrument was taken from the Dragon capsule and installed on the Japanese Experiment Module–Exposed Facility (JEM-EF) on December 12. GEDI will go through a short initial testing phase before starting science data collection. GEDI's first data products will be made publicly available through the LP DAAC approximately six months after the start of data collection.

We previously reported on the successful launch of the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and its subsequent installation on the JEM-EF of the ISS.[1] In just a few months since launch, ECOSTRESS has already collected over 4000 scenes of data, each 400 km x 400 km in size. These data have been processed to the various product levels (L1–4) and are now publicly available from the LP

[1] See the Editorial of the July–August 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 4**, p. 1] for details.

continued on page 2



As ICESat-2 orbited over Antarctica, it took height measurements over the steep Queen Maud Mountains—some of which had never been previously measured. Over the Ross Ice Shelf, the photon return data showed a mostly flat surface, broken by terrain including the Crary Ice Rise. These data were first shown during a press conference announcing the first results of ICESat-2 at the Fall meeting of the American Geophysical Union on December 11, 2018. **Credit:** NASA Earth Observatory/Joshua Stevens

In This Issue

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

DAAC as part of the Early Adopter Program.[2] The first data were made available about three months earlier than planned and the higher level products about six months earlier than planned. The instrument is performing well, with noise and spatial resolution better than the science requirement. There was an issue with one of the mass storage units that temporarily stopped data acquisitions; the problem was solved by switching to the redundant mass storage unit, and data acquisitions are continuing. Once GEDI is installed and operational, researchers will be able to take advantage of the combined measurement capabilities of ECOSTRESS and GEDI (and later OCO-3, which is planned for launch to the ISS in 2019) to learn more about vegetation dynamics.

Continuing our review of missions launched in 2018, just three months after launch, the Ice Clouds and land Elevation Satellite-2 (ICESat-2) is already exceeding expectations. The satellite is measuring the height of sea ice to within an inch, tracing the terrain of previously unmapped Antarctic valleys, surveying remote ice sheets (see example on front cover), and peering through forest canopies and shallow coastal waters.

With each pass of the ICESat-2 satellite, the mission is adding to datasets tracking Earth's rapidly changing ice. Researchers are ready to use the information to study sea level rise resulting from melting ice sheets and glaciers, and to improve sea ice and climate forecasts. The data are expected to be available to the public in early 2019, through the National Snow and Ice Data Center *https://nsidc.org*. "ICESat-2 is going to be a fantastic tool for research and overy, both for cryospheric sciences and other disciplines," said **Tom Neumann** [NASA's Goddard Space Flight Center (GSFC)—*ICESat-2 Project Scientist*].

Meanwhile, the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission has successfully completed a switchover to a backup system in the Microwave Instrument (MWI) on one of the mission's twin spacecraft.[3] The change to the redundant system was necessitated after an anomaly occurred in a component of the primary system. On July 19, a fault monitor on the primary MWI instrument detected that it was using less current than expected, prompting the GRACE-FO Team to power it down. An anomaly response team conducted a full investigation of the anomaly, after which the GRACE-FO Team began a series of procedures required to switch over to the new unit. The backup system in the MWI was powered up on October 19. The GRACE-FO mission has now resumed in-orbit checks, which include calibrations and

[2] Learn more about the ECOSTRESS Early Adopter program at *https://ecostress.jpl.nasa.gov/early-adopters*.

[3] Like many space-based remote sensing instruments, both GRACE-FO satellites were designed with redundant systems in their MWIs, which are their primary measurement instruments that very precisely measure the distance change between the two satellites. The GRACE-FO launch and "first light" for the MWI and LRI instruments have been described in previous Editorials, most recently the July–August 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 4**, pp. 1-2 & 24].

other system tests. Testing is expected to continue until January after which GRACE-FO will move into the science phase of the mission.

While new missions progress, other older missions endure the test of time. On October 6, 2018, NASA's Terra mission (which will celebrate the twentieth anniversary of its launch next December) passed a milestone that few other Earth observing platforms have achieved: it completed 100,000 orbits. To put this in perspective, Terra has flown a distance of more than 2.5 billion miles over the past 19 years.

NASA's Terra mission, originally known as AM-1, was conceived as the first in a series of three morning platforms (AM-1, -2, -3), each with a prime mission lifetime of five years. As the EOS plans evolved, Terra morphed into a single mission that has now lasted longer than the combined planned lifetime of the original three-mission concept. Such an endurance record is a tribute to the teams of people (e.g., flight operations, subsystem engineers, subject matter experts, instrument teams, and science teams) that have worked tirelessly over the years to maintain the mission. While the Terra team is now making plans for the eventual end of mission, that is not expected for several more years. Current projections are that Terra has enough fuel to be able to continue to operate into the 2020s, with a graceful departure from its current position in polar orbit to follow. To learn more about this, see the news story on page 40 of this issue.

Inevitably, all missions must come to an end. Such is the case with NASA's Quick Scatterometer (QuikSCAT) mission. The SeaWinds instrument was turned off on October 2, 2018, in accordance with its end-of-mission plan. QuikSCAT was launched in 1999, and was so named because it was conceived, developed, and launched in less than two years as a replacement for the NASA Scatterometer (NSCAT), which flew on Japan's short-lived Advanced Earth Observing Satellite (ADEOS). The SeaWinds scatterometer measured winds over the global ocean surface with unprecedented accuracy. The wind measurements were used by the world's weather forecasting agencies to improve forecasts and identify and monitor hurricanes and other storms far out in the open seas. The data provided critical information for monitoring, researching, modeling, and forecasting the atmosphere, ocean, ice, and climate.[4]

Shortly after the tenth anniversary of QuikSCAT's launch, an age-related problem caused its spinning antenna to stop rotating, reducing its observing swath to only 30 km. However, the continued accuracy and exceptional stability of the SeaWinds instrument over this narrow swath allowed QuikSCAT to take on a new objective to calibrate more recent scatterometers (e.g., from ISRO, ESA, and NASA) and thereby enable ocean wind data record continuity. This function proved so important to the research community that QuikSCAT's decommissioning was postponed twice to allow time for new scatterometers to be launched and calibrated.

Reflecting on the mission's accomplishments, **Mike Freilich** [NASA Headquarters—*Director of Earth Science's Division* and former *QuickSCAT Principal Investigator*] said "QuikSCAT operated in space for nearly two decades, and we are certain that its impact and legacy will last much longer."

It's worth noting that another venerable Earth science instrument recently made its final flight. The launch of EUMETSAT's MetOp-C[5] on November 7, 2018 from Kourou, French Guiana carried the last Advanced Very High Resolution Radiometer (AVHRR) instrument into orbit. For 40 years this instrument flew on a variety of NASA, NOAA, and international platforms and supplied data on vegetation, soil moisture, snow cover, land and ocean surface temperature, clouds, and aerosol and fire detection. The original AVHRR design was a four-channel radiometer, first carried on TIROS-N (launched October 1978). This was subsequently improved to a five-channel instrument (AVHRR/2) that was initially carried on NOAA-7 (launched June 1981). The latest instrument version, AVHRR/3, has six channels and was first launched on NOAA-15 in May 1998. On a personal note, my first satellite data analysis experience goes back to AVHRR on NOAA-9. The instrument has had a remarkable run.

It has been said that time flies when you're having fun; I'm certain that also applies to being very busy. Both were true of this past year. As I watch another year rush to an end, a note of personal appreciation to the thousands of individuals—both within and outside of NASA—whose sustained and dedicated work enabled the many scientific, application, and technical achievements that were reported in our newsletter and elsewhere. I look forward to reading about your future accomplishments! On behalf of the staff of *The Earth Observer*, I wish everyone a festive holiday season and the very best in the new year. ■

[4] To learn more about the QuikSCAT mission's accomplishments, see *https://www.nasa.gov/feature/jpl/after-two-long-careers-quikscat-rings-down-the-curtain.*

[5] Metop is a series of three polar-orbiting meteorological satellites which form the space segment component of the overall EUMETSAT Polar System (EPS).

Note: List of undefined acronyms from the *Editor's Corner* and the *Table of Contents* can be found on **page 47**.

feature articles

A Report from the GEO-CAPE Air Quality Science Workshop and the Fourteenth Meeting of the CEOS AC-VC Working Group

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This article focuses on the Atmospheric Composition Virtual Constellation whose goal is to collect and deliver data to improve monitoring, assessment, and model predictions for changes in the ozone layer, air quality, and climate forcing.

Introduction: NASA's Participation in CEOS

Scientific collaboration with the international community has been a pillar of NASA's mission since its inception in 1958, and has been reaffirmed in subsequent updates in the nation's space policy directives. International scientific cooperation encompasses a broad range of space activities that includes partnerships on major space- and Earth-science missions; flights of foreign instruments on NASA spacecraft and NASA instruments on foreign spacecraft; exchanges of data from research conducted from space and field campaigns; and coordination of ground-system assets to insure data interoperability.

In addition to bilateral cooperation with nations around the world, NASA's Earth Science programs contribute to multilateral forums such as the Committee on Earth Observation Satellites (CEOS), whose purpose is to coordinate Earth observation activities, globally. CEOS supports the goals established by several international bodies, such as the World Meteorological Organization (WMO), the Global Climate Observing System, and the Group on Earth Observations.

Virtual Constellations (VC) are functional elements within CEOS, where selected Earth science disciplines are expected to coordinate missions in order to optimize space mission capabilities, field campaigns, and data-delivery systems to meet a common set of requirements. The Virtual Constellations include Atmospheric Composition, Land Surface Imaging, Ocean Colour Radiometry, Ocean Surface Topography, Ocean Surface Vector Wind, Precipitation, and Sea Surface Temperature.[1]

This article focuses on the Atmospheric Composition Virtual Constellation (AC-VC) whose goal is to collect and deliver data to improve monitoring, assessment, and model predictions for changes in the ozone (O_3) layer, air quality (AQ), and climate forcing. More specifically, international space agencies such as the European Space Agency (ESA) and the Korean Aerospace Institute (KARI) have partnered with NASA on a program to share AQ observations from satellites in geostationary (GEO) and low Earth orbits (LEO) using the AC-VC as the venue.

With the success of the AQ Constellation, the formation of a Greenhouse Gas (GHG) Constellation was initiated within the AC-VC. Its overarching goal is to track changes in the natural carbon cycle caused by human activities and corresponding climate variations, and to provide critical policy-relevant scientific information. This article reviews the contributions to this goal by the international space agencies' representatives who participated in this meeting.

Meeting Overviews

The fourteenth meeting of the CEOS AC-VC was held at the National Oceanic and Atmospheric Administration (NOAA) Center for Weather and Climate Prediction (NCWCP) in College Park, MD, from May 2-4, 2018. This meeting was preceded by the GEO-CAPE[2] Air Quality science workshop on May 1, also at NCWCP. Each of the two meetings were attended by about 100 scientists and engineers from

[1] To learn more, visit *http://ceos.org/ourwork/virtual-constellations*.

[2] GEO-CAPE stands for the Geostationary Coastal and Air Pollution Events. The mission was recommended as a Tier-2 priority in the National Research Council's First (2007) Earth Science Decadal Survey—*https://www.nap.edu/catalog/11820/earth-science-and-applications-from-space-national-imperatives-for-the*.

the various European space agencies, the European Commission, the Japan Space Exploration Agency (JAXA), the Chinese Academy of Sciences (CAS), KARI, NOAA, and NASA. Members from several academic and private research institutions from the U.S. and abroad also participated. Contributions also came from Canadian and European operational weather and climate agencies, as well as NOAA. The presentations for the AC-VC meeting can be found at *http://ceos.org/meetings/ac-vc-14*. *The Earth Observer* earlier reported on the eleventh meeting of the AC-VC [which at that time was known as the Atmospheric Composition Constellation (ACC)], held at ESA's European Space Research Institute (ESRIN)[3] facility in Frascati, Italy, from April 28-30, 2015.[4]

This article will first summarize the GEO-CAPE workshop—as some of the results from a decade of preformulation efforts on this Tier 2 Decadal Survey mission feed directly into the AC-VC activities—followed by a summary of the fourteenth AC-VC meeting—focusing on progress made on the AQ and GHG Constellations since the eleventh meeting in 2015.

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GEO-CAPE Workshop Summary

The GEO-CAPE mission definition and preformulation efforts were funded for 10 years to further define instrument design and performance and how their data would be collected and applied. The mission was originally conceived of as a dedicated spacecraft; however, alternative mission implementations were considered, such as a *hosted payload,* whereby the instruments would be carried on a commercial GEO satellite. In addition to the instrument studies, the mission definition period supported several complementary activities, such as development and test of algorithms, forward model calculations, and performing Observing Systems Simulation Experiments (OSSE). There were also several aircraft field campaigns conducted in the U.S. and abroad to provide evidential, as well as scientific, data to support the mission. The agenda and presentations for the GEO-CAPE Workshop are posted at *https://GEO-CAPE.larc.nasa.gov/events-2018-05Workshop.html*.

Jai Al-Saadi [NASA's Langley Research Center—*GEO-CAPE Formulation Lead* and *AC-VC Co-Chair*] announced that NASA Headquarters (HQ), in response to budget constraints and to the latest Decadal Survey recommendations,[5] would end GEO-CAPE's preformulation mission studies in FY18. However, the good news is that the effort has not been in vain; much of the work accomplished on GEO-CAPE led to the selection of two Earth Venture missions:[6] the Tropospheric Emission Monitoring of Pollution (TEMPO)[7] and the Geostationary Carbon Observatory (GeoCarb).[8] These studies also led to refined science requirements, instrument definition, and the concept of coordinated international observing systems for tropospheric composition research, AQ applications, GHG monitoring, and carbon cycle assessments. As a final close-out activity, the preformulation mission participants were directed to submit a final report in September 2018, which (as of this writing in November 2018) will soon appear on the GEO-CAPE website.

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[3] This facility is also known as the European Space Agency's Centre for Earth Observations.
[4] To read a summary of this meeting, see "Geostationary Orbit as a New Venue for Earth Science Collaboration: Eleventh CEOS Atmospheric Composition Constellation Workshop" in the July–August 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 4**, pp. 17-22—*https://eospso.gsfc.nasa.gov/sites/default/files/eo_pdfs/July%20August%202015_col_508.pdf#page=17*].
[5] The Second (2017) Decadal Survey for Earth science can be found at *http://sites.nationalacademies.org/DEPS/esas2017/index.htm*.
[6] Find out more about the elements of NASA's Earth Venture program at *https://essp.nasa.gov/projects*.
[7] To learn more about TEMPO see "NASA Ups the TEMPO on Air Quality Measurements" in the March–April 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 2**, pp. 10-15—*https://eospso.gsfc.nasa.gov/sites/default/files/eo_pdfs/March_April_2013_508_color.pdf#page=10*.
[8] More information on GeoCarb can be found at *http://www.ou.edu/geocarb* and *https://www.nasa.gov/feature/jpl/geocarb-a-new-view-of-carbon-over-the-americas*].

The workshop focused on the findings of the GEO-CAPE AQ Working Groups (WGs) for Emissions, Aerosols, Methane, Airborne Simulators, and both regional/urban and global OSSEs. These WGs provided the rationale for GEO-CAPE science data collection and how those data would be applied for the benefit of society. Summaries of the objectives and accomplishments of each of these WGs are summarized below.

The workshop focused on the findings of the GEO-CAPE AQ Working Groups for Emissions, Aerosols, Methane, Airborne Simulators, and OSSEs—both regional/urban and global.

Aerosol Working Group

This WG was formed to define the aerosol science questions, objectives, and measurement requirements, and how to best use a spacecraft in GEO to answer them. As an example, how would aerosol algorithms designed for LEO spacecraft (e.g., Terra and Aura) be applied to observations from GEO? One solution came from the demonstration that the Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm developed for MODIS and VIIRS[9] for high-spatial-resolution measurements of aerosol optical depth performed quite well for GEO observations. Most important, the WG concluded that GEO-CAPE aerosol requirements can be met using TEMPO–GOES[10] synergy.

Emissions Working Group

The goal of this WG was to determine if high-resolution data from aircraft and ground-based measurements combined with modeling could establish the benefits of measurements obtained from GEO to constrain models of emissions and chemical processes. They found that using new retrievals that employ nonlinear methods will result in a better understanding of the impact of meteorology on AQ at the lowest levels of the atmosphere.

Airborne Simulators Working Group

This WG also demonstrated that extended *field campaigns,* such KORUS-AQ, SARP, and DISCOVR-AQ,[11] made major contributions to proving GEO-CAPE's potential by testing prototype satellite instruments on aircraft, verifying algorithms, and demonstrating the value of high-resolution data. These campaigns introduced and provided a way forward for calibration and validation (cal/val) of AQ missions once they are in orbit.

OSSE Working Group

The workshop outcomes can be summarized with examples from this WG, whose members ran numerous simulations that included data from ground-based observations, aircraft missions, and satellites for current and future missions. These experiments demonstrated that TEMPO synergy with other atmospheric composition measurements will meet most of GEO-CAPE's objectives by including satellites flying as part of a constellation. For example, one OSSE revealed that a LEO mission can detect fluxes at sufficient resolution to test biogeochemical processes that are central to understanding the evolution of the North American methane (CH_4) budget. Furthermore, the experiments showed that continuous measurements over a specific location with high temporal and spatial resolution—only available from the vantage point of GEO—can capture episodic emissions such as industrial accidents and gas well leaks.

[9] MODIS stands for Moderate Resolution Imaging Spectroradiometer, which flies on NASA's Terra and Aqua platforms; VIIRS stands for Visible Infrared Imaging Radiometer Suite, which flies on Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA-20.
[10] GOES stands for Geostationary Operational Environmental Satellite system, which is a series of satellites launched by NASA and operated by NOAA. Currently GOES-16 and -17 hover over the eastern and western portions of the U.S., respectively.
[11] KORUS-AQ stands for International Cooperative Air Quality Field Study in Korea; SARP stands for Student Airborne Research Program; and DISCOVR-AQ stands for Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality.

CEOS AC-VC Meeting Summary

The Fourteenth CEOS AC-VC meeting took place right after the GEO-CAPE Workshop at the same location. It was organized around four objectives, which were to:

- discuss the current and future capabilities and status of the AQ Constellation;
- refine the requirements of and report on the status of the Greenhouse Gas Constellation;
- review upcoming instruments and missions that will contribute to both these Constellations; and
- review progress in developing a consistent global O_3 dataset from several O_3-monitoring instruments flying on various CEOS agencies' missions.

In all, there were 59 oral and 17 poster presentations given at the fourteenth meeting. The agenda—and most of the presentations—can be found at *http://ceos.org/meetings/ac-vc-14*.

Air Quality Constellation

Satellites in LEO have demonstrated the ability to observe local and regional environmental conditions on a global scale. However, they have limited temporal coverage (usually once per day over any given spot on Earth's surface) and spatial resolution of the order of 10 km (~6 mi) for atmospheric composition. In light of these limitations, observations from a geostationary vantage point afford another dimension for tracking and assessing environmental processes over time. Furthermore, GEO measurements can observe atmospheric progressions throughout the day at higher spatial resolution than measurements from LEO. A limitation of GEO observations, however, is that they are restricted solely to the region below the satellite, and therefore do not cover the whole globe. A good example of using both types of orbits is provided by the data from operational meteorological satellites, where combined observations have led to major improvements in short- and long-term weather forecasting skills. The deployment of the AQ Constellation takes this concept and applies it to monitoring air pollution and its precursors on a global scale, with high-horizontal and -temporal resolutions.

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New and Planned Air Quality Missions

Representatives from CEOS space agencies attending the meeting were eager to present their contributions to this Constellation, describing instrument technologies, mission capabilities, and forthcoming applications that will lead to better understanding of the origins of poor AQ and improved forecasting, overall.

There were detailed presentations on three GEO missions, four LEO missions, and proposed synergy with the international operational meteorological missions in both LEO and GEO. The operational satellites make crucial complementary measurements: e.g., clouds, aerosols, temperature, and derived winds. **Figure 1** (next page) depicts the missions that either are currently or will be part of the AC-VC's AQ Constellation. The presentations included updates on instrument status and performance, algorithm development, calibration, validation, and data availability. All the missions will measure a suite of constituents relevant to AQ and stratospheric O_3 using advanced spatial scanning hyperspectral capabilities. Some examples of these constituents include ozone (O_3), sulfur dioxide (SO_2), aerosols and their precursors, nitrogen dioxide (NO_2), formaldehyde (HCHO), carbon monoxide (CO), and volatile organic compounds (VOCs).

Some components of the AQ Constellation are already in orbit while others are under development. Relevant details of the missions appear in **Table 1** (next page), which is followed by further discussion of their supporting programs.

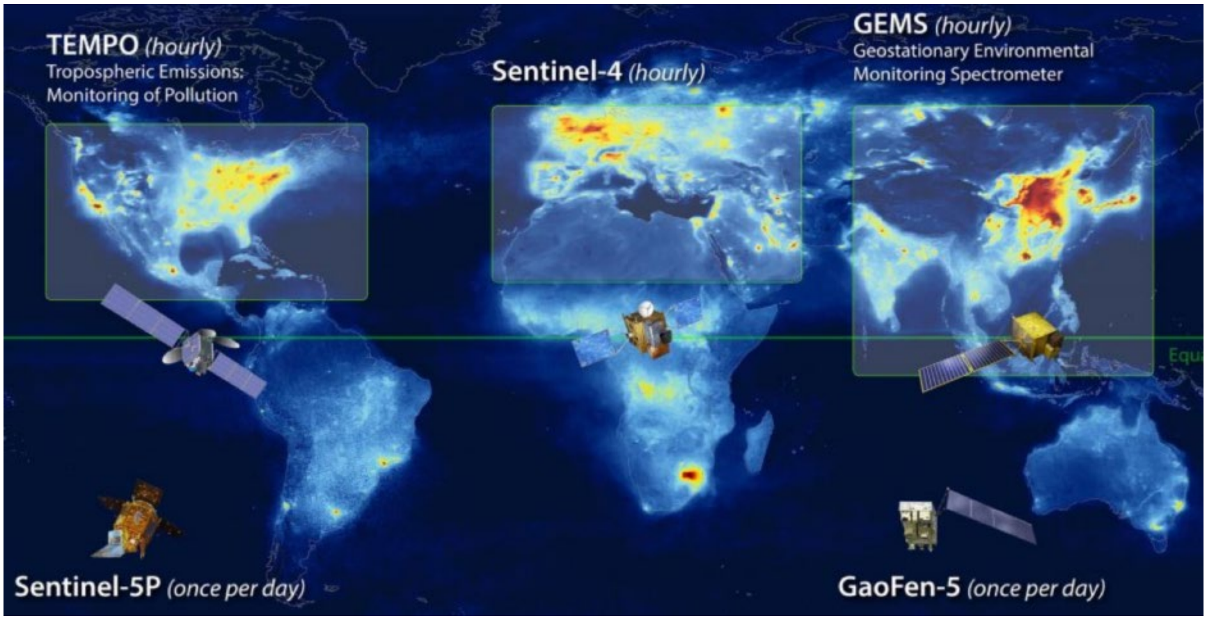


Figure 1. This figure illustrates the missions whose instruments are dedicated to the AC-VC's AQ Constellation. For example, the Sentinel-5P mission, carrying the Tropospheric Monitoring Instrument (TropOMI), has been in orbit for about a year and is flying in formation with Suomi National Polar-orbiting Partnership. The Environmental Monitoring Instrument, which flies on the Chinese GaoFen-5 satellite, launched in May 2018, is also part of the constellation. The geostationary components of the constellation include NASA's TEMPO, ESA's Sentinel-4, and Korea's GEMS—all to be launched by 2022. They are designed to hover over Earth's major industrial regions at 100° W, 0°, and 128° E longitudes, respectively. Not shown in the figure are other polar-orbiting satellites that also collect AQ data, e.g., NASA's Aura, Terra, and Aqua satellites, and the U.S. (NOAA) and European (MetOp) operational meteorological satellites. **Image credit**: NASA and ESA

Table 1. The Sentinel missions are supported by the European Union's (EU's) Copernicus program (see Footnote 13). MetOp-SGs are the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT's) Second-Generation (SG) polar-orbiting satellites. The instrument measurements are hyperspectral and operate in the ultraviolet (UV), visible (VIS), near-infrared (NIR), and shortwave-infrared (SWIR), as indicated. The spatial resolutions range from about 4 to 40 km (~2.5 to 25 mi). Other agency acronyms used in the Table appear in the text.

Measurement System	Agency	Instrument Type	Platform	Orbit	Coverage	Launch Year
SAGE III	NASA	UV-VIS Occultation	International Space Station	LEO Inclined	Global, 60°N-60°S	2017
Sentinel-5P/ TropOMI	ESA/KNMI	UV-VIS-NIR-SWIR	ESA/dedicated satellite	LEO Polar	Global	2017
EMI	CASC	UV-VIS	GaoFen-5	LEO Polar	Global	2018
Sentinel-5	ESA/EUMETSAT	UV-VIS-NIR-SWIR	MetOp-SG 1A	LEO Polar	Global	2021
IASI-NG	CNES/ EUMETSAT	IR	MetOp-SG 1A	LEO Polar	Global	2021
TEMPO	NASA/SAO	UV-VIS	Commercial	GEO	Central-North America	2019
GEMS	KARI	UV-VIS	GEO-KOMPSAT 2B	GEO	Eastern Asia	2020
Sentinel-4A Sentinel-4B	ESA/EUMETSAT	UV-VIS	MTG-S	GEO	North Africa-Europe	2022 2027

- **Stratospheric Aerosol Gas Experiment-III** (SAGE III) is a follow-on to several earlier SAGE missions that began in 1979. It has been operating on the International Space Station (ISS) for about one year as of this writing.

- **Sentinel-5P** [P stands for precursor] carries the Tropospheric Monitoring Instrument (TropOMI) instrument, an advanced version of the Ozone Monitoring Instrument (OMI) flying on NASA's Aura satellite. The Royal Netherlands Meteorological Institute [Koninklijk Nederlands Meteorologisch Instituut (KNMI)] is responsible for the instrument, its calibration, validation, algorithms, and data processing.[12]

- **Environmental Monitoring Instrument** (EMI) was developed by the China Aerospace Science and Technology Corporation (CASC) and flies on the Chinese GaoFen-5 satellite. The satellite carries five other Earth-observing instruments, which were not discussed at this meeting.

- **Sentinel-5** will have the same performance specifications as Sentinel 5P, but the instrument will be built by ESA and flown on MetOp as part of the Copernicus[13] program.

- The MetOp operational sounder instrument is being upgraded to the **Infrared Atmospheric Sounding Interferometer-New Generation** (IASI-NG) by France's Centre National d'Études Spatiales (CNES). It will fly on follow-on MetOps and has capabilities to measure both AQ and GHGs.

- The U.S. contribution to the Constellation will be NASA's **TEMPO**, developed by the Smithsonian Astronomical Observatory (SAO); the mission is directed by NASA's Earth Venture program. Efforts are underway to find a commercial host GEO satellite.

- South Korea's contribution to the AQ Constellation is the **Geostationary Environmental Monitoring Spectrometer** (GEMS), which will fly on the Geostationary Korea Multi-Purpose Satellite (GEO-KOMPSAT) 2B. It is being developed by KARI.

- Europe's contribution will be the Copernicus **Sentinel-4** instrument developed by ESA and hosted by EUMETSAT's Meteosat Third Generation-S (MTG-S) meteorological satellite.

Measurements of GHG sources, distribution, and sinks have become a high priority internationally in order to achieve a better understanding of why and how Earth's climate is changing.

Early Results from the AQ Constellation

An early example of the type of data expected from the constellation is shown in **Figure 2,** which illustrates Sentinel-5P/TropOMI's high spatial resolution of 3.5 km x 7 km (~2.2 mi x 4.3 mi)—the best ever retrieved for satellite-based atmospheric composition measurements to date. The instrument is capable of measuring ozone in the troposphere and stratosphere and a host of other gases important to AQ and climate research and applications.

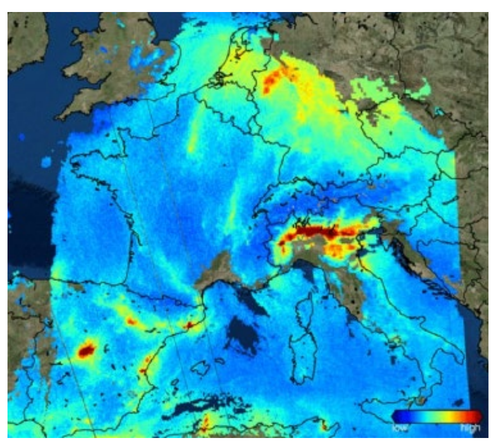


Figure 2. This figure illustrates Sentinel-5P/TropOMI's high spatial resolution over Western Europe. These data are column amounts of tropospheric nitrogen dioxide (NO_2). Red denotes high concentrations, while light blue denotes lower concentrations; grey indicates cloud cover. NO_2 results from fossil fuel burning include emissions from cars, power plants, and manufacturing. The high levels of NO_2 over northern Italy are from industry in the Po Valley; those over northeastern Germany are from cities in the Ruhr Valley. Madrid, Spain, is having a particularly bad air day. **Image credit**: ESA and KNMI

Greenhouse Gas Constellation

Measurements of GHG sources, distribution, and sinks have become a high priority internationally in order to achieve a better understanding of why and how Earth's climate is changing. Of utmost importance is defining how anthropogenic GHG sources affect natural cycles. The most important man-made climate forcing GHGs are carbon dioxide (CO_2) and CH_4. CO_2 has been measured from the ground for

[12] To learn more about recent activity with TropOMI, see the "OMI Science Team Meeting Summary" on page 31 of this issue.
[13] Find out more about the European Union's Copernicus program at *http://www.copernicus.eu/main/satellites*.

several decades with an increasing number of stations that also include CH_4 measurements. Upward global trends have been precisely quantified from these ground measurements. However, ground-station distribution is too sparse to quantify point sources and sinks on regional scales, so measurements from space are the only way to capture their magnitudes. An increasing number of high-performance satellite observations with high precision and spatial resolution are being brought online by the world's national space agencies. CEOS has responded to the international call for GHG measurements with a report titled the *CEOS Strategy for Carbon Observations from Space*.[14] The report calls for an overall understanding of the carbon cycle and its connection to land, sea, and air processes, and using space-based resources to provide an unequivocal assessment of their anthropogenic impacts.

An increasing number of high-performance satellite observations with high precision and spatial resolution are being brought online by the world's national space agencies.

Greenhouse Gas Constellation Formulation

CEOS has delegated the responsibility for implementation of the various discipline-specific satellite constellations to the CEOS Virtual Constellations and WGs. As noted earlier, in response, the AC-VC has established a GHG Virtual Constellation group that will coordinate the GHG missions now in orbit and those planned for the future. The GHG Constellation group has written a white paper titled, *A Space-Based Constellation Architecture for Estimating Atmospheric Carbon Dioxide and Methane Concentrations and Fluxes from Natural and Anthropogenic Sources and Sinks*. **David Crisp** [NASA/JPL—*Orbiting Carbon Observatory-2 (OCO-2) Science Team Leader*] is the white paper's first author. He led this portion of the meeting, which focused on the status and finalization of the document.[15] This session also included presentations on missions now in orbit and on future missions and how they will be coordinated. Coordination includes refining instrument specifications to ensure science requirements are met, algorithm development and testing, OSSE studies, cal/val plans, data processing and archiving, and satellite system operations that include coordinated observations from LEO and GEO.

The group's first activity was to account for and report on missions in orbit and those planned to fly by producing a timeline that identifies the mission, GHGs measured, instrument spatial sampling resolution, and the operational timeline. The results from this activity appear in **Figure 3.**

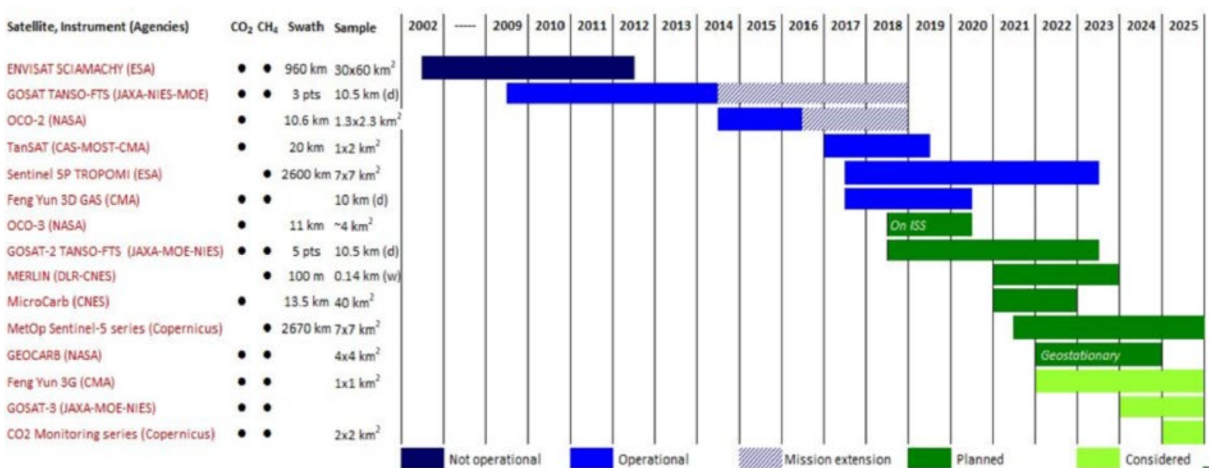


Figure 3. Greenhouse gas mission overlaps until 2025. Contributions come from the U.S., EU, ESA, China, France, and Japan. All missions are in LEO except GeoCarb, which is proposed for GEO. **Image credit:** NASA

Operating GHG Missions' Performance

Although no data were shown at the meeting, ESA's SCIAMACHY[16] was acknowledged as the first instrument to measure and produce regional-scale seasonal maps of

[14] The background for this document and the document itself can be found at *http://ceos.org/home-2/the-ceos-carbon-strategy-space-satellites*.

[15] **UPDATE:** This white paper has now been completed and endorsed by the CEOS Principals as of October 2018 and submitted to the participating space agencies.

[16] SCIAMACHY stands for the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography instrument which flew on ESA's Envisat satellite from March 2002 to April 2012. Its purpose was to measure trace gases, clouds, and aerosols.

column CO_2 and CH_4 using reflected near NIR and SWIR sunlight over the continents. One notable result from SCIAMACHY data show that *fugitive CH_4 emissions*[17] from fracking over several large oil and gas fields in the U.S. exceed the amount of the supposed "climate benefit" threshold from switching from coal to natural gas, i.e., the benefit of using the cleaner-burning (meaning fewer CO_2 emissions) natural gas is offset by the methane leakage resulting from extracting the gas from the ground. This is an important result that needs to be verified and further quantified by the upcoming high-performance instruments.

A good example of using both types of orbits is provided by the data from operational meteorological satellites, where combined observations have led to major improvements in short- and long-term weather forecasting skills.

The JAXA-built **Greenhouse Gases Observing Satellite** (GOSAT) has been in orbit since 2009; GOSAT-2 is being prepared for launch by the end of this year.[18] The GOSAT-2 instrument is a Fourier-transform spectrometer (FTS), which is an improvement over GOSAT with regard to radiometric sensitivity, spatial resolution, and coverage. Aerosols will be measured directly and will be correlated with GHG emissions. The satellite will fly in an LEO. A sample of GOSAT results since launch presented at the meeting included the consistency (with a small bias) with ground-based measurements of global CO_2 trends. GOSAT's monthly global averages have been used to constrain CO_2 and CH_4 regional scale fluxes from the biosphere and oceans, used to quantify anthropogenic sources. GOSAT continues its validation campaigns with comparisons with ground observations and the Orbiting Carbon Observatory-2 (OCO-2), which is discussed next.

NASA's **OCO-2** has been in orbit since 2014; significant improvements in calibration and algorithms continue to this day. These efforts have revealed several errors in the current algorithm that will be corrected in the next release this year. These include small errors in geolocation, long-term radiometric drift, and surface-pressure drift. Nevertheless, OCO-2 has made important contributions to carbon-budget science. For example, measurements of solar-induced chlorophyll fluorescence (SIF),[19] discovered by GOSAT, along with CO_2 column amounts from OCO-2, provided high-resolution distributions of the atmospheric carbon global cycle. With its high spatial resolution, OCO-2 data have also been used to spot CO_2 variations across megacities and even to quantify fossil fuel emissions from individual power plants. An example of OCO-2's capabilities appears in **Figure 4**.

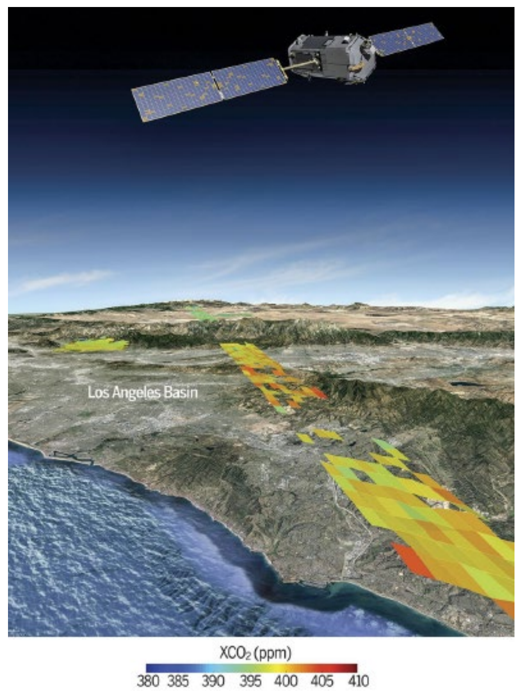


Figure 4. OCO-2 detects urban CO_2 signals over Los Angeles, CA. Individual "footprints" of OCO-2 images from early fall 2014 and summer 2015 over Los Angeles strongly contrast with values over the distant, rural Antelope Valley. The scale is X_{CO2}, the average dry-air molar CO_2 concentration between the spacecraft and Earth's surface. **Image credit:** NASA, Science

OCO-3 is a complete stand-alone payload built using the spare OCO-2 flight instrument, with additional elements added to accommodate installation and operation on the International Space Station (ISS). As of this writing, thermal vacuum tests have been completed and the NASA/JPL team is making preparations for a launch to the ISS in early 2019.

Sentinel-5P was mentioned earlier as a contributor to the Air Quality Constellation as it measures pollution and precursor gases. Using the SWIR channel, Sentinel-5P is also able to measure CH_4. Sentinel-5P flies in formation with Suomi NPP, which allows the Sentinel-5P CH_4 measurements to be correlated with cloud information from Suomi NPP, thus offering a way to correct the CH_4 data for the presence of clouds.

The mission is also producing other climate-related products such as cloud and aerosol maps. Most data products will be available in near-real time for short-term forecasting. While preliminary data show a small bias when compared to GOSAT, useful global maps are still being produced at 7 km x 7 km (4.3 mi x 4.3 mi) spatial resolution. With

[17] Natural gas is mainly composed of methane, some of which escapes during the drilling, extraction, and transportation processes. Such outbreaks are known as fugitive emissions.
[18] **UPDATE:** GOSAT-2 was launched successfully on an H-IIA rocket from Japan's Tanegashima Space Center on October 29, 2018.
[19] Solar-induced chlorophyll fluorescence is directly related to changes in vegetation photosynthesis and plant stress.

this resolution, quantifying CH_4 point sources will far surpass the SCIAMACHY results discussed at the beginning of this section.

TanSat, also known as CarbonSat, is a Chinese Earth observation minisatellite dedicated to monitoring CO_2. It was developed by the CAS and launched into a LEO in December 2016. The satellite carries two instruments: a high-spectral-resolution spectrometer for CO_2, and a cloud and aerosol polarimeter. Extensive comparisons have been made with the Total Carbon Column Observing Network (TCCON)[20] ground network showing agreement within error bars. Monthly maps of global CO_2 and SIF have been compared with OCO-2 maps, and show good agreement.

The performance and instrument suite capabilities of the Chinese GaoFen-5 satellite were described at this meeting, about a month before its successful launch on May 9, 2018. The satellite is also in an LEO and carries six hyperspectral imaging instruments to measure GHGs, trace gases, and aerosols. The satellite was developed by the CASC. The GHG algorithms were described and results were shown that used GOSAT data for testing.

The U.S. contribution to the geostationary component to the GHG Constellation is the GeoCarb mission. The mission is the second Earth Venture Mission (EVM-2) selection.

Upcoming GHG Missions

Several upcoming missions with advanced instruments to measure GHGs were described in this session.

In addition to the IASI-NG described earlier, CNES has two additional missions in their pipeline. The first, called **MICROCARB**, scheduled for launch early in 2021, is a microsatellite, weighing only 170 kg (~77 lbs), which is larger than a CubeSat but smaller than a minisatellite. It will carry an echelle grating spectrometer and a cloud imager. The spatial resolution, 5 km x 9 km (3.1 mi x 5.6 mi) is similar to the LEO satellite GHG measuring instruments described above. The second CNES mission, being implemented in collaboration with the German space agency [Deutsches Zentrum für Luft-und Raumfahrt (DLR)], is called the **Methane Remote Sensing Lidar Mission** (MERLIN), scheduled for launch in 2021 to fly in LEO. As its name implies, it is dedicated to CH_4 measurements. Its measurement targets will be the major anthropogenic CH_4 emission sources (e.g., power and waste treatment plants, landfills, cattle, rice paddies, and incomplete combustion of biomass) as well as natural sources (e.g., wetlands and thawing permafrost). The lidar instrument has advantages because of its extremely high spatial resolution [100 m (328 ft)] that will be able to pinpoint emission sources with smaller errors from aerosol and cloud interference.

Up to this point, GHG missions flying and to be flown are all in polar LEO. The U.S. contribution to the geostationary component to the GHG Constellation is the **GeoCarb** mission. The mission is the second Earth Venture Mission (EVM-2) selection. GeoCarb is designed to collect observations of the column averaged concentrations of CO_2, CH_4, CO, and SIF at a spatial resolution of 5 to 10 km (3.1 mi to 6.2 mi). With these measurements, GeoCarb will provide new measurements related to Earth's natural carbon cycle and allow monitoring of vegetation health. The satellite coverage includes the Americas between 55° N and 55° S latitudes, hovering in orbit near 85° W longitude. GeoCarb will use much of OCO-2's technology and algorithms. Launch is scheduled for June 2022.

There were two presentations on Europe's program for GHG monitoring. The first provided an overview of the program, including justification and scientific requirement established by the EU's Copernicus program. The second presentation was given by a representative from ESA, the Copernicus partner, for implementation of its space component. The high-level requirements for the system are to detect and monitor hotspot emissions, assess their changes, and determine effectiveness of regulations. The EU

[20] The TCCON is a globally distributed network of ground-based spectrometers that record the solar spectra in the NIR. From these spectra, accurate and precise column-averaged amounts of a range of GHGs can be derived. To learn more, see "Integrating Carbon from the Ground Up: TCCON Turns Ten" in the July–August 2014 issue of *The Earth Observer* [**Volume 26, Issue 4**, pp. 13-17—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/JulyAug_2014_color508.pdf#page=13*].

is establishing a task force to perform system simulation, assess existing infrastructure for GHG monitoring, and recommend the architecture for an operational system.

ESA envisions a fleet of three satellites, possibly evolving into Sentinel-7, in LEO. Two parallel Phase A/B system studies (concept/system design) and a Mission Advisory Group were started this year, with a target launch date of 2025–2026. The missions will surely be part of the GHG Constellation.

The **AbsoRption spectRometric patHfindEr for carboN regIonal flUx dynamicS** or **ARRHENIUS**[21] is a proposed GEO mission for ESA's Earth Explorer solicitation[22] to observe carbon processes over the African continent, which will have the highest population growth rate by 2030; Europe, which will transition to a low-carbon economy; and the Middle East, to monitor the how the fossil fuel industry will adapt to changing demands. Its science goals are to provide data on the terrestrial carbon cycle and its responses to climatological, meteorological, and human forcing to better estimate climate sensitivity. The mission would be a major contributor to the proposed GHG Constellation, and its technology can be adapted from GOSAT, OCO-2, and Sentinels-5 and -7 thereby reducing costs and development time.

The consensus is that Earth's atmosphere is about to emerge into a phase of ozone recovery as is also predicted by chemistry/transport climate models.

Global Ozone Data Consistency

In addition to dealing with major efforts like organizing satellite constellations, the AC-VC also deals with more down-to-Earth projects. The fourth theme of the meeting is the reconciliation of differences between ozone datasets resulting from various space observations. The WMO Ozone Assessment project provided the motivation and requirements for this effort, which then became a project supported by the AC-VC. This work is needed to ensure the 1987 Montreal Protocol is being followed and because of the connection between stratospheric ozone and climate. This effort is being conducted in two parts: The first, focusing on total column ozone, is complete; the second, focusing on ozone profiles, is underway.

With regard to reconciliation of total column ozone data, there are currently four different satellite datasets available. Two of them rely on the series of Solar Backscatter Ultraviolet (SBUV)[23] instruments covering the period 1979 to 2017, while the other two datasets combine the data from European nadir sounders such as SCIAMACHY, Global Ozone Monitoring Experiment-2 (GOME-2), with those from the OMI on NASA's Aura platform. The European datasets go back to 1995. A fifth dataset is comprised of measurements from a variety of ground-based ozone monitoring instruments. All datasets have been refined and carefully analyzed. Subsequent analysis confirmed that total ozone reached a minimum in about 1994 and has been stable since about 1996, with a signal indicating a positive trend over a major part of the globe. The consensus is that Earth's atmosphere is about to emerge into a phase of ozone recovery as is also predicted by chemistry/transport climate models.

The second ozone project is called Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS).[24] The scientific community has a strong interest in using the recent satellite measurements to evaluate ozone recovery over time as a function of altitude. **Stacy Frith** [NASA's Goddard Space Flight Center] is leading the U.S. effort. She found that ozone profile datasets from space and ground observations differ in amounts that make a definitive statement on trends versus height difficult and depend on assumptions made. Frith examined six satellite datasets, each containing a mix of

[21] This name is homage to Svante Arrhenius. A Nobel Prize winner for Chemistry in 1903, he was the first scientist to investigate the effect of increased CO_2 on Earth's climate.

[22] Earth Explorer missions fall under ESA's Living Planet Programme. For more information, visit *http://www.esa.int/Our_Activities/Observing_the_Earth/Call_for_new_Earth_Explorer_mission_ideas*.

[23] The first SBUV flew on NASA's Nimbus-7 satellite (operating from 1978–1994) with subsequent advanced instruments (SBUV/2) flying on NOAA operational LEO missions until December 2017.

[24] This project is described at *https://www.sparc-climate.org/activities/ozone-trends*. SPARC is a member of the World Climate Research Program.

instruments viewing in the limb and nadir at various wavelengths, and five ground-based datasets. An overarching concern is the instruments' calibration drift over time. **Figure 5** illustrates trends in ozone profiles for the period before 2000 and since. There is clearly a reversal in the profile ozone downward trend after 2000. In all cases, the uncertainties are large, but consistent with model calculations.

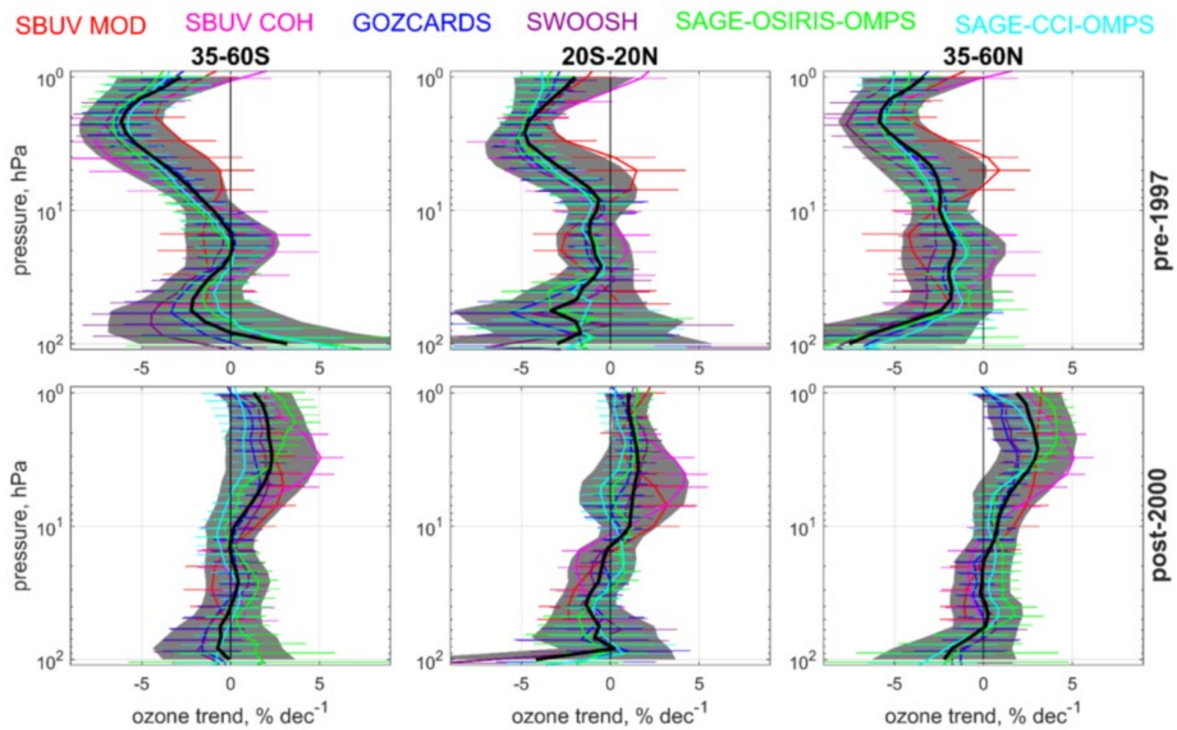


Figure 5. Plotted here are O_3 profile trends as a function of altitude, in percent per decade, for three latitude zones using a number of datasets indicated by the acronyms at the top. For example, post-2000 profiles show significant (+2 to +4% per decade) trends in upper stratosphere in the Northern Hemisphere midlatitudes, while positive trends at lower levels are less pronounced. **Image credit:** Stacy Frith

Subsequent presentations on nadir O_3 instruments operating in the UV focused on calibration and algorithm sensitivity. One presentation employed EUMETSAT's operational IR sounder to measure total O_3 and profiles. Eight years of data showed good agreement with ground-based data. Another presentation showed that upper- and lower-tropospheric O_3 fields could be differentiated when enhanced with data assimilation. Finally, there was discussion about combining data from both IR and UV instruments flying on European and U.S. satellites using coincident data to retrieve more realistic ozone profiles in the troposphere.

Other presentations during this session featured O_3 data from SAGE-III on ISS and TropOMI. The SAGE-III efforts have been primarily directed to checkout and validation of the primary products, which include O_3. The provisional dataset accuracy meet the requirements, and are already available at the NASA Atmospheric Science Data Center archive. Groups on both sides of the Atlantic will continue this study as new data arrive, and will report their findings at the next AC-VC meeting.

Summary

The constellation concept for maximizing data value from orbit is a maturing architecture for space missions. A constellation can be missions flying in formation such as the A-Train[25] or missions in different orbits—such as the Global Precipitation Measurements (GPM) constellation[26]—making similar measurements in the same discipline. The AC-VC provides a forum for exploiting complementary measurements with regard to instrument requirements, algorithm development, cal/val activities, and data accessibility. The AC-VC is formulating two constellations for atmospheric composition measurements. The first, for AQ, is well underway, with missions in

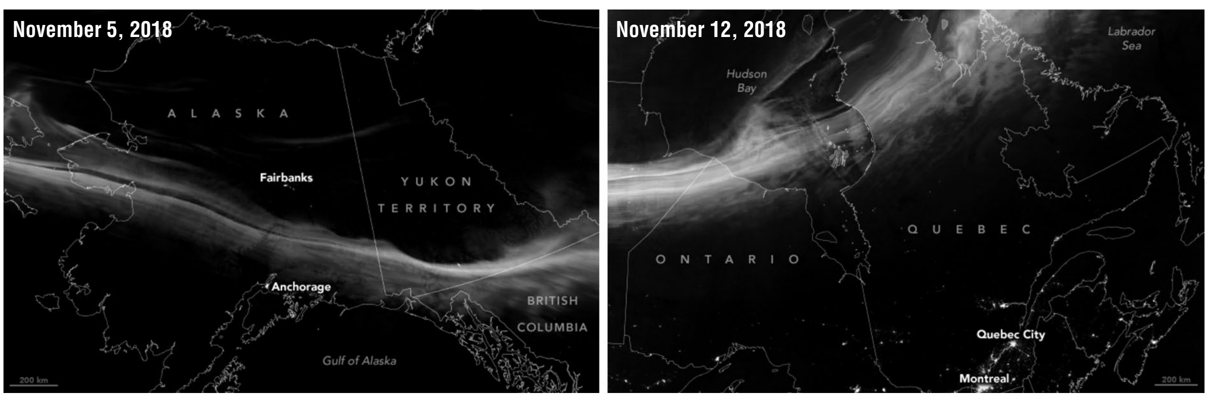
[25] Find out more about the A-Train at *https://atrain.nasa.gov*.
[26] Find out more about the GPM constellation at *https://www.nasa.gov/content/goddard/meet-the-members-of-nasas-gpm-constellation*.

orbit or scheduled for both GEO and LEO operations. An important outcome of the GEO-CAPE formulation effort was the selection of TEMPO, the first of the GEO missions dedicated to AQ observations. It was shown through several OSSEs that TEMPO—along with the operational meteorological satellites—can meet most of GEO-CAPE's requirements for AQ measurements.

The second constellation, for GHG measurements, is still under formulation, but three missions are already in orbit: one each from the U.S., Japan, and China, all in LEO. Two GEO missions, one from the U.S. (approved for flight) and one from ESA (proposed) will join the constellation. A white paper describing a GHG constellation and its implementation has been submitted to the participating space agencies. The report identifies 13 different GHG-monitoring missions that are operating or will operate during the period 2010–2025. The report then calls for each contributing space agency to agree to coordinate their missions and collaborate in their science activities and applications.

A final remark (summarized from the earlier-referenced GHG white paper) concerns the overlapping characteristics of GHG sources and pollutants that affect AQ and how they are measured from space. Surface emissions and the chemistry and transport processes that affect AQ are modified by climate change. Conversely, air pollutants, particularly GHGs, O_3, and aerosols, are significant climate forcers. Moreover, climate forcers and air pollutants are often emitted from common sources, e.g., power plants. Consequently, emerging energy policies designed to moderate climate change and policies designed to improve AQ are inherently connected. The CEOS AC-VC provides a venue for the space agencies to plan their missions to reflect this relationship. ■

The report identifies 13 different GHG-monitoring missions that are operating or will operate during the period 2010–2025. The report then calls for each contributing space agency to agree to coordinate their missions and collaborate in their science activities and applications.



Bright Auroras Light Up the Sky and the Land. From sunset to sunrise, brilliant auroras—also known as the Northern Lights—provided a dazzling light show for Alaskans on November 5, 2018. Seven days later, they appeared again over Alaska and Canada. Those dancing lights were also visible from space.

The image on the left shows the aurora over Alaska very early on November 5, 2018. The light was so bright that it illuminated the terrain below. The aurora likely appeared brighter that night because it occurred two days before a new moon, meaning the sky was darker than at other times in the lunar cycle. The image on the right shows the aurora over eastern Canada on November 12. Satellite imagery and ground reports indicate the aurora was also visible from Alaska, Norway, and Scotland around that time.

Both images were acquired by the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) satellite. VIIRS has a "day-night band" (observing mode) that detects city lights and other nighttime signals such as auroras, airglow, and reflected moonlight. In these images, the sensor detected the visible light emissions that occurred when energetic particles rained down from Earth's magnetosphere and into the gases of the upper atmosphere.

These auroras come at a time known as *solar minimum*, a relatively calm period of activity on the Sun that occurs every 11 years or so. During this time, the Sun experiences fewer sunspots and solar flares—phenomena that can lead to auroras. During a solar minimum, however, auroras are more often caused by coronal holes. These regions of open-ended magnetic fields allow relatively fast streams of solar particles to escape the Sun. This high-speed stream can energize our space environment, shaking Earth's magnetic bubble enough to trigger auroral displays.

Both auroras were caused by high-speed streams, though from different coronal holes. The coronal hole that sparked the November 5 aurora was particularly notable because it has been persistent for months, said **Mike Cook**, space weather forecaster lead at Apogee Engineering and team member of the citizen science project Aurorasaurus (*http://www.aurorasaurus.org*). This coronal hole first appeared in August 2018, and it has sent high-speed streams toward Earth and caused at least four fairly strong geomagnetic storms around Earth. NASA satellites are currently observing the Sun and Earth to see what may be in store when this coronal hole and others turn toward Earth again.

Credit: NASA Earth Observatory images by Joshua Stevens, using VIIRS day-night band data from the Suomi National Polar-orbiting Partnership. Story by Kasha Patel.

Summary of DSCOVR EPIC and NISTAR Science Team Meeting

Alexander Marshak, NASA's Goddard Space Flight Center, alexander.marshak@nasa.gov
Alan Ward, NASA's Goddard Space Flight Center/Global Science & Technology Inc., alan.b.ward@nasa.gov

Introduction

The DSCOVR EPIC and NISTAR Science Team Meeting (STM) was held at NASA's Goddard Space Flight Center (GSFC) from September 17-18, 2018. Overall attendance was estimated between 75 and 90 people. While most participants were from GSFC, several were from other NASA centers, U.S. universities, and Department of Energy government labs; one person came from as far away as Estonia.

Since this is the first time *The Earth Observer* has reported in detail on the DSCOVR mission, this article begins with a brief overview of the mission and its two Earth-observing instruments to place the meeting in context, and then summarizes the meeting. The full presentations summarized herein can be found at *https://avdc.gsfc.nasa.gov/pub/DSCOVR/Science_Team_Presentations_Sept_2018*.

DSCOVR Mission Overview

Until recently, most satellites observing the Earth have done so from relatively short distances: typically just a few hundred kilometers above us in low Earth orbit (LEO), slightly higher in polar orbit, or two orders of magnitude further away in geostationary orbit (GEO)—see **Figure 1**, *left*. The National Oceanic and Atmospheric Administration's (NOAA) Deep Space Climate Observatory (DSCOVR), however, views Earth from a whole new perspective. The mission launched in February 2015 to the *first Lagrange Point* (L_1)—a "balance" point between the Sun and the Earth. DSCOVR is now effectively parked in space a million miles away (~1,609,000 km) from Earth, the tiny spacecraft held stationary in the balance between the gravitational pulls of the two much larger celestial bodies and the centripetal force acting on the orbiting satellite—see **Figure 1**, *right*.[1]

Originally conceived in the late 1990s, the mission then known as Triana[2] (or "Goresat" in some circles because the then U.S. Vice President had been the one to propose it to NASA Administrator Dan Goldin), was to be an Earth Science mission that would have been launched from the Space Shuttle, and provided a near-continuous view of Earth and measure its complete albedo. After 21 months of development, the original

[1] To learn more about these "parking places in space", visit *https://www.nasa.gov/audience/forstudents/postsecondary/features/f-lagrange_prt.htm*.
[2] The name Triana was chosen in honor of the name of the lookout in Christopher Columbus's fleet, who is alleged to have been the first to see the "New World."

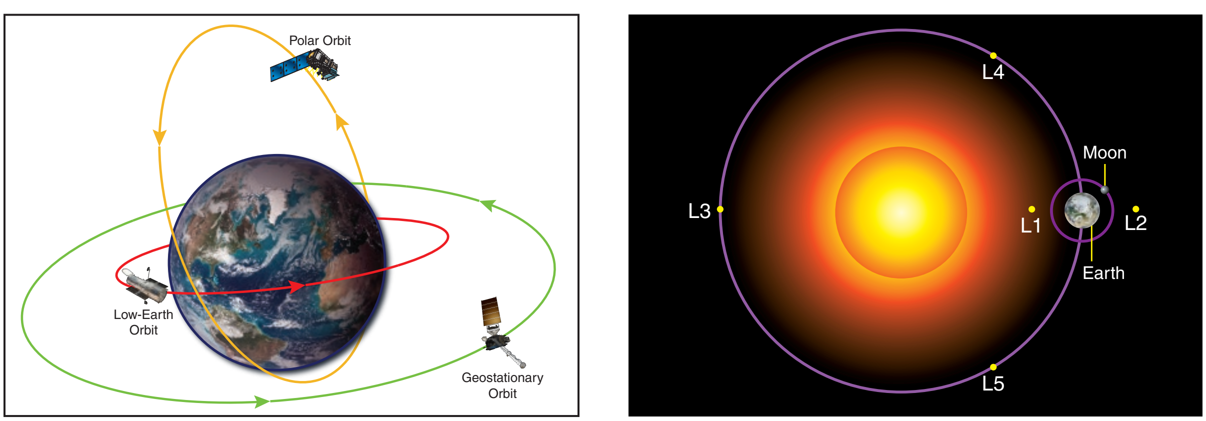


Figure 1. The diagram on the left shows the most common orbits for Earth-observing satellites. All are relatively close to Earth. By contrast, the diagram on the right shows DSCOVR's vantage point nearly one million miles away at the first Lagrange point (L_1) held in place by the offsetting gravitational pull of the Earth and the Sun and the centripetal force acting on the satellite. The diagram on the right also shows the locations of the other four Lagrange "balance" points (L_2–L_5) in the Sun–Earth–Moon system. There are other NASA spacecraft that either occupy or will occupy some of these other positions. For example, the James Webb Space Telescope will be positioned at L_2—a great fixed position to observe deep space. **Image credit**: NASA

mission was cancelled and removed from the Space Shuttle's manifest. The nearly-completed spacecraft was put into a state of "stable suspension" and stored in a clean environment at GSFC in November 2001. There it would sit in hibernation until 2008.

In 2005 NASA, NOAA, and the U.S. Air Force realized that they needed a successor for NASA's aging Advanced Composition Explorer (ACE), which was the only satellite providing real-time solar wind observations from the L_1 orbit at the time. Fortunately, someone remembered that there was a satellite in mothballs that might be a perfect replacement. In 2008, engineers at GSFC performed a *limited aliveness* test of the spacecraft—i.e., proving its systems were in good working order. The spacecraft was removed from storage, reserviced, and given a new name: DSCOVR.

DSCOVR Earth-Observing Instruments

While the DSCOVR mission's primary focus is on the Sun, studying solar flares and other space weather phenomena, the Earth-viewing instruments designed for the former Triana mission were also available.[3] And even though the focus had now flipped to "the other side" of the spacecraft,[4] the new mission still offered the perfect vantage point for monitoring Earth from L_1 orbit—essentially a continuous view of Earth from sunrise to sunset. Between 2009 and 2011, the original instrument designers refurbished and recalibrated the two Earth-viewing instruments onboard: the Earth Polychromatic Imaging Camera (EPIC) and the National Institute of Standards and Technology (NIST) Advanced Radiometer (NISTAR).

It is the Earth-facing side of the satellite that is the focus of this article. Since the material that follows makes frequent references to EPIC and NISTAR, their characteristics are briefly described next.[5]

EPIC

EPIC is a 10-channel spectroradiometer, covering a wavelength range between 317 and 780 nm. It provides 10 narrow band spectral images of the entire sunlit face of Earth using a 2048 x 2048 pixel charge-coupled device (CCD) detector coupled to a 30-cm (~12-in) aperture Cassegrain telescope. EPIC has a field of view of 0.62°, which is sufficient to image the entire Earth, which has a nominal size of 0.5°at that orbital position. Owing to the tilted orbit around L_1, the apparent angular size of the Earth changes during the 6-month orbital period from 0.45° to 0.53°.

As the meeting summary that follows will show, imagery from EPIC are being used in science applications to measure total column ozone, sulfur dioxide (SO_2) from volcanic eruptions, visible (VIS) and ultraviolet (UV) properties of aerosols, cloud height and phase, vegetation properties, and atmospheric correction, including surface reflectance.

Table 1 lists the ten channels along with their primary applications.

Table 1. EPIC Channels and primary applications (relating to Level-2 data products).

Wavelength (nm)	Primary Application(s)
317.5	Ozone and sulfur dioxide
325	Ozone and sulfur dioxide
340	Ozone, sulfur dioxide, and aerosols
388	Sulfur dioxide, aerosols, and clouds
443	Aerosols and clouds
551	Aerosols and vegetation
680	Aerosols, vegetation, and clouds
687.75	Cloud height
764	Cloud height
779.5	Clouds and vegetation

NISTAR

NISTAR employs three electrical substitution radiometers and a photodiode to measure reflected sunlight and infrared emission from Earth. NISTAR measures the absolute irradiance integrated over the entire sunlit face of Earth in four broadband channels, minute-by-minute—see **Figure 2** on page 18.

The data collected by NISTAR on Earth's albedo, incoming shortwave (SW) and longwave (LW) radiation, and outgoing LW radiation has never been measured from this position before. DSCOVR's unique location at L_1 permits long integration times because no scanning is required. These measurements complement other existing energy balance data, and help to improve our understanding of the Earth's radiation budget.

[3] To learn more about DSCOVR's primary mission and Sun-viewing instruments, see *https://www.nesdis.noaa.gov/sites/default/files/asset/document/dscovr_program_overview_info_sheet.pdf*.
[4] In the original Triana mission concept, the Earth-viewing instruments were the primary focus of the mission with Sun-viewing instruments secondary.
[5] This information is adapted from *https://www.nesdis.noaa.gov/sites/default/files/asset/document/dscovr_epic_instrument_info_sheet.pdf* and *https://www.nesdis.noaa.gov/sites/default/files/asset/document/dscovr_nistar_instrument_info_sheet.pdf*, respectively. View these documents for more information on EPIC and NISTAR, respectively.

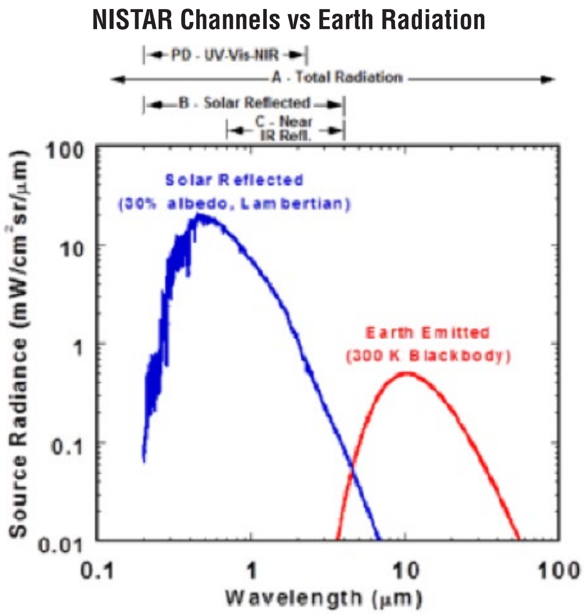


Figure 2. The NISTAR instrument looks at the outgoing radiation from Earth in a variety of wavelength ranges, or bands, indicated in the plot. Band A measures the total radiant power in the UV, visible, and infrared wavelengths emerging from Earth. Band B measures the amount of sunlight directly reflected from Earth (solar reflected curve). By subtracting the light collected in band B from that of band A it is possible to determine the radiation emitted from Earth in the infrared (Earth emitted curve). The reflected solar energy may be further resolved by subtracting band C measurements from band B measurements. **Note:** A fourth band (band D, *not shown*) is used for calibration, tracking the stability of the filters, and verifying coalignment of NISTAR and EPIC. **Image and text credit**: *https://epic.gsfc.nasa.gov/about/nistar#*

Opening Presentations

Alexander Marshak [GSFC—*DSCOVR Deputy Project Scientist*] opened the meeting; he announced that the mission successfully passed its End of Prime Mission review on July 24, 2018, and that the team was directed to prepare and submit a proposal to the 2020 Earth Science Senior Review.[6] The review recommended that EPIC and NISTAR receive continued funding through FY20 (and possibly beyond, depending on the outcome of the 2020 Senior Review) for continued operations and data analysis.

Adam Szabo [GSFC—*DSCOVR Project Scientist*] reported on the status of both EPIC and NISTAR, noting that both instruments are healthy. He also said that new Research Opportunities in Space and Earth Sciences (ROSES) DSCOVR science team proposals were under review.

[6] Periodically, NASA Headquarters conducts a review of a subset of its Earth Science missions to assess overall progress toward achieving mission objectives and viability for continuation or extension of the mission. The most recent review took place in 2018; the next is scheduled for 2020.

Steve Platnick [GSFC—*Deputy Director for Atmospheres in the Earth Science Division*] welcomed meeting participants to GSFC. Platnick noted that this is an exciting time for DSCOVR's Earth viewing instruments as products are being released and the broader science community can be engaged through these products. He thanked NASA HQ for their continued strong interest in the mission.

The next two presentations provided NASA Headquarters' (HQ) perspective on the DSCOVR mission, including the plans for the next two years (i.e., up to FY20) and potentially beyond. Participants first heard from **Richard Eckman** [NASA HQ—*DSCOVR EPIC/NISTAR Program Scientist*] who discussed the current status of the DSCOVR program and its positive funding outlook following Congressional committee action on the FY19 budget. He also discussed the DSCOVR science team re-competition. Proposals had been received in response to the ROSES call in September and the evaluation process was underway. Eckman also described the very positive NASA HQ view of the science team's delivery of Level-2 science programs to the Langley ASDC for public access and recent peer reviewed DSCOVR publications.

Jack Kaye [NASA HQ—*Associate Director for Research in the Earth Science Division*] also spent time at the meeting and made an impromptu overview presentation on the NASA Earth science budget, its multiyear outlook, and the status of NASA's implementation of recommendations from the National Academies' 2017 Earth Science Decadal Survey.

Updates on Science Operations, Data Products and Processing, and the Mission Website

Carl Hostetter [GSFC—*DSCOVR Science Operation Center (DSOC) Manager*] reported on the status of the DSOC. After that, **Marshall Sutton** [GSFC] discussed generating and archiving EPIC Level 2 (L-2) products. He mentioned that since DSCOVR EPIC L-2 processing began in November 2017, 93,519 data files and over 18 terabytes of data have been produced.

Susannah Pearce informed the science team about the new developments on the EPIC website (*epic.gsfc.nasa.gov*). Enhancements include the addition of a *Science* tab (upper right) that includes information on calibration (UV, VIS, and O_2 bands) and data products (ozone, SO_2, UV aerosols, atmospheric corrections, clouds, vegetation). A description of the NISTAR instrument has also been added to the *About* tab.

Karin Blank [GSFC] reported on the newest version of the L-1 data (Version 3) that will be publicly available in October 2018.[7] She described how the task of geolocating EPIC images is challenging because it requires making corrections for atmospheric refraction, incorporating input from an optical model, correcting for attitude, and precise latitude/longitude determination. The new version will include the algorithm that brings the geolocation solution within requirements.

Walt Baskin [NASA's Langley Research Center (LaRC) Atmospheric Sciences Data Center (ASDC)] held an interactive dialog with science team PIs and data managers in which he illustrated the process for an EPIC/NISTAR product to promote a new data collection making it available for order by the public. Baskin also briefed the science team on user metrics, presenting a monthly breakdown of the number of distinct users and number of orders for EPIC and NISTAR L-1A and L-1B products.

EPIC Calibration

Liang Huang [GSFC/Science Systems and Applications, Inc.] described the calibration efforts for the EPIC UV channels. The data from EPIC are being compared to data from the Ozone Monitoring Profiler Suite (OMPS) Nadir Mapper,[8] which is currently very stable, showing sensitivity drift rates of less than 0.6% per year. **Igor Geogdzhaev** [NASA Goddard Institute for Space Studies (GISS)] discussed the calibration of the VIS and near-infrared (NIR) channels on EPIC using matching data from the Moderate Resolution Imaging Spectroradiometer (MODIS).[9] He noted that improvements and corrections to successive EPIC data releases require new radiometric calibration. His team proposed to develop an improved EPIC calibration process comparing Earth and Moon observations with data from multiple satellites in low Earth orbits. Finally, **Matthew Kowalewski** [GSFC/Universities Space Research Association] discussed how the oxygen absorption channels on EPIC were calibrated using lunar observations, and reviewed the stability of the calibration factors.

NISTAR Status Report

Allan Smith [L_1 Company] gave an overview of a current status of NISTAR. He said that the NISTAR radiometer SW channel, band B, currently measures approximately between 8 and 13% more flux than predicted using the Clouds and the Earth's Radiant Energy System (CERES)[10]-derived models (see **Wenying Su**'s presentation in Table 2 on page 21), which is much larger than the NISTAR measurement uncertainty of ~2%. Given the large discrepancy, potential sources of unquantified error in the NISTAR measurements are being investigated. These include the on-orbit stability of the instrument, an unexpected transient observed on orbit but not during laboratory calibration. Thus far, the explanation for the discrepancy between the CERES-derived model and NISTAR remains elusive, but the investigation continues.

EPIC Level 2 Product Updates

This year the EPIC L-2 products were generated and their first version was released to the public through LaRC's ASDC between November 2017 and June 2018. There were seven presentations from Science Team members discussing the status of various EPIC L-2 data products and one describing a combined EPIC–NISTAR product. **Table 2** on pages 20-21 summarizes these presentations. For more details, refer to the original presentations via the URL referenced in the Introduction.

Science Results from EPIC and NISTAR

The second day of the meeting was dedicated to presentations of the latest science results obtained by using EPIC and/or NISTAR data.

Alexei Lyapustin [GSFC] addressed EPIC atmospheric correction over the ocean. Good quality MAIAC EPIC cloud detection and aerosol retrieval over the ocean translates into a good quality water-leaving reflectance (R_w) in the UV-VIS. The derived EPIC R_w in the UV (340 and 388 nm) shows strong inverse relationship to the MODIS Aqua chlorophyll (Chl) concentration. Broadening of R_w–Chl relationship in the UV compared to 412 nm (from MODIS Aqua) for eutrophic waters indicates good sensitivity of EPIC UV R_w to the Colored Dissolved Organic Material (CDOM), and offers the possibility of mapping CDOM by combining with MODIS ancillary information on Chl and R_w at 412 nm. Comparisons with MODIS Aqua concentration demonstrate the utility for Chl concentration and CDOM.

Jay Herman described how EPIC observed the global reduction in sunlight during the total solar eclipse of August 21, 2017. These data were compared with ground-based SW flux observations from Casper, WY,

[7] **UPDATE**: As of this writing, this product has not been publicly released.
[8] OMPS Nadir flies on the Suomi National Polar-orbiting Partnership (NPP) platform.
[9] MODIS flies on NASA's Terra and Aqua platforms.
[10] CERES currently flies on NASA's Terra and Aqua platforms, Suomi NPP, and National Oceanic and Atmospheric Administration-20 (NOAA-20).

continued on page 21

Table 2. Status summary of the EPIC L-2 products.

EPIC L-2 Product	Presenter [Affiliation]	Brief Description
Ozone	**Jay Herman** [University of Maryland, College Park]	Discussed validation of ozone measurements derived from EPIC's UV channels. He compared ozone data obtained by EPIC on the same days as two low-Earth-orbiting instruments, the Ozone Monitoring Instrument (OMI)* and OMPS, noting that EPIC can be compared to either satellite dataset with no statistical difference. There are some hemispheric differences, the likely causes of which are errors in temperature profiles and ozone effective temperature assumed in the Southern Hemisphere where there is much less data than in the Northern Hemisphere.
Sulfur Dioxide	**Simon Carn** [Michigan Tech]	Showed EPIC measurements of SO_2 emitted by several volcanic eruptions in 2018, using the publicly available EPIC Level 2 (L-2) SO_2 product. Two eruptions in the Galapagos Islands (Fernandina and Sierra Negra) in 2018 demonstrate EPIC's unique ability to provide 8–9 hourly UV observations of volcanic SO_2 in a single day, revealing short-term trends in eruption intensity and tracking SO_2 cloud transport. Data analyzed to date indicate that EPIC volcanic SO_2 retrievals are consistent with measurements from polar-orbiting UV sensors (OMI and OMPS). Future work will include analysis of EPIC SO_2 sensitivity variations with solar zenith angle and improvement of the UV Aerosol Index for volcanic ash detection.
Atmospheric Correction	**Dong Huang** [GSFC/SSAI] on behalf of **Alexei Lyapustin** [GSFC]	Reported on results from an evaluation of global EPIC aerosol retrievals from the Multi-Angle Implementation of Atmospheric Correction (MAIAC) model. Over land, aerosol optical depth (AOD) is in reasonably good agreement with Aerosol Robotic Network (AERONET) measurements. Comparison of EPIC and MODIS MAIAC surface reflectance over vegetation and deserts shows a good agreement in the red and NIR spectral regions.
Vegetation	**Yuri Knyazikhin** [Boston University]	Discussed the *provisional* Vegetation Earth System Data Record (VESDR) product—noting that DSCOVR/EPIC provides the first space-based measurements of Sunlit Leaf Area Index. The retrievals for solar zenith angles (SZA) >55° are unstable, owing to geolocation errors and a specific atmosphere correction algorithm. Focus is currently on obtaining new information on canopy structure from the VESDR parameter suite for use in ecological models. Described plans for further research to achieve "Stage-1 validated" maturity level.
UV Aerosol	**Omar Torres** [GSFC]	Described the standard EPIC aerosol products, which consist of the UV aerosol index (UVAI), AOD, single scattering albedo (SSA), and above-cloud AOD (ACAOD). Comparison with AERONET shows good agreement. Future work includes an algorithm upgrade to retrieve aerosol layer height and reprocessing of the entire record as a new version of EPIC L-1B data becomes available.
Ozone and Sulfur Dioxide	**Kai Yang** [University of Maryland, College Park]	Described the validations and comparisons of the publicly released EPIC ozone (O_3), sulfur dioxide (SO_2), and aerosol index (AI) [O3SO2AI] product based on the advanced direct vertical column fitting (DVCF) algorithm. DSCOVR EPIC has obtained high-quality total ozone and volcanic SO_2 measurements. EPIC's total ozone product is better than or similar to those of other satellite ozone products from several instruments, using the heritage Total Ozone Mapping Spectrometer (TOMS) algorithm.

* OMI flies on NASA's Aura platform.

Table 2. Status summary of the EPIC L-2 products.

EPIC L-2 Product	Presenter [Affiliation]	Brief Description
Clouds	**Yuekui Yang** [GSFC]	Showed that the standard L-2 products, including cloud mask, cloud effective pressure/height, and cloud optical thickness, compare well with results from GEO/LEO derived by the CERES-cloud team. Issues of cloud mask over ice- and snow-covered areas are observed and efforts are ongoing to improve the product. A long-term data record over the South Pole station is being established to track the performance of oxygen (O_2) A- and B-band channels. Results show that the instrument has been very stable for the past three years with regard to the O_2 A- and B-band observations.
Earth Radiation Budget from DSCOVR*	**Wenying Su** [LaRC]	Explained how EPIC composite data identify the scene by mapping the LEO/GEO cloud properties and other ancillary data into the EPIC pixels. She also described how NISTAR fluxes are generated based on band choice and targeted algorithms. The EPIC-based SW fluxes are in close agreement with CERES SW fluxes. EPIC VIS and NIR bands exhibit excellent radiometric stability over time, and the EPIC navigation is significantly improved in Version 3 (R06) dataset.

* This product uses data from both EPIC and NISTAR.

and Columbia, MO—see Guoyong Wen's presentation below. Radiances reflected from the sunlit Earth were reduced by about 10% while the shadow was in the vicinity of Casper and Columbia. For contrast, data taken on two noneclipse days (August 20 and 23) found that in each case the change in reflected sunlight is much smaller across all ten wavelength channels.

Jan Pisek [University of Tartu/Tartu Observatory, Estonia] discussed *clumping index*, which is a key structural parameter of plant canopies that influences canopy radiation regimes and controls canopy photosynthesis and other land–atmosphere interactions. He discussed how to retrieve it using DSCOVR EPIC Vegetation Earth System Data Record (VESDR) data. The initial validation over select sites with vertical profiles of foliage clumping provided very encouraging results. It is envisioned that synergy between EPIC VESDR parameters and other satellite products would provide a stimulus for future applications of the photon recollision probability concept for global and local monitoring of vegetation using Earth-observation data.

Guoyong Wen [GSFC/Morgan State University, Goddard Earth Sciences Technology and Research (GESTAR)] also reported on observations of the 2017 total solar eclipse, to quantify its top-of-the-atmosphere (TOA) impact and surface SW radiation budget. His team deployed ground-based radiometers in Casper, WY and Columbia, MO, to obtain surface shortwave flux and spectral radiance measurements before, during, and after the eclipse. EPIC was coordinated to make observations at totality at the two ground sites. The results revealed that modeled clear sky downward flux is significantly lower than the observations at the Casper site, possibly due to the presence of thin cirrus clouds, which EPIC observed from a million miles away! The estimate is that the eclipse led to a 6% reduction on global averaged reflected solar irradiance for Casper and 8% for Columbia. The latter is close to the estimated solar radiance reduction based on EPIC observations. There were more clouds at the Columbia site, making this estimate a more realistic approximation of the actual conditions.

Qilong Min [State University of New York, Albany] described efforts to measure cloud height using the EPIC O_2 A- and B-band channels. He discussed the efforts and results to develop a physically based cloud-top pressure from DSCOVR EPIC O_2 A- and B-bands. She also presented results from a fast forward radiative transfer (RT) model developed by his team for simulating EPIC channels of both O_2 A- and B-bands. The model provides a powerful tool for DSCOVR EPIC O_2 A- and B-band observation data analysis.

Anthony Davis [JPL] described efforts to decipher the cloud information content in EPIC's O_2 A- and B-band channels. He noted that the investigation revealed much redundancy in EPIC's O_2 A- and B-bands in terms of the information they convey about cloud vertical structure. Consequently, effort should be directed toward implementing a single unbiased retrieval of cloud top height using both O_2 absorption bands. One exception is for moderately opaque clouds at high latitudes where a significant amount of sunlight filters through to the highly reflective snow/ice-covered surface, and thus gets another pass through the clouds, thus accumulating more absorption by O_2, before escaping back to space. This "exception" turns out to be of considerable interest in climate science. Davis speculated that it may be possible to discern between geometrically thick and thin cloud layers using both of EPIC's O_2 A- and B-band channels.

Tamás Várnai [University of Maryland, Baltimore County, Joint Center for Earth Systems Technology (JCET)] discussed some excellent opportunities EPIC offers in characterizing ice clouds, thus helping to represent these clouds in climate studies more accurate. Two features of the EPIC instrument—a filter wheel for multispectral observations and measuring reflectances at O_2 absorption bands—can help characterize cloud ice crystals at a systematic horizontal orientation. These features can be used to identify sunglint caused by horizontally oriented ice crystals. Varnái also outlined plans to use glint observations to characterize the prevalence, size, tilt, and radiative impacts of such horizontally oriented ice crystals.

Andy Lacis and **Barbara Carlson** [both from GISS] described an analysis of data from 2017 that shows promising comparisons between NISTAR L-1B data from 2017 and CERES, International Satellite Cloud Climatology Project (ISCCP), and global climate model (GCM) data for the total ongoing radiation (TOR) and its SW and LW global-mean radiative flux seasonal variability in response to the solar seasonal SW radiative forcing. Their finding has important implications for validating climate model treatment of the spectral dependence of cloud, snow/ice, ocean, desert, and vegetation via their diurnal and seasonal variability, while also demonstrating the viability of the NISTAR spectral ratio approach as an informative exoplanet observation strategy—see Renyu Hu's presentation for more information on this.

Jun Wang [University of Nebraska, Lincoln] addressed the uniqueness of DSCOVR/EPIC in characterizing the diurnal variation of aerosol layer height over ocean and dark land surfaces. He presented preliminary results of AOD and aerosol layer height retrieval from EPIC. Intercomparison with data from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) shows promising results.[11] He also showed some case studies where EPIC UV Aerosol Indext (UVAI) data constrain the modeling of pyrocumulonimbus smoke aerosol transport.

Charles Gatebe [GESTAR] described unique ocean color products from DSCOVR EPIC L-1B measurements. Validation of the new products will be performed using the long-term AERONET-Ocean Color field measurements, the NASA Sea-viewing Wide Field-of-View (SeaWiFS) Bio-optical Archive and Storage System (SeaBASS) database and cross validation with MODIS/Aqua ocean data products. The team will implement a machine-learning based cloud-screening algorithm suitable for turbid coastal water areas, and heavy aerosol conditions for accurate determination of clear-sky conditions. Similar techniques will be used to implement a new atmospheric correction (AC) algorithm.

Pengwang Zhai [JCET] discussed a radiative transfer simulator for DSCOVR/EPIC, that accounts for the multiple scattering processes in the atmosphere–ocean system. The simulator has been used to generate EPIC measurements in response to the water cloud microphysical properties, including optical depth, cloud top height, geometric thickness, and droplet size. This sensitivity study will be used to improve the EPIC cloud data product. In addition, the simulator is used to generate the Rayleigh reflectance table, which provides a useful tool to perform AC for EPIC images. The Rayleigh corrected images can be used to detect and monitor algal blooms.

Renyu Hu [NASA/Jet Propulsion Laboratory] described using the DSCOVR/EPIC observations to attempt to detect the rotation rate of an Earth-like extrasolar planet. Reduced to single-aperture photometric time series, EPIC observations at any wavelength channel from UV to NIR show that a periodicity peaked at 24 hours. This signal is mainly driven by the vastly different land and sea albedos. Linear operations based on the EPIC wavelength channels can effectively remove the contribution from the clouds and reveal the components that correspond to the land and the sea.

Conclusion

Overall, the meeting was very successful. It was an opportunity to learn the status of EPIC and NISTAR—the Earth-observing instruments on DSCOVR, the status of recently released L-2 data products, and the science results being achieved from L_1. Both EPIC and NISTAR are operating nominally and both instruments have received recommendations from NASA HQ for continued funding—at least through FY'20. In terms of data products, a new version of the L-1 data products will be released shortly; meanwhile the L-2 products have been released to the public over the past year.

The next STM will be held in the fall of 2019 and it will be open for general public. The focus will be mostly on science results from EPIC and NISTAR. ■

[11] CALIOP flies on the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission.

Summary of the 2018 Vector-Borne and Water-Related Disease Workshop

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Introduction

The 2018 Vector-Borne and Water-Related Disease Workshop was held May 17, 2018, at The Wilson Center in Washington, DC.[1] The workshop was designed to bring together diverse stakeholder communities who are engaged in vector-borne and water-related disease research, response, and mitigation. The range of participants reflects that it succeeded. A total of 124 people took part (86 in person and 38 online); among them were scientists, public-health practitioners, citizen science and outreach specialists, and representatives from the local community. The workshop included three panels that focused on emerging research, public health, and citizen science; three keynote presentations; and one breakout session with a focus on how data retrieved from NASA's fleet of Earth observing satellites, henceforth referred to in this article as NASA *Earth observations*, may be used to determine when and where outbreaks may occur. NASA's Goddard Space Flight Center (GSFC) and The Wilson Center served as coleaders for the workshop, the main objectives of which were to:

- provide a broader perspective on the availability and accessibility of NASA Earth observations to enhance the prediction of and response to vector-borne and water-related diseases;
- highlight the needs and decision-making processes of operational end-users, such as public health officials, government agencies, and nongovernmental organizations (NGOs), who work to reduce the onset of and/or respond to outbreaks of these diseases;
- share research results of how NASA Earth observations are used both in research and operational applications on the topic of disease; and
- communicate the wide range of resources available to conduct outreach activities to make the general public aware of the possibilities of using NASA Earth observations—and specifically data from the Global Precipitation Measurement (GPM) mission—to predict and respond to vector-borne and water-related diseases.

[1] The Woodrow Wilson International Center for Scholars was chartered by Congress in 1968 as the official memorial to President Woodrow Wilson. It is the nation's key nonpartisan policy forum for tackling global issues through independent research and open dialogue to inform actionable ideas for the policy community. Learn more at *https://www.wilsoncenter.org/about-the-wilson-center*.

In addition to the workshop, there were also two related opportunities for online training: one before the workshop and one after it—see *The GPM Disease Initiative* on page 24 to learn more. More information on the workshop is available at *pmm.nasa.gov/disease-initiative*. Click on the *Workshop* tab beneath the banner images at the top of the page to view the full agenda, the overall vision, and anticipated outcomes, as well as videos of several key presentations.

Opening Remarks

Dorian Janney [GSFC/ADNET—*GPM Outreach Specialist*] and **Anne Bowser** [The Wilson Center—*Director of Innovation*] began with welcoming remarks on behalf of both the GPM Applications Team and The Wilson Center. **Lawrence Friedl** [NASA HQ—*Director of NASA's Applied Sciences Program*] spoke next, and offered a broad perspective on the use of NASA Earth observations for real-world applications and opportunities to expand relevant research and operational activities. **Dalia Kirschbaum** [GSFC—*GPM Associate Deputy Project Scientist for Applications*] introduced the GPM mission and described the data products, which are freely available at *https://pmm.nasa.gov/data-access*.

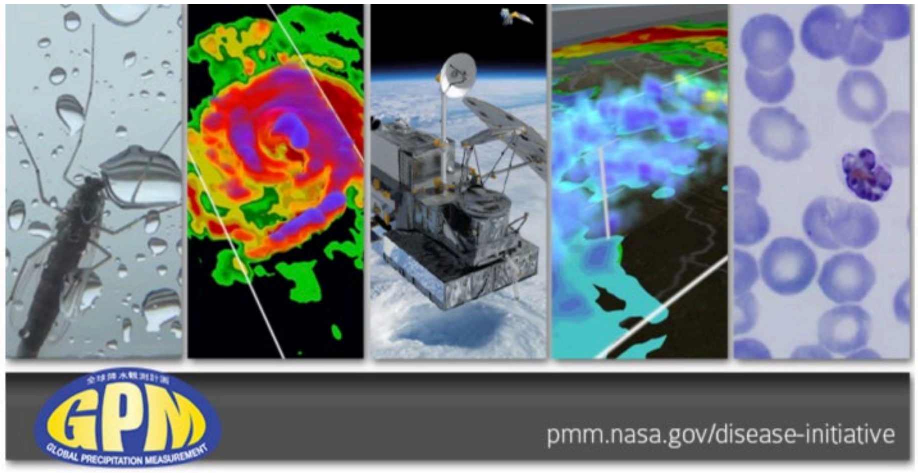
First Keynote: Remarks from a Physicist Turned Politician

Congressman Bill Foster [IL, Eleventh District] provided an overview of the importance of having an experienced scientist in the House of Representatives and described some of the work he has done both before and during his tenure as a government official. Foster received his bachelor's degree in physics from the University of Wisconsin-Madison, and went on to earn his Ph.D. from Harvard University in 1983. During his 45-minute presentation, he shared what life was like as a member of Congress, and gave the audience a sense of what led him to decide he could best serve science and bring about change as a politician. He described his transition into the political arena as being filled with plenty of roadblocks and challenges but ultimately, he stated, "…it's all about trying to do the right thing for people who elected you."

Panel 1: New and Emerging Research

John Haynes [NASA HQ—*Health and Air Quality Program Manager*] described the scope of work for NASA's Health and Air Quality Applications Program, and introduced the three panelists. Each panelist had 10 minutes to present his or her research, after which all panelists participated in a discussion on the opportunities and challenges of using NASA Earth observations within their fields of study.

The GPM Disease Initiative



In an effort to further explore the linkages and research/operational applications of NASA water resource data and disease, GPM's Outreach Team launched an applications campaign titled the GPM Disease Initiative. This initiative included the workshop discussed here and two opportunities to participate in online training.

Amita Mehta [University of Maryland, Baltimore County (UMBC)—*Applied Remote Sensing Training (ARSET) Disaster Management Lead*] and **Dorian Janney** [GSFC/ADNET—*GPM Outreach Specialist*] led both of the training sessions. The first training webinar took place May 8, 2018, and provided an introductory webinar on the use of Earth observation data for water-related diseases. The second webinar took place June 28, 2018—following the workshop—and was a more advanced session to demonstrate how NASA Earth observations are used in specific research.

In addition to having these resources and others on the website, there is also a monthly newsletter that is sent out to those who asked to be included on the mailing list. This newsletter includes information about upcoming events related to vector-borne and water-related disease, recent research results, and other items of interest. The archived training sessions, archived workshop presentations, and a way to sign up for the monthly newsletter can be found at *http://pmm.nasa.gov/disease-initiative*.

Antar Jutla [West Virginia University (WVU)] described his research on how combining data from many missions and instruments is being used to better predict and respond to cholera outbreaks. Specifically, he is using:

- data from the Tropical Rainfall Measuring Mission (TRMM) and GPM to look at precipitation anomalies;
- Normalized Difference Vegetation Index (NDVI) data from Landsat to monitor vegetation;
- data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua platforms and from the European Space Agency's former Medium Resolution Imaging Spectrometer (MERIS) on Envisat to monitor surface temperature and ocean color;
- data from the Surface Water and Ocean Topography (SWOT) to monitor river discharge [planned for launch in 2021];[2]
- data from the Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow On missions to monitor water storage and river discharge;[3]
- data from the Ocean Topography Experiment (TOPEX) and Jason series of missions to monitor sea surface height;[4] and
- data from the National Oceanic and Atmospheric Administration's (NOAA) series of Advanced Very High Resolution Radiometer (AVHRR) instruments to monitor sea surface temperature.

[2] SWOT is an international collaboration managed by NASA and the French Centre National d'Études Spatiales (CNES), with contributions from the Canadian Space Agency and the U.K. Space Agency.

[3] GRACE was, and GRACE-FO is, a joint venture between NASA and the German Deutsches Zentrum für Luft- und Raumfahrt (DLR).

[4] TOPEX and Jason-1, -2, and -3 are international cooperative satellite altimetry missions that provide scientists with critical information about circulation patterns in the ocean, global and regional changes in sea level, and the climate implications of a warming world.

Using these data, Jutla and his colleagues have been able to classify cholera into three distinct modes: epidemic, endemic, and mixed-mode outbreaks—see **Figure 1**.

Mike Wimberly [University of Oklahoma (OU)] presented information on the use of GPM precipitation data, MODIS land surface temperate data, and MODIS surface reflectance data, to both predict and monitor outbreaks of malaria in the Ethiopian highlands. This work has resulted in the development of the Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment (EPIDEMIA—*http://globalmonitoring.sdstate.edu/epidemia*), a malaria informatics system for epidemiological and environmental data acquisition and

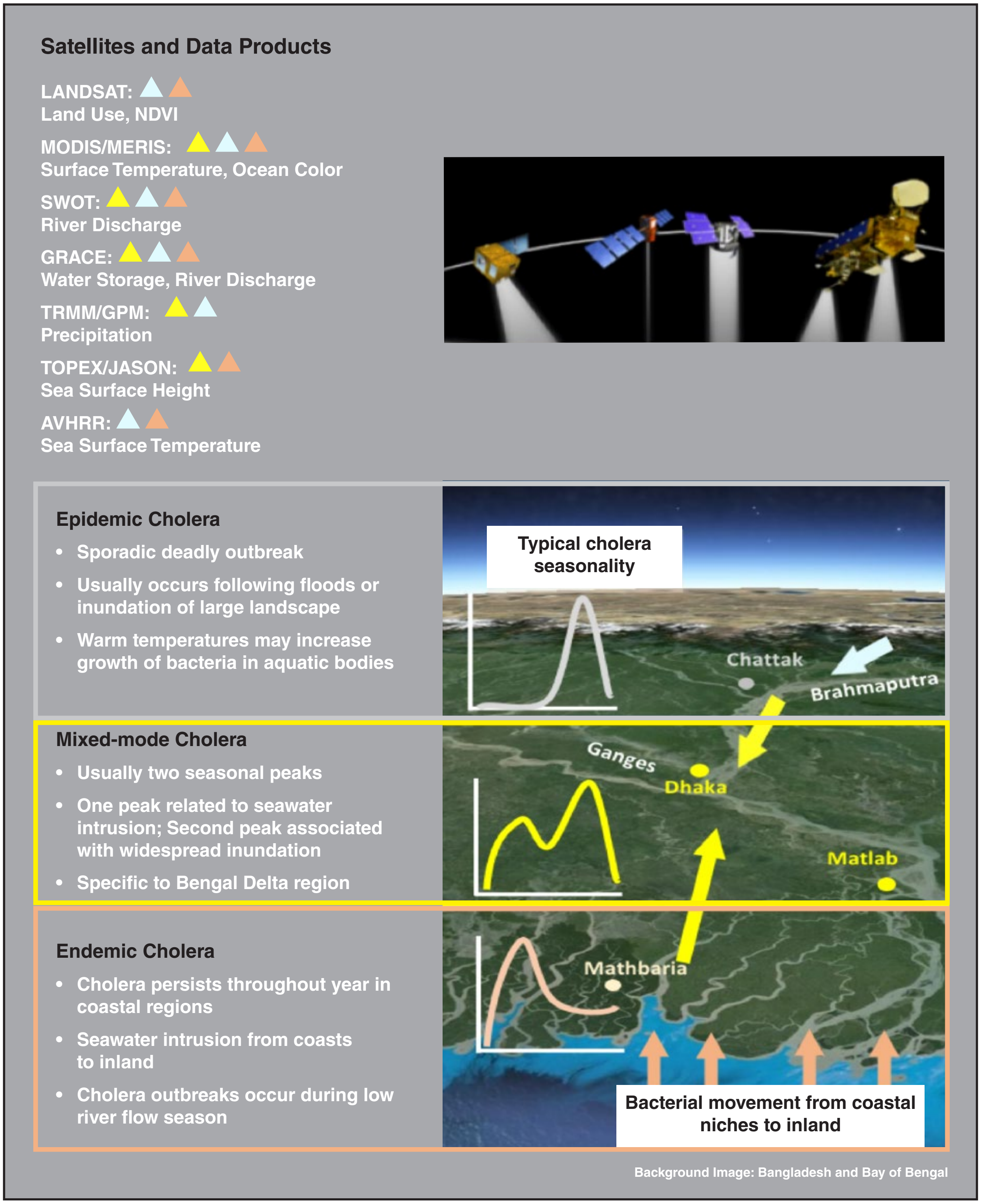


Figure 1. A constellation of NASA satellites provides data for assimilation into a cholera early-warning framework for Bangladesh. Triangles correspond to the type of cholera monitored using each satellite's data. The satellites mentioned in the graphic are defined in the text of the article. For more details visit *svs.gsfc.nasa.gov/12958*. **Image credit:** Antar Jutla

harmonization to improve situational awareness of potential outbreaks—see **Figure 2**.

Ben Zaitchik [Johns Hopkins University (JHU)] described the work that he and his team have been doing in the Peruvian Amazon region to predict and respond to the threat of malaria. He explained that these malarial species are sensitive to land cover, soil moisture, climate, and hydrological conditions, and thus the Earth observing satellites which measure these environmental parameters prove quite useful, especially in regions that lack the technology to monitor these variables from the ground or air. By identifying the malarial hot spots, government health officials are better able to use their resources effectively. Zaitchik's work also identified several human interaction factors, e.g., deforestation and land use, which have significant impacts on malarial incidence.

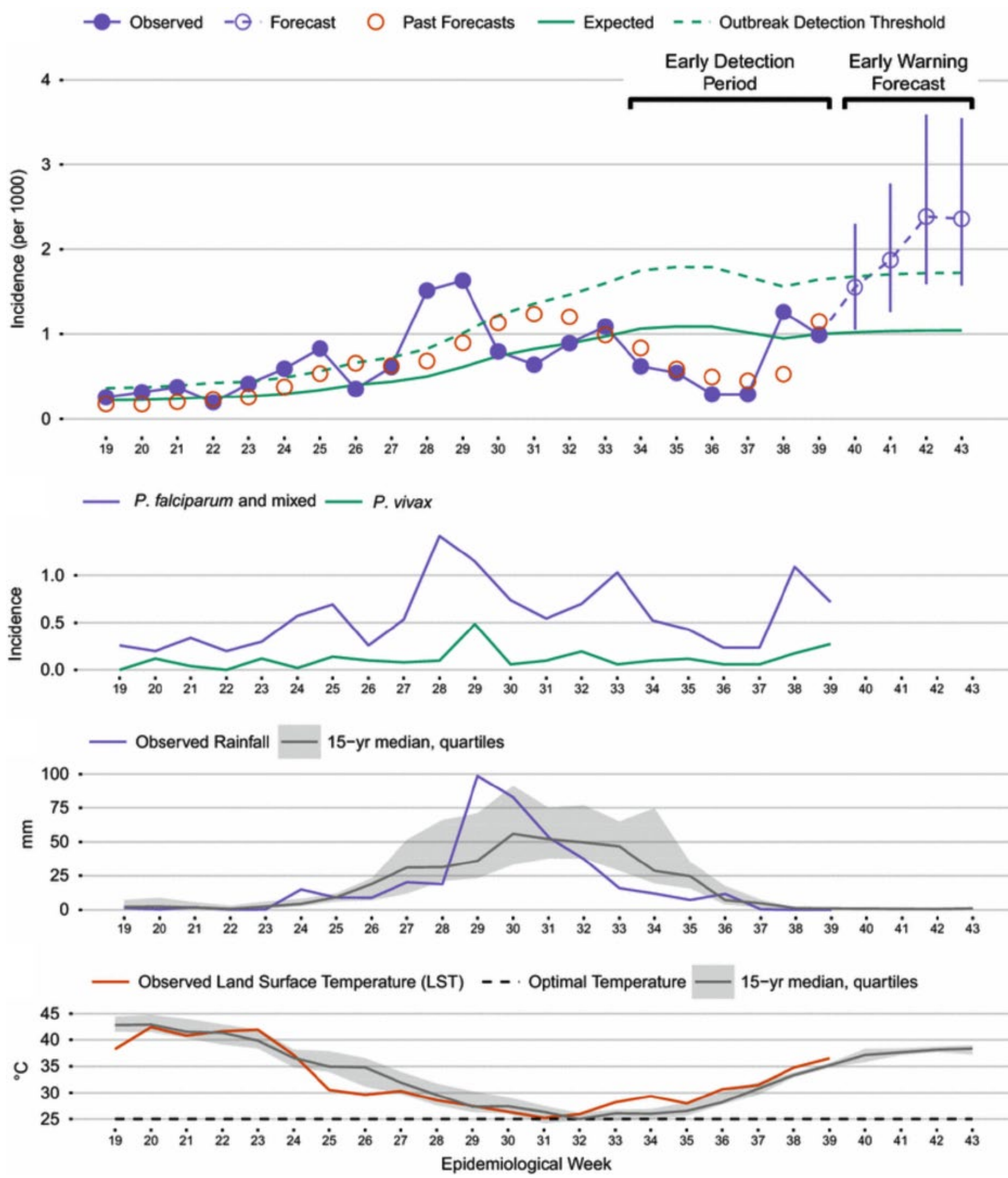


Figure 2. In order to accurately predict when an outbreak of malaria might occur, land surface temperature and precipitation data are correlated with the actual incidence of malaria-transmitting mosquitoes to generate a predictive model. The EPIDEMIA system brings this information together in one place. Four malaria forecasting charts generated by the EPIDEMIA system are shown here. *From top to bottom*: Control chart with observations, outbreak thresholds estimated from historical data, and forecasts four weeks into the future; incidence of *Plasmodium falciparum* and *Plasmodium vivax* malaria-causing protozoans; GPM precipitation with historical climatology; and MODIS land surface temperature with historical climatology. **Image credit**: Michael Wimberly

Panel 1 Discussion Summary

Following Panel 1, there was discussion during which workshop participants asked panelists where they saw the next emerging opportunities or threats. As not all mosquitoes are the same and their ecologies are so different, NASA Earth observations are important tools to assist with developing models and supporting understanding of emerging diseases. Further, the variability in sea surface temperatures as well as large populations near coastlines will necessitate understanding the agents of infections and know when they emerge and disappear and travel from region to region. Finally, there is a need to understand extant conditions when new and emerging disease outbreaks occur.

The panelists were also asked about barriers potential end-users face when they try to gain access to and/or make use of NASA Earth observations. One barrier appears to be lack of end-user awareness: both that the data exist and that they are freely available for public use. There are also barriers with regard to spatial and temporal resolution. The path forward is multifaceted and includes creating greater awareness that these data are being used for these applications, and providing concrete examples of how incorporating Earth observation data into models has improved the ability to predict, monitor, and respond to disease outbreaks. End-users need to use the currently available data-access tools and determine how these datasets can be made more useful for their purposes. Finally, in order to keep moving forward in this application area, the dialogue between end-users, research scientists, Earth-observing-data archivers, and other stakeholders needs to continue.

Second Keynote Presentation: Impact of Water-Related Diseases on Global Population

Rita Colwell [University of Maryland, College Park (UMD)] gave the second keynote presentation of the day, which focused on the impact of water-related diseases on the global population. She provided insight into how increasing technological capabilities to predict and respond to disease have included not only Earth-observing satellites, but also the use of citizen scientists armed with cell phones to record and distribute data, as well as the use of DNA to determine which strain of bacteria causes specific outbreaks.

Panel 2: Health, Data, and Complexity

This panel, moderated by **Alex Long** [The Wilson Center—*Program Assistant for the Science and Technology Innovation Program*], was intended to give participants a broad overview of the decisions that public health officials need to make and the complexity of their decision-making process, with a focus on how NASA Earth observations may be useful to this process.

Bernadette Dunham [George Washington University (GWU)] and **Helena Chapman** [NASA HQ] introduced the One Health Initiative (*www.onehealthinitiative.com*), which is an approach that considers not only the humans who are involved (i.e., those populations at risk from potential disease outbreaks), but also their environment and the animals in that environment. This approach seeks to promote, improve, and defend the health and well-being of all species by enhancing cooperation and collaboration between physicians, veterinarians, and other scientific health and environmental professionals.

Nicole Wayant [U.S. Army Corp of Engineers Geospatial Research Laboratory (GRL)] described the Vulnerability Assessment Software Toolkit (VAST) that she and employees at the GRL developed in an effort to reduce the potential for U.S. soldiers to contract vector-borne diseases. She also described the role of NASA Earth observations in this process. For example, GPM data are added to a machine learning model to predict cases of Lyme in the U.S. Data from several NASA Earth observations (e.g., land surface temperature data from MODIS and precipitation data from GPM) are incorporated into the final product that predicts the outbreak of and spatial and temporal extent of Dengue Fever with varying infection rates for armed forces who might encounter this disease internationally—see **Figure 3** on page 28.

John Balbus [National Institute of Environmental Health Science (NIEHS)] described the ways in which climate change and climate variability will impact vector-borne and water-related disease outbreaks. His work on the Global Change Research Program (GCRP) Climate Health Assessment has found direct correlations between climate change and variability and the spread of West Nile Virus in the U.S. He stressed the need for raising awareness of the impact of environmental factors on public health.

Cristina Schneider [Pan American Health Organization (PAHO)] described the use of remotely sensed and ground-based data in developing models to predict, monitor, and respond to outbreaks of leptospirosis and yellow fever. She described how these data can be used to identify risk areas and optimum time of year for intervention to reduce potential disease outbreaks. These models were developed to understand possible drivers (i.e., environmental, geographic, socio-economic, and others) for infectious diseases as a tool to support design making at PAHO/World Health Organization (WHO) and for Nicaraguan health authorities. This is a joint effort between PAHO staff and government staff in these countries.

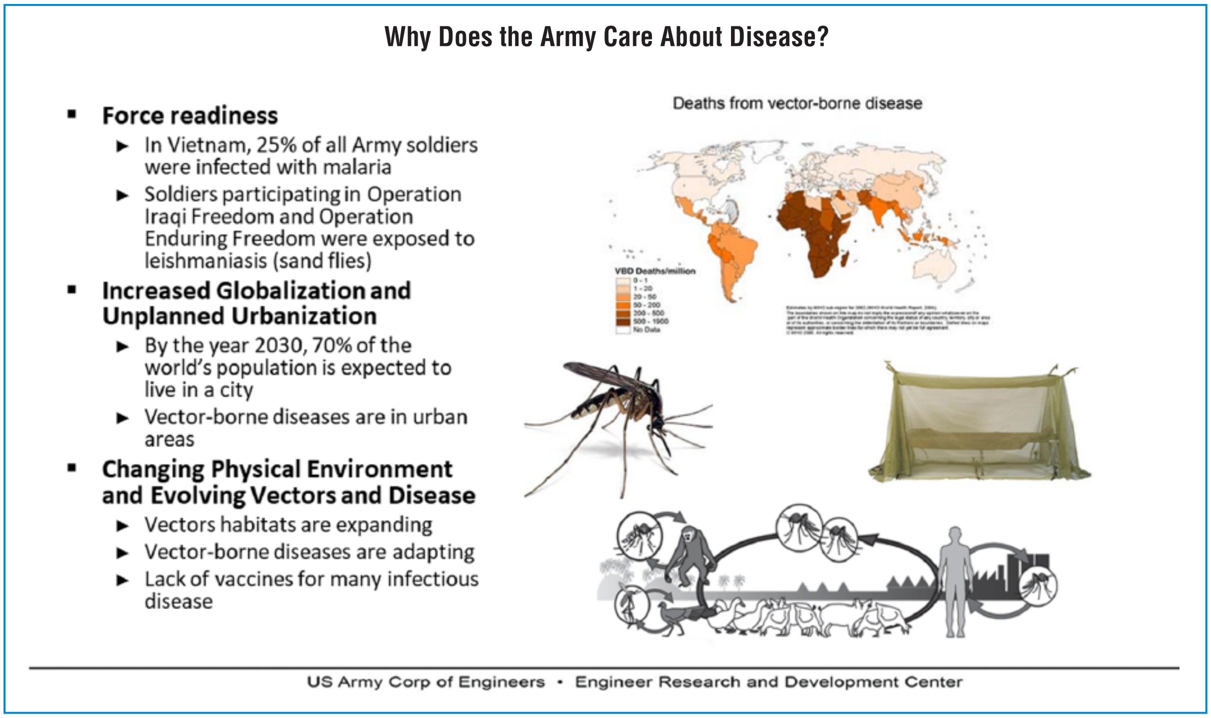


Figure 3. This figure describes why the U.S. Army is concerned with disease outbreaks. **Image credit**: Nicole Wayant [U.S. Army Corp of Engineers]

Panel 2 Discussion Summary

Following the second panel, three key questions were discussed:

- What challenges do you (or your organization) face with regard to communicating data uncertainty?
- What makes applying environmental Earth-observations to disease prediction and monitoring applications more feasible?
- How do you go from publicly available data to an actionable plan?

The responses included some discussion about the need to have some reanalysis or parameterization of raw satellite data and to build up a longer time series of environmental data linked to disease outbreaks in order to validate model results. The One Health Initiative supports a multidisciplinary approach, with different kinds of experts being involved. The fact that there are many sources of uncertainty when dealing with these types of disease was discussed, as was the complexity involved in dealing with so many different types of diseases and potential vectors.

Panel 3: Citizen Science and Public Awareness

Anne Bowser introduced the panelists and described the importance of including citizen scientists[5] in these efforts.

John Palmer [Pompeu Fabra University, Spain] described *Global Mosquito Alert*, an app developed by the European Citizen Science Association (*https://ecsa.citizen-science.net/global-mosquito-alert*) for use in a program in which participants identify the species and density of adult mosquitoes and share the information with a central database.

Julia Heslin [Baltimore Greenmap/NASA DEVELOP] described how citizen science data and NASA Earth observations were integrated to make the mosquito-related information publicly accessible. The work involved creating an interactive map showing mosquito habitats. The team used Google Earth Engine to develop and host several habitat suitability models and to input environmental factors, using with citizen science-derived data points.

[5] To learn more, see "GLOBE Observer: Citizen Science for Earth System Science" in the November–December 2017 issue of *The Earth Observer* [**Volume 29, Issue 6**, pp. 15-21—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Nov_Dec_2017_color_508.pdf#page=15*].

Rusty Low [Institute for Global Environmental Strategies (IGES)] shared information on the GLOBE Observer (*https://observer.globe.gov*) *Mosquito Habitat Mapper* app, which was released one year ago to engage the public in identifying and often eliminating potential mosquito breeding habitats, as well as to provide opportunities to identify which species of mosquito larvae the citizen scientists have found.

Panel 3 Discussion Summary

After this panel, the questions raised for discussion included:

- How far along are we in using citizen science data to influence decision making?
- Can citizen science data be used for surveillance to validate models? Are the data openly available?
- How are classroom teachers becoming aware of and making use of citizen science initiatives?

Some of the responses addressed the need to gather more data in an effort to validate and use these data effectively, as well as the need for ensuring that the data are collected in a reliable, scientific, and statistically significant manner. There is also great need to provide feedback to citizen scientists to show how their data are being used and applied to improve public health. Such positive feedback helps to encourage future involvement by the citizen scientists. Finally, it is essential to get citizens working in their communities to collectively decide to take specific actions to reduce the mosquito population.

Break-Out Sessions

In the afternoon, three break-out groups were convened, aligning with the three main topics of the day. Summaries of the discussion in each breakout are provided below.

New/Emerging Research

The questions posed to this group were:

- What decisions need to be made in areas of water-related and vector-borne disease?
- How have NASA Earth observations been used to support these decisions?
- What are the opportunities, challenges, and barriers to using NASA Earth observations within this space?

In response, the group surfaced a wide variety of ways in which decisions were being made and how Earth observations are being used by the researchers who were in this breakout group. These decisions included disease forecasting, predicting and responding to malaria outbreaks, predicting cholera outbreaks, biomarker development, assessing water quality, responding to disasters, and landslide modeling. Two-thirds of this group had experience using NASA Earth observations in their research. The opportunities, challenges, and barriers drew many responses from the group. There were questions about the spatial and temporal resolution of the data products, as well as the challenges incurred in accessing and layering the datasets. All participants felt that despite these challenges, the use of NASA Earth observations was essential to their work.

Health, Data, and Complexity

The questions posed to this group were:

- What decisions need to be made in the area of vector-borne and water-related diseases?
- What needs to happen to make NASA Earth observations more accessible and useful to potential end-users in this subgroup?

This conversation looked at the complexity of including different countries, each with different methods of surveillance and abilities to respond effectively to vector-borne and water-related disease outbreaks—wherever they occur. The group agreed that the decisions that need to be made are multilayered and complex. The specific choices made depend upon the types of data available both on the ground and from satellite observations; the needs of different end-users (e.g., emergency responders versus vaccine developers); and the need for a multidisciplinary approach to dealing with disease outbreaks of these kinds. The discussion around how to make NASA Earth observations more accessible also included conversations about how to reconcile the different spatiotemporal scales of resolution, and about how much error in these measurements was acceptable. GeoHealth Community of Practice (*http://www.geohealthcop.org*) was introduced as one forum which could be useful in helping to establish some of these standards and to foster collaboration among many of the key players in this effort.

Citizen Science/Public Awareness

The questions posed to this group were:

- What makes citizen science data actionable?
- How easy or feasible is it to go from datasets to outreach and action?
- What are "best practices" to consider when trying to reach out to the public and involve them in understanding how and why NASA Earth observations can be used to help improve global health?

During this discussion, it was noted that there is a wide variety in the potential audiences being addressed when talking about citizen science and public outreach. Many people around the world are interested in the work that NASA does, but few realize the ways in which NASA data are being used to improve global health. Many efforts have been designed to allow the public to learn about the variety of different ways they can personally engage in and interact with scientific endeavors. Social media appear to have a huge reach; however, the lasting impact they have on engaging the public to get them to interact with datasets and take actions in their communities remains unclear.

Third Keynote Presentation: Tracking and Responding to Malaria—Past and Present

Madeleine Thomson [World Health Organization (WHO) Collaborating Center on Early Warning Systems for Malaria—*Senior Research Scientist*] was the final keynote speaker. She described the history of tracking and responding to the threat of malaria over the past century and explained the threat that climate change has on increasing the range of the vectors. Thomson described a few programs that have utilized Earth observation data in addition to other sources to predict, monitor, and respond to malaria outbreaks in many countries. She also reiterated the complexity involved in being able to respond proactively to outbreaks, as well as the importance of involving and engaging the at-risk communities in being part of the surveillance and proactively taking preventative measures.

Breakout Summaries and Post-Meeting Social

The workshop concluded with a brief report from each breakout group and a discussion of next steps to be taken following the workshop. The group then adjourned for a social hour held at the Hay Adams Hotel in combination with the U.S. Department of State's *Mission Mosquito* training group, which had met on the same day. The event was sponsored by Johnson & Johnson and featured a preview of the "Outbreak" exhibit that was opening the following day at the Smithsonian Museum of Natural History.

Conclusion

Overall, feedback from the various stakeholders involved in this meeting indicates the workshop was very beneficial. It represented the first opportunity they have had to come together to gain insight and share potential challenges for using NASA Earth observations to improve global health. To maintain momentum, the workshop participants agreed to communicate monthly via an online newsletter (for those who sign up to be on the mailing list) to share the latest updates, training opportunities, and other information pertinent to the use of NASA Earth observations for predicting, monitoring, and responding to these types of disease. ■

Summary of the Twenty-First OMI Science Team Meeting

Joanna Joiner, NASA's Goddard Space Flight Center, joanna.joiner@nasa.gov

Introduction

The twenty-first Ozone Monitoring Instrument (OMI) Science Team Meeting (STM) was held September 11-13, 2018, at the Royal Netherlands Meteorological Institute [Koninklijk Nederlands Meteorologisch Instituut (KNMI)] in de Bilt, the Netherlands. With more than 14 years of OMI data now available and the successful launch of OMI's successor, the TROPOspheric Monitoring Instrument (TROPOMI),[1] the aims of this meeting were to:

- highlight the importance of OMI–TROPOMI overlap;
- explore the potential of combined OMI–TROPOMI data records; and
- discuss and plan the future of OMI (which flies on NASA's Aura platform).

There were also updates on operations and data product status, as well as planning for ongoing activities. The complete list of presentations given during the meeting can be viewed on the *Meeting Agenda* page posted at *projects.knmi.nl/omi/research/project/meetings/ostm21*.

Instrument, Mission, and Product Updates

As is customary at OMI STMs, the first morning of the meeting focused on the instrument, its data products, and mission status, with presentations by **Pieternel Levelt** [KNMI—*OMI Principal Investigator* (PI)] and **Dominic Fisher** [NASA's Goddard Space Flight Center (GSFC)—*Aura Mission Director*], respectively. The Aura satellite continues to perform well, with all systems "green" and a data capture rate of over 99.99%. OMI also continues to produce high-quality datasets with all its systems in the green. In her overview talk, Levelt pointed out that OMI data were used in recent reports from the U.S. Environmental Protection Agency (EPA) to show the positive effects of pollution controls on U.S. air quality, with significant reductions in both sulfur dioxide (SO_2) and nitrogen dioxide (NO_2), two criteria pollutants identified by the EPA. She also discussed KNMI's plans to apply TROPOMI retrieval algorithms to OMI data in order to create consistent datasets from the two instruments.

Quintus Kleipool and **Mirna van Hoek** [both from KNMI] gave overview presentations focusing on OMI operations and calibration, respectively. OMI continues to perform well and has been in full operations mode more than 99.6% of the time with very little degradation. **Sergey Marchenko** [GSFC] discussed how OMI data are being used to monitor the Sun with extremely high precision through solar cycle 24. OMI has become an important instrument for monitoring solar spectral irradiance and its variation over long and short time scales. **Johanna Tamminen** [Finnish Meteorological Institute (FMI)—*OMI Co-PI*] and **Joanna Joiner** [GSFC—*U.S. OMI Science Team Leader*] discussed ongoing activities in Finland and the U.S., respectively. Tamminen showed that OMI continues to be used in the Finnish *Instantly delivered direct readout products* system, called Satellite Measurements from Polar Orbit (SAMPO; *sampo.fmi.fi*) along with products from the Ozone Mapping Profiler Suite (OMPS) that flies on both the Suomi National Polar-orbiting Partnership (NPP) and NOAA-20 missions. This system utilizes the satellites' direct broadcast capability to produce maps with coverage of Europe, Alaska, and the Arctic within twenty minutes of the satellite overpass. This is especially important for monitoring volcanic eruptions and forest fires. Joiner discussed how the U.S. OMI core team supports OMI algorithm developers by providing new products, such as collocated meteorological fields, that facilitate improvements to OMI trace gas, cloud, and aerosol products.

There were also several presentations on the status of OMI algorithms. **Can Li** [University of Maryland, College Park] described updates to the pollution SO_2 product. The latest version, planned for release in early 2019, improves noise performance over low-pollution areas and reduces a high bias over snow-covered regions. **Juseon Bak** [Harvard Smithsonian Astrophysical Observatory (SAO)] discussed improvements to the SAO ozone profile and tropospheric ozone research product. There is now better agreement with ozonesondes, particularly for long-term trends. **Wenhan Qin** and **Alexander Vasilkov** [both from Science Systems and Applications, Inc. (SSAI)] described the use of surface data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA's Terra and Aqua platforms to improve OMI cloud, aerosol, and trace gas products. **Lok Lamsal** [Universities Space Research Association (USRA)] reviewed the status and plans for updating the NO_2 standard product, and showed how the use of the MODIS surface data is improving the product. **Folkert Boersma** [KNMI] described a large European effort to construct a 23-year (1995–2017) NO_2 data record with four satellite sensors including OMI. **Marina Zara** [KNMI] detailed high-resolution NO_2 trends covering 2004 through 2017 from this long-term record linked to economic activity and environmental policy.

[1] TROPOMI flies on the European Space Agency's Copernicus Sentinel-5 satellite, launched on October 13, 2017.

The first day concluded with a presentation from **Gerard Hoek** [Utrecht University, the Netherlands] who discussed the implications of OMI and TROPOMI satellite data for human health studies. He stressed the importance of having a fine spatial scale for health research in which both models and satellite data can play a part. Hoek also stressed the importance of having a historical record of pollutant exposure, where OMI data can play an important role.

Summary of Science Results

The meeting featured numerous presentations on scientific research using OMI trace gas, cloud, and aerosol products. The focus was on air quality and emissions monitoring and trends in trace gases that OMI measures, such as ozone (O_3), NO_2, and SO_2. **Fei Liu** [USRA] discussed merging satellite and ground-based data to provide a more accurate and more timely SO_2 emission inventory for the atmospheric chemistry modeling community—see **Figure 1**. **Debora Griffin** [Environment Canada Climate Change] gave a talk on estimating power plant carbon dioxide (CO_2) emissions by using fine spatial-scale information from OMI NO_2 data. **Iolanda Ialongo** [FMI] gave examples of how OMI and TROPOMI SO_2 total column data are being used to monitor emissions before and after a clean-tech company installed a sulfuric acid plant in order to capture SO_2 smelter emissions and subsequently utilize the sulfur to produce sulfuric acid—see **Figure 2**.

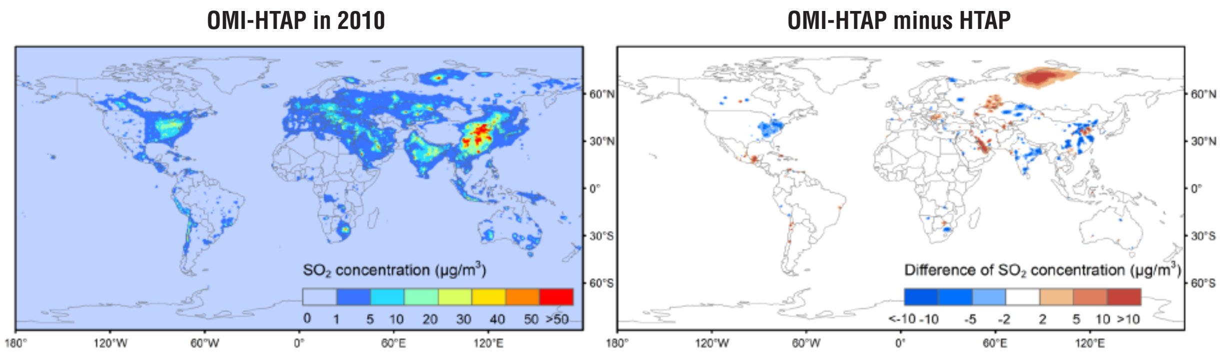
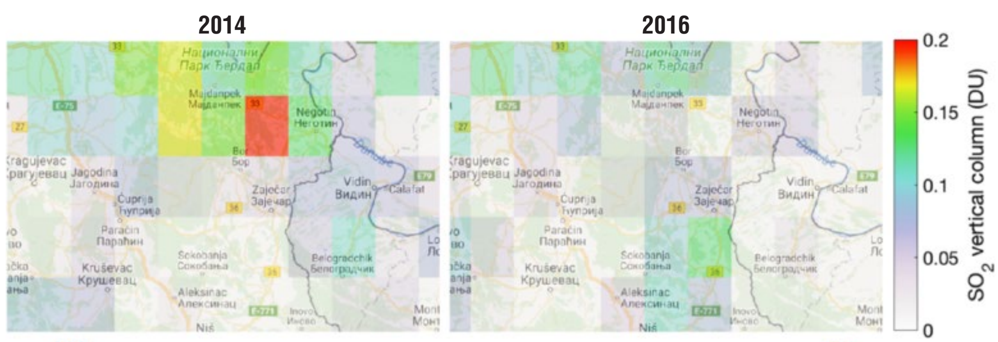


Figure 1. Recent work done to support global modelers has combined estimated "top-down" SO_2 emissions from OMI for large sources (which may be misplaced, missing, or under- or over-reported in emissions inventories) with "bottom-up" estimates contained in leading emissions inventories—such as Hemispheric Transport Air Pollution (HTAP)—for smaller sources that are not detected by OMI. The resulting merged inventory is called OMI–HTAP. When this new source of information is incorporated into the NASA Global Modeling Assimilation Office aerosol model, it results in SO_2 surface concentrations shown in the left panel. Differences between models run with this new approach and the currently used HTAP inventory are shown in the right panel. The differences suggest that for 2010 the bottom-up SO_2 emissions are generally overestimated in the U.S. and parts of Asia and underestimated in the Persian Gulf and parts of Mexico. **Image credit**: Fei Liu [USRA]



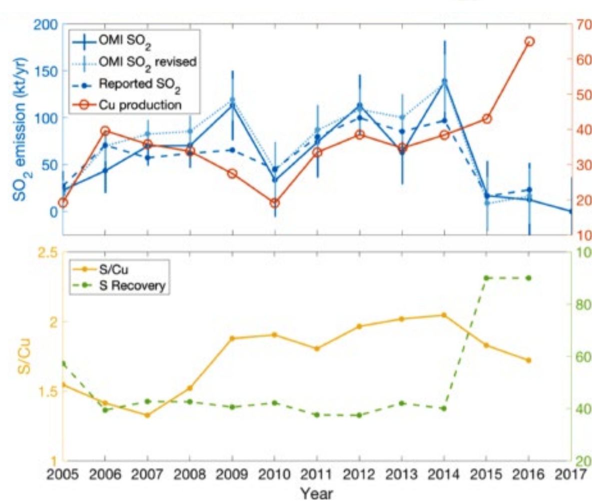


Figure 2. The implementation of a sulfuric acid plant (designed to capture and reduce SO_2 emissions) at a smelter in Bor, Serbia, by a Finnish cleantech company in 2015 resulted in a significant reduction in SO_2 concentrations and emissions. Note the differences in SO_2 vertical column concentrations over the region between 2014 and 2016 [*compare top maps*]. Using OMI data allowed an inference of a reduction in the observed SO_2 total column over the smelter area between 2014 and 2016, even as copper (Cu) production increased during that same time [*middle graph*]. The percent of sulfur recovered jumped dramatically in 2015 [*dashed line, bottom graph*]. **Image credit**: Iolanda Ialongo [FMI]

The second day also included a session on TROPOMI. **Pepijn Veefkind** [KNMI—*OMI Deputy PI* and *TROPOMI PI*] presented an overview of the first year of OMI–TROPOMI overlap. TROPOMI is performing at expected levels and has higher spatial resolution as compared with OMI. [TROPOMI has a 3.5-km x 7-km (~2.2-mi x 4.3-mi) ground footprint for most products in the center of its swath, where OMI's footprint is 12-km x 25-km (~7.5-mi x 15.5-mi).] With TROPOMI's groundbreaking spatial resolution, much more detail can be seen in images of trace gas retrievals. For example, NO_2 plumes from ships can now be seen in a daily snapshot with TROPOMI, whereas with OMI, data over many days had to be averaged in order to see such ship tracks. Very distinct plumes of SO_2 and NO_2 can also be seen in a single day's image from sources such as power plants. **Henk Eskes** [KNMI] showed comparisons of OMI and TROPOMI NO_2 retrievals. TROPOMI is able to produce NO_2 retrievals on a much finer scale, showing emissions from small cities as well as from cars being driven on the highways that connect them. **Ilse Aben** [Space Research Organization Netherlands (SRON)] described early results on methane and carbon monoxide retrieved from the TROPOMI shortwave infrared channel—which is not present on OMI.

Poster Session

There was also a poster session during the meeting. Researchers used this medium to show that OMI algorithms continue to improve after over a decade in orbit, and several posters described data product updates. The **Table** below lists the presenters and the topics of their posters.

Discussion of Future Plans for Aura and OMI

The last day concluded with planning for the future of Aura and OMI. Breakout groups convened to discuss a proposal to have Aura exit the Afternoon "A-Train" constellation of satellites after the desired two-year overlap between OMI and TROPOMI. This would be done primarily in order to save fuel and extend Aura's lifetime, in particular the unique measurements made by the Microwave Limb Sounder (MLS). To exit the constellation, the usual inclination adjustment maneuvers that are performed each year to keep Aura in a precise orbit would no longer be done starting in 2020 or 2021. This would cause Aura to drift in its polar orbit and cross the Equator at later and later times in the afternoon, whereas it currently crosses the Equator at around 1:30 PM local time. The satellite would also be lowered in altitude with a maneuver to prevent Aura's path from intersecting with those of other satellites. A drift in Aura's orbit would potentially allow for unique late afternoon trace gas observations from OMI that would complement those from other instruments, such as TROPOMI whose host satellite currently has a similar equator crossing time as Aura. This would also help to fill data over parts of the Earth not well covered

Table. Presentations from the poster session.

Presenter [Affiliation]	**Summary of Poster Content**
David Haffner [SSAI]	Described evaluations of a new version of OMI total column ozone products
Richard McPeters [GSFC]	Described intercomparisons of ozone retrievals from OMI with those from OMPS
Christian Borger [Max Planck Institute for Chemistry, Germany]	Discussed total column water vapor retrievals from OMI and TROPOMI in the blue spectral range
Yeonjin Jung [Harvard SAO]	Described a study of aerosol effects on trace-gas retrievals
Deborah Stein Zweers [KNMI]	Described the use of NO_2-sondes to better understand OMI retrievals
Chris Chan Miller [Harvard SAO]	Described a project to produce long-term records of the trace gases formaldehyde, glyoxal, and water vapor, using several different satellite sensors, including OMI
Anu-Maija Sundström [FMI]	Described satellite-based analysis of surface-level ozone sensitivity to NO_x and volatile organic compounds
James Johnson [GSFC]	Discussed OMI/TROPOMI data support from NASA's Goddard Earth Sciences Data and Information Services Center (GES-DISC)
Zachary Fasnacht [SSAI]	Discussed evaluation of MODIS surface products for OMI data products using OMI radiances
Nick Gorkavyi [SSAI]	Described a method to flag saturation and non-linearity of OMI radiance measurements in bright scenes such as Sun glint
Brad Fisher [SSAI]	Described a new version of the OMI-MODIS collocated cloud product (OMMYDCLD)

by a planned future constellation of geostationary satellites that will observe throughout the day but with limited coverage over the Southern Hemisphere and tropics. Participants identified several complications and risks to OMI operations associated with a drifting orbit. These will be carefully considered before a final decision is made as to if and when an Aura A-Train exit will take place. There will be further discussions with the Aura community and MLS team at the upcoming Aura STM in Pasadena, CA, January 22-24, 2019.

Conclusion

OMI continues to perform well after more than fourteen years in orbit and as data processing algorithms continue to improve. A number of long-term OMI data records are being used for studies on atmospheric composition and air quality, including health studies. OMI and Aura STMs provide an opportunity for team members and collaborators from all over the world to share recent results and discuss future plans. Future OMI science team meetings likely will be held in conjunction with those for the TROPOMI project. ■

May the Force be with GEDI. On December 5, 2018, at 1:16 PM EST SpaceX's Commercial Resupply Mission 16 to the International Space Station (ISS) soared into orbit via a Falcon 9 rocket launched from Cape Canaveral Air Force Base in Florida. Included on that payload was the Global Ecosystem Dynamics Investigation, or GEDI, instrument. GEDI is now installed on the Japanese Experimenter Module–Exposed Facility on ISS and will go through a short initial testing phase before starting science data collection. GEDI will provide high-resolution, laser-ranging observations of the three-dimensional structure of Earth's near-surface, including precise measurements of forest canopy height, canopy vertical structure, and surface elevation, which will greatly advance our ability to characterize important carbon and water cycling processes, biodiversity, and habitat. **Photo credit:** Daniel Teodoro

Summary of the Thirtieth CERES Science Team Meeting and 2018 Earth Radiation Budget Workshop

Walter Miller, NASA's Langley Research Center, Science Systems and Applications, Inc., walter.f.miller@nasa.gov

Introduction

The 2018 Earth Radiation Budget Workshop was held September 10-13, 2018, at the Mesa Laboratory of the National Center for Atmospheric Research (NCAR) in Boulder, CO. **Norman Loeb** [NASA's Langley Research Center (LaRC)—*Clouds and the Earth's Radiant Energy System (CERES) Principal Investigator (PI)*] conducted the workshop. The workshop included the thirtieth CERES Science Team Meeting (STM) along with technical sessions for the Geostationary Earth Radiation Budget (GERB) and Scanner for Radiation Budget (ScaRab) instrument teams. Members of these three instrument teams have gathered every other year since 2010 to discuss their mutual concerns and progress in creating Earth Radiation Budget (ERB) data records.

The first day of the meeting focused on programmatic updates from CERES, including the semi-annual *State of CERES* address from the CERES PI, as well as reports from the various working groups and the data management team. The second day was devoted to technical sessions on GERB and ScaRab; to learn more, see *Updates from GERB and ScaRab* on page 38. There were three invited presentations on the afternoon of day two, and a series of science presentations—discussing topics relevant to all three missions—beginning on the afternoon of the second day and running through the end of the workshop.

Background on Three ERB Missions: CERES, GERB, and ScaRab

ERB instruments are designed to measure the full spectrum of the energy leaving Earth, which includes reflected solar and emitted thermal energy, also referred to as shortwave (SW) and longwave (LW) radiation, respectively. The various instruments are designed to provide synergy in contributing to our understanding of ERB.

The six operational CERES instruments are on four different satellites in polar orbit.[1] With the exception of Terra, which crosses the Equator at 10:30 AM local time, all of the other platforms carrying CERES instruments cross the equator at 1:30 PM local time. These orbits provide daily global coverage across a narrow range of times and solar zenith angles outside the polar regions, with more frequent coverage within the polar regions. NASA built and operates the CERES instruments.

The GERB instruments are on satellites in a geostationary orbit.[2] They provide 15-minute observations, but over only a limited longitude band, with poor coverage at the poles. However, the high frequency of observation captures the diurnal variation in the fluxes. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) operates the GERB mission; Imperial College in the U.K. is responsible for calibration and science products.

The ScaRab is a joint project of France and India and provides ERB data over the tropics from a low-inclination orbit aboard the Megha-Tropiques satellite, a joint mission between the Indian Space Research Organization (ISRO) and Centre National d'Études Spatiales (CNES) [French space agency]. ScaRab is in an inclined orbit that only covers the tropics, but it is a precessing orbit that allows observations to be made at different local times each day, thereby capturing variations over a 24-hour period.

The emphasis of the remainder of this article will be on CERES, as the other two missions are outside the primary focus of this publication except insofar as when they impinge on NASA's activities. Such connections are summarized in the text box on page 38.

CERES Science Team Summary

The CERES STM held sessions throughout the larger four-day ERB Workshop. The presentations and videos are available online at *https://ceres.larc.nasa.gov/science-team-meetings2.php?date=2018-09*. In the text that follows, there are references to some specific presentations where more information can be found online at *https://ceres.larc.nasa.gov/science-team-meetings2.php?date=2018-09*.

Programmatic and Technical Presentations

Norman Loeb outlined the major objectives of the CERES STM, which were to:

- review the performance of the CERES instruments;
- discuss data product validation;

[1]This includes two on Terra [Flight Model (FM)-1 and -2]; two on Aqua [FM-3 and -4]; one on the Suomi National Polar-orbiting Partnership (NPP) [FM-5]; and one on National Oceanic and Atmospheric Administration's NOAA-20 satellite [FM-6].

[2] Four Meteosat Second-Generation (MSG) satellites (MSG-1, -2, -3, and -4) have been launched, the most recent in 2015. MSG-1, -2, -3, and -4 have been renamed Meteosat-8, -9, -10, and -11, respectively. The GERB instruments were not flown in order, so GERB-2 is on MSG-1 and GERB-1 on MSG-2; GERB-3 and -4 are on MSG-3 and -4, respectively. These satellites have at least one operating instrument, but GERB-1 is no longer operational on MSG-2.

- assess the improvements from reprocessing data between March 2016 and March 2018 using Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6.1 data; and

- decide upon the path forward for the next edition of CERES products.

Now nearly a year into its mission, the CERES FM-6 instrument on NOAA-20 has gone through intensive validation—see **Susan Thomas**'s [LaRC/Science Systems and Applications, Inc. (SSAI)] presentation for details. Both the onboard calibration sources and solar diffuser show an increase in total sensor detector response of 2.5% and SW detector response of 1.8% since the first observations in January 2018. The changing response will be corrected using updated gains in Edition 1 processing. However, the change has stabilized in the last few months as outgassing and adjustment to the vacuum of space have been completed. The radiance value from the new LW channel and the historical method of obtaining LW radiance derived from the total minus SW channel are very consistent. The coastline detection method, which is used to determine where the transition between hot land and cold ocean occur, has shown that the pointing accuracy of the measurements is well within 1 km (~0.6 mi). This is consistent with the accuracy of the other CERES instruments.

The first data from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on NOAA-20 have been processed through the cloud retrieval subsystem—see **Sunny Sun-Mack**'s [LaRC/SSAI] presentation for details. The radiances are about 8% higher in the NOAA-20 solar channels than those retrieved from VIIRS on Suomi NPP. This is causing a large discrepancy in cloud optical depth obtained from the cloud retrieval using the imager data from the two satellites.

The CERES instruments on Terra and Aqua use cloud information derived from collocated MODIS imagers along with surface information to determine the scene types for converting radiances to fluxes. CERES Edition 4 production began by using MODIS Collection 5, but it was superseded by Collection 6 for data after February 2017. However, MODIS Collection 6.1 was released earlier this year with major calibration improvements in the 6.72-μm and 8.6-μm channels on Terra–MODIS and for all the visible channels on Aqua–MODIS. The CERES data have been reprocessed with the MODIS Collection 6.1 beginning with data from March 2016, after Terra-MODIS went into safe mode and the Terra–MODIS water-vapor channel showed a large loss of sensitivity. The CERES adjustment to the Terra calibration in these channels has resulted in more nighttime polar clouds. The *single satellite products* (i.e., instruments on Terra only or Aqua only) have been reprocessed, and the merged product that uses information from both Earth Observing System (EOS) and geostationary satellites should be completed in spring 2019. The resulting products using the reprocessed data will be renamed Edition 4.1.

Planning has begun for Terra and Aqua Edition 5 CERES products. Several topics that have current activities include:

Global Modeling and Assimilation Office (GMAO) improvements to their atmospheric reanalysis system. Members from GMAO and CERES are meeting regularly and working to validate the latest Goddard Earth Observing System (GEOS) Model Forward Processing (FP) or FP for Instrument Team (FPIT) version. An example of the validation done by the CERES team is using CALIPSO[3] data, which detects thin clouds better than MODIS, to select which Aqua-MODIS pixels are free from clouds before determining the skin temperature in Polar Regions to compare with the model results—see **Seiji Kato**'s [LaRC] presentation for details.

Timing of replacing use of data from the FM-3 instrument on Aqua with those from FM-6 on NOAA-20 as the Aqua orbit drifts from the Mean Local Time (MLT) of 1:30 PM.[4] The hope is to develop new VIIRS-based Angular Distribution Models (ADMs) with Suomi NPP by placing FM-5 into Rotating Azimuth Plan (RAP) mode. A study using Aqua data indicates a minimum requirement of at least one year of RAP data from Suomi NPP is needed for the task—see **Wenying Su**'s [LaRC]) presentation for details.

CERES algorithm improvements. The specific focus here was on those algorithms that need to be adapted to new instruments being used on more-recent satellites, to enable a seamless transition across satellite platforms. For MODIS cloud property determination, the 6.7- and 13-mm channels will not be used since they are not available on VIIRS. A consistent approach for clear-sky radiance estimates and atmospheric correction will be applied to both MODIS and VIIRS calculations—see **William Smith Jr.**'s [LaRC] presentation for details.

CERES production code improvements. An independent analysis using machine learning and associated timing is being done on the CERES Fortran production code to identify candidate sections for targeted improvements—see **Jonathan Gleason**'s [LaRC]) presentation.

[3] CALIPSO stands for Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation.

[4] Around 2022, the Aqua satellite will no longer have enough fuel to maintain its positiion and will begin a slow drift from its current orbit.

The Suomi NPP Edition 2 products will place CERES FM-5 on the same radiometric scale as FM-3 and correct the FM-5 spectral response function as it changes over time. Also, beginning with Edition 2, VIIRS radiances will be placed on the same radiometric scale as Aqua-MODIS creating more consistency in cloud properties (e.g., optical depth and cloud detection) between the two imagers.

David Considine [NASA Headquarters (HQ)] spoke about the Earth Venture-Continuity (EV-C), a low-cost, cost-capped mission to extend current NASA measurements. The program is in response to the 2017 Decadal Survey[5] recommendation to continue the *Program of Record*, but do it more efficiently. A Science Working Group consisting of 22 NASA and NOAA civil servants has recommended instruments and measurement characteristics for an EV-C ERB instrument. The recommendation was basically a duplicate of FM-6, but perhaps with reduced scanning capability (cross-track with azimuthal rotation capability for lunar and solar calibration). The draft was published in July 2018 for public comment. The finalized recommendations will not be incorporated into the Announcement of Opportunity (AO) as requirements, only as a reference.[6]

Invited Science Presentations

The modeling community is a primary user of CERES radiation and flux data, and fall meetings such as this are traditionally held at a modeling center to allow interaction with this community. A number of the science presentations were from modelers who attended, including the three invited presentations, as summarized next.

John Fasullo [NCAR] provided details on the Climate Model Analysis Tool (CMAT) developed at NCAR. He described how his team conducted a survey of climate scientists, asking what variables were important to include in a model evaluation. The results identified SW and LW cloud forcing, rain flux, sea level pressure, and zonal mean relative humidity as some important variables that should be included. CMAT includes these parameters and does *model scoring* by looking at seasonal contrast and El Niño/Southern Oscillation (ENSO) pattern correlations for variables related to the energy budget, water cycle, and atmospheric dynamics. These variables will allow a comprehensive and objective model evaluation. Fasullo then discussed the development of the Community Earth System Model 2 (CESM2). He emphasized the impact minor perturbations in the initial conditions can have on the Earth Energy Imbalance (EEI).

Jen Kay [NCAR] presented recent information on detecting and attributing climate change. There was a large decline in Arctic sea ice extent at the end of September 2017 (corresponding to the minimum extent before the ice begins expanding in winter), dipping to as low as half the value measured in September 1979. Before 1979, the Arctic sea ice extent changed very little. Since 1979 there has been an overall downward trend in sea ice extent, which results in increased absorbed SW radiation during the summer—see **Figure**. This occurs because cloud amount has remained constant regardless of whether the underlying surface is water or ice. The CESM1 Ensemble was run for 2000 years with a constant preindustrial forcing to determine internal variability. The same model was then rerun multiple times with miniscule perturbation in atmospheric temperature (10^{-14} K) starting in 1920. The results show that the current decrease in sea ice extent is outside the modeled preindustrial internal variability. Likewise, recent Arctic surface air temperatures are emerging as a climate change signal. The increase in measured Arctic surface air temperature since 2005 is outside the range of model internal variability using preindustrial forcing.

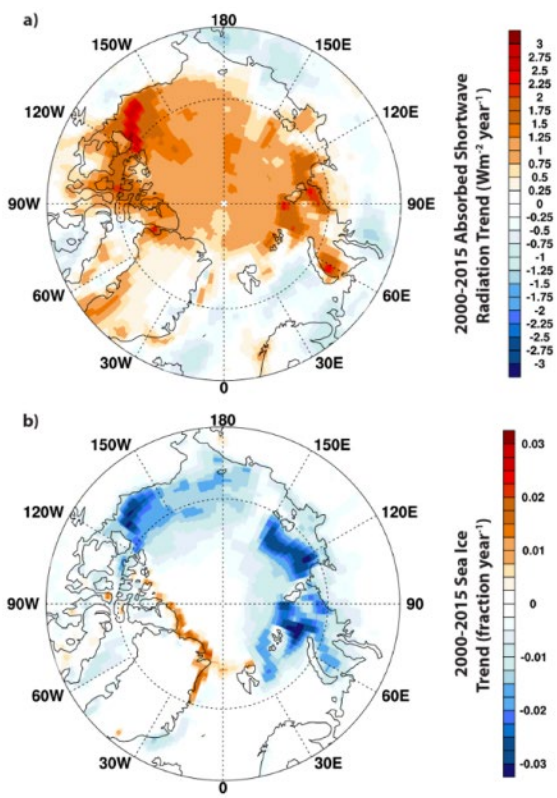


Figure. The large surface temperature anomalies between 2000 and 2015 led to the following Arctic responses: A positive trend in absorbed SW radiation [*top*]; a decrease in Arctic sea ice concentration in most areas [*bottom*]. **Image credit**: Jen Kay [NCAR]

[5] The 2017 Earth Science Decadal Survey, "Thriving on a Changing Planet: A Decadal Strategy for Earth Observation from Space," can be viewed at and downloaded from *https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

[6] **UPDATE**: A draft AO was released on November 20, 2018.

Updates on GERB and ScaRab

The second day of the meeting included technical sessions on GERB and ScaRab, which are briefly summarized below.

GERB Technical Session

Helen Brindley [Imperial College, London] led the GERB technical session. In her opening remarks she discussed current and future operational plans for the instrument and the status of data processing efforts.

There are currently two operational instruments: GERB-2, in orbit in the vicinity of India, and GERB-4, at the Greenwich, England, longitude (Earth's canonical prime meridian). The two other instruments (GERB-1 and GERB-3) can be returned to operation if the primary GERB instrument data quality drops. A dedicated ERB instrument is not part of the Meteosat Third Generation (MTG) satellites going forward; however, the European Space Agency's (ESA) proposal to include one on EarthCARE[1] has been accepted.

A GERB diurnal monthly hourly average product is waiting for the final product definition from the Observations for Model Intercomparisons Project (Obs4MIPs) before being released. Significant work is required to account for changes associated with the aging mirror characterizations. Updated calibration and radiance-to-flux calculation improvements have been implemented in the Edition 2 processing system, but cloud optical depth thresholds and aerosol ADMs are still in development. The hardware stream also needs to be set up before processing can begin.

ScaRab Technical Session

Thomas Fiolleau [Centre National de la Recherche Scientifique (CNRS), France] reported on recent activities performed by the ScaRab team. The CERES Programmable Azimuth Plan Scan (PAPS) campaign, held in conjunction with ScaRab, showed a +2.5% bias in ScaRab SW measurements as compared with those of CERES. This is within the error budget of the two instruments.

An improved flux algorithm will be applied for the next edition of the data products. The team is also developing a 0.5 x 0.5° flux product.

A five-year Mesoscale Convective System climatology over the tropics has been developed using six geostationary satellites: GOES 13 and 14; Meteosat-7, -9, and -10; and MTSAT-2, during the period 2012 through 2014.[2] ScaRab brightness temperature is used to adjust matched geostationary imager brightness temperature to a common standard, thereby reducing bias to near zero across the geostationary satellites.

[1] To learn more about EarthCARE, visit *http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/EarthCARE/ESA's cloud_aerosol_and_radiation_mission*.

[2] GOES stands for the Geostationary Operational Environmental Satellite, a series of satellites operated by NOAA. Meteosat-7 was the last "first generation" Meteosat satellite series, operated by the European Organization for Meteorological Satellites (EUMETSAT). Meteosat-9 and -10 are part of the Meteosat Second Generation (MSG) series also operated by EUMETSAT. MTSAT stands for Multifunction Transport Satellite, a series procured by the Japan Civil Aviation Bureau and Japan Meteorological Agency, and funded by the Japanese Ministry of Land, Infrastructure and Transport.

Andrew Gettelman [NCAR] discussed challenges associated with determining radiance imbalance due to uncertainties in aerosol feedback and heat content of the ocean. These parameters represent two of the unknowns in Earth's radiation balance equation. In addition to the direct aerosol effect, aerosols have indirect effects on cloud composition by reducing droplet size. A radiative kernel is used to constrain aerosol forcing by doing two runs, one using today's aerosol concentration, and the other using preindustrial levels. The uncertainty feedback between model runs is related to SW and LW cloud radiative feedbacks. This variation is likely tied to the different responses of tropical cirrus and subtropical stratocumulus clouds, and phase changes in polar clouds due to aerosol differences.

Contributed Science Presentations

This section of the meeting began with presentations from two well-known veteran scientists. Following those, a variety of topics were covered during the many contributed science presentations

Kevin Trenberth [NCAR], lead author of the 2001 and 2007 Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment of Climate Change, presented a review on the flow of energy through the climate system and how it changes with time, noting that Earth's radiant energy is transformed to internal heat, potential energy (gravity), latent energy, and kinetic energy. The atmosphere and ocean transport energy while the ocean, land surface, and ice store energy. For the climate to remain in equilibrium, all these sources and sinks of energy need to be in balance. So, the planet needs to warm with increased greenhouse gases until outgoing longwave radiation (OLR) matches the absorbed solar radiation. This manifests itself in increasing surface temperatures. Clouds have different effects on SW and LW radiation, but their impact generally cancels out in the net calculation, except for along the Western coasts of North and South America, where the presence of stratus clouds interrupts the net pattern that otherwise follows the Earth-Sun geometry. The energy balance goes to warm the atmosphere and land, heat the ocean, melt sea ice, and evaporate moisture. The atmosphere and ocean transport heat from the tropics to the poles. The remainder of Trenberth's presentation went into details of the ocean meridional heat transport over the last two decades and its impact on climate.

Thomas Vonder Haar [Colorado State University] presented his first-person perspective on early ERB satellite measurements. He provided a summary of his two-decade quest to measure the ERB from space, specifically focusing on the measurement of planetary albedo. In 1917 the estimate of the planetary albedo was 50%. By the 1950s, improved understanding of radiative transfer in the atmosphere, better cloud climatology, and balloon measurements of cloud reflectance had refined the estimate to 33%. The next step forward in accuracy came in the satellite era, when radiometers were included on the Television Infrared Observation Satellite (TIROS) and U.S. Air Force Defense Meteorological Satellite Program (DMSP) Block 1 satellites in the 1960s. Piecing together these early satellite measurements led to a new estimate of 29% for planetary albedo. These early measurements implied a warmer and darker planet then was previously assumed. A warmer planet required that 40% more energy be transported poleward by the atmosphere and ocean circulations than had previously been assumed. Subsequently the Nimbus-3, -6, and -7 missions carried Earth Radiation Budget sensors between 1963 and 2004, which lengthened the timeseries of ERB data and provided further verification of the earlier albedo estimate of 29%.[7]

To continue the ERB measurement time series and add capability to investigate ERB variability and cloud forcing, a three-satellite constellation known as the Earth Radiation Budget Experiment (ERBE)[8] launched between 1984 and 1986. Vonder Haar explained how ERBE set the stage for CERES and led to an increased focus on understanding the impact of clouds on the ERB. He noted that while these later instruments have further reduced the uncertainty in the planetary albedo measurement, they have not significantly changed the value obtained in the 1960s.

Other topics discussed during presentations in this session included:

- model validation with respect to boundary layer clouds;
- changes in the Arctic radiation budget due to ice amounts, clouds, and circulations from models and observations;
- determination of heating rates throughout Earth's atmosphere with higher resolution cloud information;
- analysis of the Earth Energy Budget;[9]
- ERB from current and future instruments;
- improvements to existing ERB products;
- efforts to improve algorithms for future CERES products; and
- validation of CERES products.

Conclusion

The CERES FM-6 instrument on NOAA-20 has been validated and is an excellent candidate to continue the nearly 20-year CERES record. The CERES team highlighted changes to their derived cloud properties with the use of the latest MODIS data product collection. They also discussed recent steps toward changes that will be included in Edition 5 products. The GERB and ScaRab teams provided updates on new products being made available to the community. Modelers from NCAR described the development of CESM2 including the important role that CERES observations have played. Their presentations also described how the CESM2 addresses climate change in the Arctic and its response to different aerosol forcing.

The next CERES STM will be held May 7-9, 2019, at LaRC. ■

[7] To learn more about these missions and instruments see "Nimbus Celebrates Fifty Years" in the March–April 2015 issue of The Earth Observer [Volume 27, Issue, pp. 18-30—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Mar_Apr_2015_color_508.pdf#page=18*].

[8] ERB instruments flew on the Earth Radiation Budget Satellite (ERBS), launched from Space Shuttle Challenger in 1984, NOAA-9, launched in 1985, and NOAA-10, launched in 1986. While the ERB scanning instruments on all three satellites failed early in their life, the non-scanning instruments functioned until 2005.

[9] In this context, Earth Energy Budget encompasses ERB, which includes SW and LW radiation, as well as latent and sensible heating. In practice, however, Earth Energy Budget and ERB end up being used interchangeably in the literature.

NASA's Terra Satellite Celebrates 100,000 Orbits

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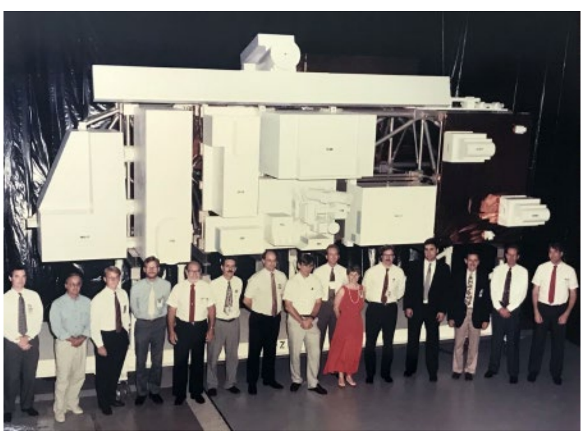
EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

More than 400 mi (~644 km) above Earth, a satellite the size of a school bus is earning its frequent flyer miles. On October 6, 2018, NASA's Terra satellite completed 100,000 orbits around Earth. Terra joins a handful of satellites to mark this orbital milestone, including the International Space Station, Earth Radiation Budget Satellite (ERBS), Landsat 5, and Landsat 7. Terra, which launched December 18, 1999, is projected to continue operation into the 2020s.

The five scientific instruments aboard Terra provide long-term value for advancing scientific understanding of our planet—one of the longest running satellite climate data records—and yield immediate benefits in such areas as public health. For example, recently scientists analyzed 15 years of pollution data in California, collected by the Multi-angle Imaging Spectroradiometer (MISR) instrument, and discovered that the state's clean air programs have been successful in reducing particle pollution. More urgently, data from the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) and MISR provided crucial information about the air quality and land change conditions around Hawaii's erupting Kilauea volcano, informing critical public health and safety decisions.

But just as a plane can't fly without a crew, the Terra satellite never could have provided these vital benefits to society for this long without decades of dedicated work by engineers and scientists.



Members of the Terra design team stand in front of a true-to-size model of the satellite in the mid-1990s. **Photo credit:** courtesy of Dick Quinn

Completing more than 2.5 billion miles (~4 billion km) of flight around Earth over almost 19 years, by a satellite designed to operate for five years, does not happen unless a satellite is designed, constructed, and operated with great care.

"Multiple, different aspects in the team make it work," said **Eric Moyer** [NASA's Goddard Space Flight Center (GSFC)—*Deputy Project Manager, Earth Science Mission Operations*].

"The Terra team includes flight operations, subsystem engineers, subject matter experts, the instrument teams, and the science teams for each of the instruments. Overall it all has to be coordinated, so one activity doesn't negatively impact another instrument," said Moyer, who worked on Terra during construction and continues to be involved with its operations today.

Dimitrios Mantziaras [GSFC—*Terra Mission Director*] summed up what it takes: "A well-built spacecraft, talented people running it, and making great science products, with lots of people using the data, that's what has kept Terra running all these years."

Designing a Pioneer

Terra was unique from the beginning. It was one of the first satellites to study Earth system science, and the first to look at land, water, and the atmosphere at the same time. Unlike many previous, smaller satellites, Terra didn't have a previously launched satellite platform to build upon. It had to be designed from scratch.

"Unlike the Landsat mission, which continues to improve upon its original design, nothing like Terra had ever been built," said Terra's spacecraft manufacturing representative **Dick Quinn** [Lockheed Martin], who still works part-time with the team responsible for Terra's continued flight.

Terra was meant to be the first in a series of satellites, known as AM-1, -2 and -3, each with a design life of about five years. Instead, the mission team ended up designing a satellite that lasted longer than the combined design life of three generations of Terra satellites.[1]

Constructing and Operating a Solid Satellite

The built-in redundancies and flexibility of the satellite were put to the test in 2009, when a micrometeoroid struck a power cell, degrading the thermal control for the battery.

[1] To learn more about the history of the mission that eventually became known as *Terra*, see "The Enduring Legacy of The Earth Observing System, Part II: Creating a Global Observing System—Challenges and Opportunities" in the May–June 2011 issue of *The Earth Observer* [**Volume 23**, **Issue 3**, pp. 4-14—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/May_June_2011_col_508.pdf#page=4*].

Terra's test team stands in front of the satellite during its construction and testing phase. **Photo credit:** courtesy of Dick Quinn

"We had to change the way we manage the battery to keep it operating efficiently and keep it at the right temperature," said **Jason Hendrickson** [GSFC—*Terra Flight Systems Manager*], who joined the team in 2013. To do this, the team used the charge and discharge cycle of the battery itself to generate the heat necessary to keep the battery operating. They have been finetuning this cycle ever since.

Terra engineers and scientists continually plan for worst-case scenarios, anticipating problems that may never develop.

"We are always thinking, if this were to fail, how are we going to respond?" Hendrickson said. "You can't just go to the garage and swap out parts."

Not only does the team plan for many possible scenarios, but it also looks back at the response and figures out how it can be improved.

However, most of the time, they don't have to wait for a system failure to practice contingency plans. For example, in 2017 the team executed the second lunar deep space calibration maneuver in Terra's lifetime.[2] The satellite turned to look at deep space, instead of at Earth.

"We had to take into account what would happen if the computer were to fail when we were pointed at deep space," Hendrickson said.

[2] To learn more, see "Terra Flips for Science" in the September–October 2017 issue of *The Earth Observer* [**Volume 29**, **Issue 5**, pp.18-19—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Sept_Oct_%202017_color.pdf#page=18*].

The calibration maneuver was executed successfully and the team never had to conduct their contingency plan. The science gained from calibrating Terra's data against deep space allowed the scientists to improve the data collected by the ASTER instrument. ASTER, a collaborative instrument with Japan and the U.S., monitors volcanic eruptions, among many other objectives and provides high resolution imagery of locations all over the world.

In addition to ASTER, additional instruments on Terra also make many contributions and benefit people worldwide. These include:[3]

- **The Moderate Resolution Imaging Spectroradiometer (MODIS)** collects data on land cover, land and sea surface temperatures, aerosol particle properties, and cloud cover changes. For example, MODIS data are used to protect people's lives and property through operations like MODIS rapid response, which monitors wildfires daily.

- **MISR** continues to provide data useful for health researchers studying the effects of particulate matter on populations all over the world, as well as fundamental studies of how aerosol particles and clouds affect weather and climate and investigations of terrestrial ecology.

- **Measurements of Pollution in the Troposphere (MOPITT)**, a collaboration with the Canadian Space Agency, is used to study carbon monoxide in the atmosphere, an indicator of pollution concentrations, also a contributor to global health issues.

- **Clouds and Earth's Radiant Energy System (CERES)** provides data on Earth's energy budget, helping monitor the outgoing reflected solar and emitted infrared radiation of the planet.[4]

The science teams for each instrument work with the operations and technical teams to ensure that the scientific data provided are accurate and useful to the researchers who access them.

The data are free and are valued by people all over the world. Not only can they be accessed daily, there are over 240 direct broadcast sites, where data can be downloaded in near real-time, all over the world. Moyer said that one of the most rewarding parts of working with Terra is that "the science data are truly valued by people we don't even know. People all over the world." ■

[3] To learn more about what Terra's instruments accomplished, see "15@15: 15 Things Terra has Taught Us in Its 15 Years in Orbit" in the January–February 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 1**, pp. 4–13—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/JanFeb2015_color_508.pdf#page=4*]. The author of this news story was lead author on this article.

[4] To learn more about the latest activities of CERES, see page 35 of this issue.

Ozone Hole Modest Despite Optimum Conditions for Ozone Depletion

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

EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

The ozone hole that forms in the upper atmosphere over Antarctica each September was slightly above average size in 2018, according to National Oceanic and Atmospheric Administration (NOAA) and NASA scientists—see *Ozone 101: What is Ozone and Why Does It Matter?* on page 43.

Colder-than-average temperatures in the Antarctic stratosphere created ideal conditions for destroying ozone this year, but declining levels of ozone-depleting chemicals prevented the hole from being as large as it would have been 20 years ago.

"Chlorine levels in the Antarctic stratosphere have fallen about 11% from the peak year in 2000," said **Paul A. Newman** [NASA's Goddard Space Flight Center—*Chief Scientist for Earth Science*]. "This year's colder temperatures would have given us a much larger ozone hole if chlorine was still at levels we saw back in the year 2000."

According to NASA, the annual ozone hole reached an average area coverage of 8.83 million mi^2 (22.9 million km^2) in 2018—almost three times the size of the contiguous U.S. It ranks thirteenth largest out of 40 years of NASA satellite observations. Nations of the world began phasing out the use of ozone-depleting substances in 1987 under an international treaty known as the Montreal Protocol.

The 2018 ozone hole was strongly influenced by a stable and cold *Antarctic vortex*—the stratospheric low pressure system that flows clockwise in the atmosphere above Antarctica. These colder conditions—among the coldest since 1979—helped support formation of more polar stratospheric clouds, whose cloud particles activate ozone-destroying forms of chlorine and bromine compounds.

In 2016 and 2017, warmer temperatures in September limited the formation of polar stratospheric clouds and slowed the ozone hole's growth. In 2017, the ozone hole reached a size of 7.6 million mi^2 (19.7 million km^2) before starting to recover. In 2016, the hole grew to 8 million mi^2 (20.7 million km^2).

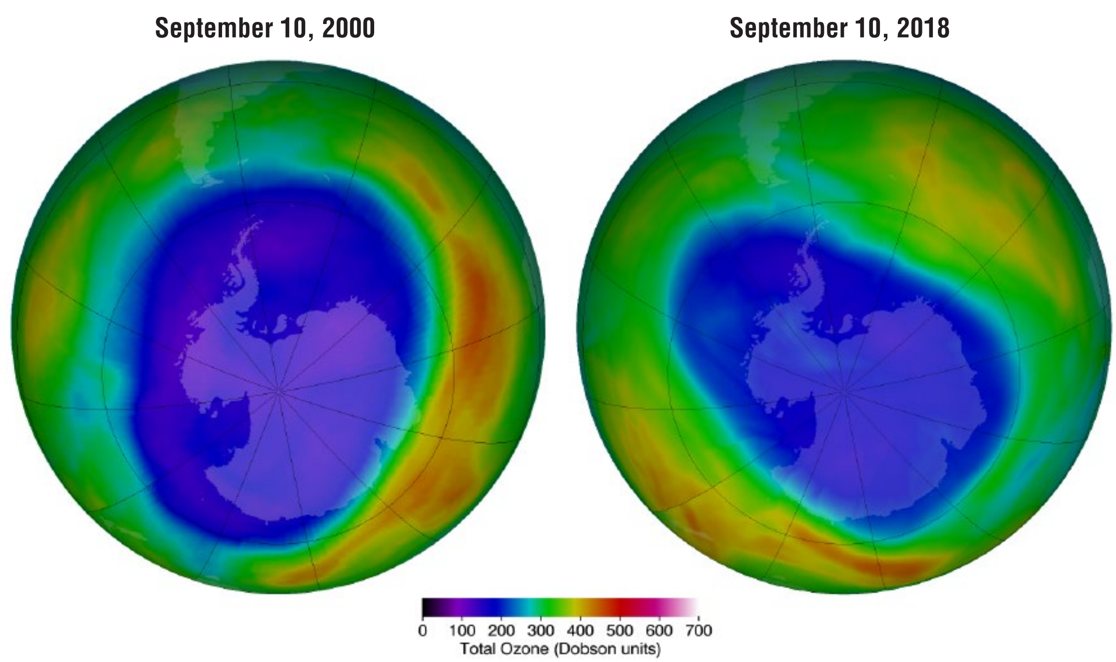


Figure. The Antarctic ozone hole forms each year and is defined as the area that is enclosed by a line with a constant value of 220 Dobson Units. This Figure shows a comparison of the ozone hole from September 10, 2000 [*left*] to that of September 10, 2018 [*right*]. The meteorological conditions for these two years were similar with a stable and cold Antarctic vortex in place. Such conditions are conducive to the formation of polar stratospheric clouds, the presence of which provides a catalyst for ozone destruction. However, owing to an 11% decline in ozone-destroying substances in the ensuing years, while still quite large in areal extent compared to the values of the early 1980s, the ozone hole in 2018 is substantially smaller than the ozone hole of 2000, when the concentrations of ozone-destoying substances were at their peak. This Figure provides evidence that the expected recovery of the ozone hole after the enactment of the Montreal Protocol is slowly but surely taking place. **Image credit:** NASA Ozone Watch

Ozone 101: What is Ozone and Why Does It Matter?

Ozone comprises three oxygen atoms and is highly reactive with other chemicals. In the stratosphere, roughly 7 to 25 mi (about 11 to 40 km) above Earth's surface, a layer of ozone acts like sunscreen, shielding the planet from ultraviolet radiation that can cause skin cancer and cataracts, suppress immune systems, and damage plants. Ozone can also be created by photochemical reactions between the Sun and pollution from vehicle emissions and other sources, forming harmful smog in the lower atmosphere. It is stratospheric ozone that is the focus of this news story.

NASA and NOAA use three complementary instrumental methods to monitor the growth and breakup of the ozone hole each year. Satellite instruments like the Ozone Monitoring Instrument on NASA's Aura satellite and the Ozone Mapping Profiler Suite on the NASA-NOAA Suomi National Polar-orbiting Partnership satellite measure ozone across large areas from space. The Aura satellite's Microwave Limb Sounder also measures certain chlorine-containing gases, providing estimates of total chlorine levels.

Named after a pioneer in ozone science, a *Dobson unit* (DU) is the standard measurement for the total amount of ozone in the atmosphere above a point on Earth's surface. It represents the number of ozone molecules required to create a layer of pure ozone 0.01 mm thick at a temperature of 32 °F (0 °C) at an atmospheric pressure equivalent to Earth's surface. A value of 104 Dobson units would be a layer that is 1.04 mm thick at the surface, less than the thickness of a dime.

To give some perspective, the total amount of ozone in the atmosphere is exceedingly small. All of the ozone in a column of the atmosphere extending from the ground to space would be 300 DU, approximately the thickness of two pennies stacked one on top of the other.

Prior to the emergence of the Antarctic ozone hole in the 1970s, the average amount of ozone above the South Pole in September and October ranged from 250 to 350 DU.

NOAA scientists monitor the thickness of the ozone layer and its vertical distribution above the South Pole by regularly releasing weather balloons carrying ozone-measuring *sondes* up to 21 mi (~34 km) in altitude, and with a ground-based instrument called a Dobson spectrophotometer.

This time-lapse photo from September 10, 2018, shows the flight path of an ozonesonde as it rises into the atmosphere over the South Pole from the Amundsen-Scott South Pole Station. Scientists release these balloon-borne sensors to measure the thickness of the protective ozone layer high in the atmosphere. **Image credit:** Robert Schwarz/ University of Minnesota

However, the current ozone hole area is still large compared to the 1980s, when the depletion of the ozone layer above Antarctica was first detected. Atmospheric levels of man-made ozone-depleting substances increased up to the year 2000. Since then, they have slowly declined but remain high enough to produce significant ozone loss.

NOAA scientists said colder temperatures in 2018 allowed for near-complete elimination of ozone in a deep, 3.1-mi (5-km) layer over the South Pole. This layer is where the active chemical depletion of ozone occurs on polar stratospheric clouds. The amount of ozone over the South Pole reached a minimum of 104 Dobson Units[1] on October 12, 2018—making it the twelfth lowest year out of 33 years of NOAA ozonesonde measurements at the South Pole, according to **Bryan Johnson** [NOAA].

"Even with this year's optimum conditions, ozone loss was less severe in the upper altitude layers, which is what we would expect given the declining chlorine concentrations we're seeing in the stratosphere," Johnson said. ■

[1] See sidebar text for a definition of Dobson Units.

With Thick Ice Gone, Arctic Sea Ice Changes More Slowly

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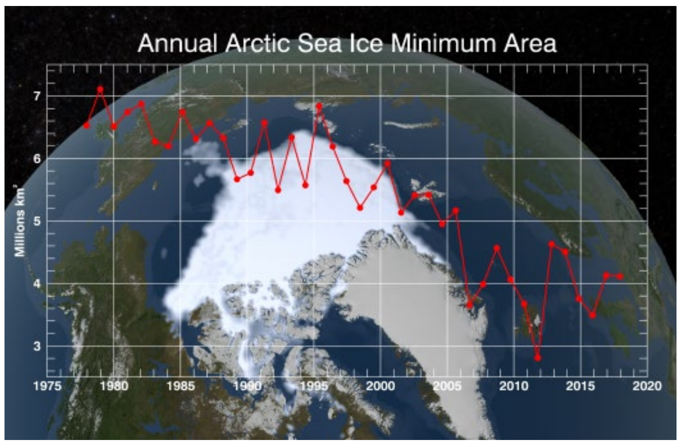
EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

The Arctic Ocean's blanket of sea ice has changed since 1958 from predominantly older, thicker ice to mostly younger, thinner ice, according to new research published by **Ron Kwok** [NASA/Jet Propulsion Laboratory]. With so little thick, old ice left, the rate of decrease in ice thickness has slowed. New ice grows faster but is more vulnerable to weather and wind, so ice thickness is now more variable, rather than dominated by the effect of global warming.

Kwok's research, published in the journal *Environmental Research Letters*, combined decades of declassified U.S. Navy submarine measurements with more recent data from four satellites to create a 60-year record of changes in Arctic sea ice thickness. He found that since 1958, Arctic ice cover has lost about two-thirds of its thickness, as averaged across the Arctic at the end of summer. Older ice has shrunk in area by almost 800,000 mi^2 (more than 2 million km^2). Today, 70% of the ice cover consists of ice that forms and melts within a single year, which scientists call *seasonal ice*.



Working from a combination of satellite records and declassified submarine sonar data, NASA scientists have constructed a 60-year record of Arctic sea ice thickness. Right now, Arctic sea ice is the youngest and thinnest its been since we started keeping records. More than 70% of Arctic sea ice is now seasonal, which means it grows in the winter and melts in the summer, but doesn't last from year to year. This seasonal ice melts faster and breaks up easier, making it much more susceptible to wind and atmospheric conditions. **Image credit:** NASA/Goddard Space Flight Center, Scientific Visualization Studio. Blue Marble data are courtesy of Reto Stockli [NASA's Goddard Space Flight Center]

Sea ice of any age is frozen ocean water. However, as sea ice survives through several melt seasons, its characteristics change. *Multiyear ice* is thicker, stronger and rougher than seasonal ice. It is much less salty than seasonal ice; Arctic explorers used it as drinking water. Satellite sensors observe enough of these differences that scientists can use spaceborne data to distinguish between the two types of ice.

Thinner, weaker seasonal ice is innately more vulnerable to weather than thick, multiyear ice. It can be pushed around more easily by wind, as happened in the summer of 2013. During that time, prevailing winds piled up the ice cover against coastlines, which made the ice cover thicker for months.

The ice's vulnerability may also be demonstrated by the increased variation in Arctic sea ice thickness and extent from year to year over the last decade. In the past, sea ice rarely melted in the Arctic Ocean. Each year, some multi-year ice flowed out of the ocean into the East Greenland Sea and melted there, and some ice grew thick enough to survive the melt season and become multiyear ice. As air temperatures in the polar regions have warmed in recent decades, however, large amounts of multiyear ice now melt within the Arctic Ocean itself. Far less seasonal ice now thickens enough over the winter to survive the summer. As a result, not only is there less ice overall, but the proportions of multiyear ice to seasonal ice have also changed in favor of the young ice.

Seasonal ice now grows to a depth of about 6 ft (2 m) in winter, and most of it melts in summer. That basic pattern is likely to continue, Kwok said. "The thickness and coverage in the Arctic are now dominated by the growth, melting, and deformation of seasonal ice."

The increase in seasonal ice also means record-breaking changes in ice cover such as those of the 1990s and 2000s are likely to be less common, Kwok noted. In fact, there has not been a new record sea ice minimum since 2012, despite years of warm weather in the Arctic. "We've lost so much of the thick ice that changes in thickness are going to be slower due to the different behavior of this ice type," Kwok said.

Kwok used data from U.S. Navy submarine sonars from 1958 to 2000; satellite altimeters on NASA's Ice, Cloud, and land Elevation Satellite (ICESat) and the European CryoSat-2, which span from 2003 to 2018; and scatterometer measurements from NASA's Quick Scatterometer (QuikSCAT) and the European Advanced Scatterometer (ASCAT) from 1999 to 2017.

NASA Earth Science in the News

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EDITOR'S NOTE: This column is intended to provide a sampling of NASA Earth Science topics mentioned 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*.

NASA Found Where that Bizarre Rectangular Iceberg Came From, November 8, *cnet.com*. A very cold internet star was born in October when a NASA survey flight over Antarctica captured a photo of a strangely squared-off iceberg—see **Figure 1**. While some people joked about a possible alien origin, NASA now has proof of the iceberg's terrestrial journey. Scientists initially thought the weird iceberg, photographed by NASA's Operation IceBridge team, had recently calved from the Larsen C ice shelf. (That's the same ice shelf that gave us monster iceberg A-68 in 2017.) Researchers sleuthed out the iceberg's starting point with the help of imagery from NASA's Landsat 8 and the European Space Agency's Sentinel-1 satellites. The iceberg originally calved off the ice shelf in November 2017. It floated north in a channel of water between the ice shelf and the A-68 iceberg. "The once-long rectangle iceberg did not make it through unscathed; it broke into smaller bits," NASA's Earth Observatory reports. The iceberg actually appears to be more a trapezoid shape than a pure rectangle in a Landsat 8 satellite image from October 14, just days before Operation IceBridge spotted it—see **Figure 2**. The infamous geometric iceberg shined brightly, but briefly. NASA says it's moved out into open water where it'll melt away in the warmer environment.

University of Oklahoma, NASA Partner on Satellite Observatory Project, November 9, *tulsaworld.com*. University of Oklahoma and NASA officials have unveiled a new program they say will give researchers a better look at where greenhouse gases are concentrated in the atmosphere. The university and the space agency are working together to develop the Geostationary Carbon Cycle Observatory (GeoCarb), which will measure concentrations of carbon dioxide, carbon monoxide, and methane in Earth's atmosphere and gather information about plant health at the surface. The project represents the largest contract in the university's history. Officials hope to launch the instrument into orbit in June 2022.

A Fire in the Ocean? NASA Spots Strange "Thermal Anomaly" in the Middle of the Atlantic, October 29, *newsweek.com*. NASA has released a satellite image that reveals a strange *thermal anomaly* in the middle of the Atlantic Ocean—see **Figure 3**. On July 14, 2017, the Suomi National Polar-orbiting Partnership (NPP)

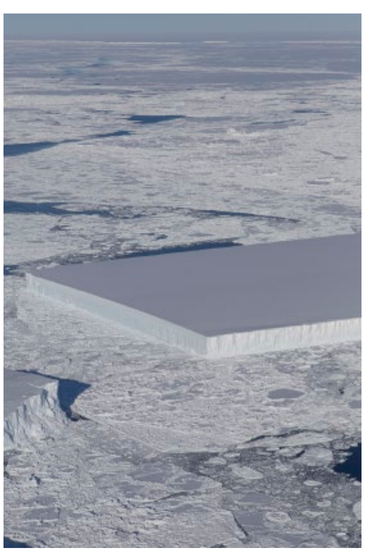

Figure 1. This rectangular iceberg made headlines after it was photographed on October 16, 2018, during an Operation IceBridge science flight. **Photo credit:** NASA/Jeremy Harbeck

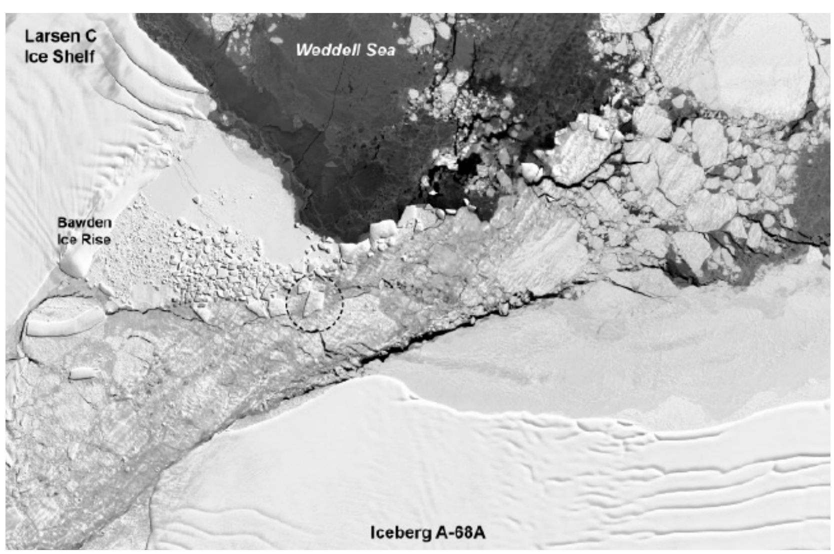

Figure 2. The iceberg is circled in this annotated Landsat 8 satellite image taken on October 14, 2018. The iceberg appears closer to the shape of a trapezoid. **Image credit:** NASA's Earth Observatory

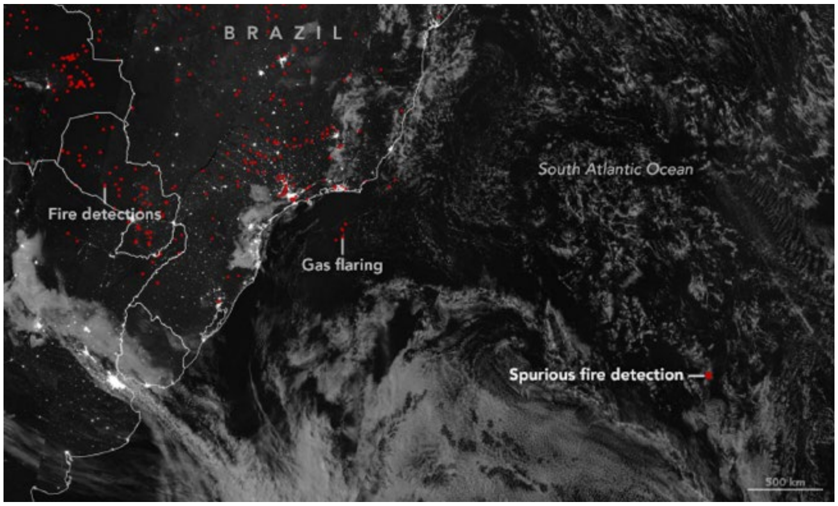

Figure 3. On July 14, 2017, Suomi NPP/VIIRS captured this night image of the South Atlantic. The red dot (annotated as "Spurious fire detection"), several hundred kilometers off the coast of Brazil, is a *thermal anomaly*—an area of Earth's surface flagged by the satellite as being unusually warm. **Image credit:** NASA's Earth Observatory

satellite observed a portion of South America and the neighboring ocean. Several hundred miles east of the Brazilian coast, you can see an isolated dot indicating an area flagged by the satellite as being unusually warm—a thermal anomaly. The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on Suomi NPP—which is jointly operated by NASA and the National Oceanic and Atmospheric Administration—detects thousands of these anomalies every night, the vast majority of which are caused by fires. "But obviously a fire isn't burning in the middle of the ocean," **Patricia Oliva** [Universidad Mayor, Chile] who was previously involved in developing a fire detection algorithm for VIIRS, said in a statement. So, what then could be responsible for the anomaly? Natural gas flares sometimes get flagged by VIIRS; however, these only occur in shallow waters near the coast. Similarly, volcanic activity can be marked as an anomaly, but there are no known volcanoes anywhere near the area on the map. "It is almost certainly SAMA," Oliva said, in reference to the South Atlantic Magnetic Anomaly. SAMA is an area where one of Earth's Van Allen radiation belts comes closest to the surface, dipping to an altitude of around 200 km (~124 mi). These belts are zones of energetic, charged particles—most of which originate from the Sun—that are captured and held around the planet by its magnetic field. The magnetic anomaly means that this region of the South Atlantic and any satellites passing above it are exposed to higher than normal levels of radiation. In fact, there are enough high-energy particles in the atmosphere here that the developers of the fire-detecting algorithm on VIIRS were surprised by how many thermal anomalies the instrument flagged when they first began using the software.

California Earthquake: NASA Finds 217-Mile-Long Fault under California and Mexico, October 12, *express.co.uk*. NASA scientists found evidence of a 217-mi- (~349-km) long earthquake fault line system extending from Southern California to Northern Mexico. A multi-year study by NASA/Jet Propulsion Laboratory (JPL) linked pre-existing fault lines into a longer chain. **Andrea Donnellan** [JPL], who led the team, said the study unearthed a 21-mi- (~34-km-) long fault line fracture connecting Mexico and the U.S. The fault line, dubbed the Ocotillo Section, was discovered just north of the Mexican border, outside of Plaster City, CA. NASA scientists believe better knowledge of this fault line system can help geologists understand how tectonic stress transfers between faults. This could in turn help researchers predict whether an earthquake along one section of a fault can grow into a much larger quake along other sections.

Hurricane Michael's Heavy Rainfall Measured by NASA, October 15, *phys.org*. NASA used satellite data to estimate how much rainfall occurred along Hurricane Michael's track between October 7-12, 2018. On Friday, October 12, Tropical Storm Michael moved out over the Atlantic Ocean and had transitioned into a powerful extratropical storm. A rainfall accumulation analysis created at NASA's Goddard Space Flight Center was derived from NASA's Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (GPM) (IMERG) data. These data were used to calculate estimates of precipitation totals from a combination of space-borne passive microwave sensors, including the GPM Microwave Imager (GMI) and geostationary infrared data. IMERG data benefit from algorithms developed by NASA's Precipitation Measurement Missions (PMM) science team that supports the GPM mission. GPM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA). IMERG rainfall accumulation data indicated that Michael frequently produced rainfall totals greater than 10 in (254 mm) along its track. IMERG data indicated that the heaviest rainfall accumulation occurred off the Yucatán where a total of over 20 in (512 mm) was estimated.

*See news story in this issue.

*Interested in getting your research out to the general public, educators, and the scientific community? Please contact **Samson Reiny** on NASA's Earth Science News Team at samson.k.reiny@nasa.gov and let him know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of **The Earth Observer**.* ■

Earth Science Meeting and Workshop Calendar

NASA Community

January 22–24, 2019
Aura Science Team Meeting, Pasadena, CA
https://mls.jpl.nasa.gov/aura2019

February 12–14, 2019
Landsat Science Team Meeting, Reno, NV
https://landsat.usgs.gov/team-meetings-agendas-and-presentations

April 1–4, 2019
ABoVE Science Team Meeting, La Jolla, CA
https://above.nasa.gov/meeting_2019/index.html

April 9–11, 2019
LCLUC STM Spring Meeting, Rockville, MD
http://lcluc.umd.edu/meetings/2019-nasa-lcluc-spring-science-team-meeting

May 7–9, 2019
CERES Science Team Meeting, Hampton, VA [LaRC]
https://ceres.larc.nasa.gov/science-team-meetings2.php

Global Science Community

January 6–10, 2019
American Meteorological Society, Annual Meeting, Phoenix, AZ
https://annual.ametsoc.org/index.cfm/2019

January 8–9, 2019
National Council for Science and the Environment (NCSE), Washington, DC
https://ncseconference.org

April 7–12, 2019
European Geosciences Union (EGU), Vienna, Austria
https://www.egu2019.eu

May 26–30, 2019
Japan Geoscience Union (JpGU), Chiba, Japan
http://www.jpgu.org/meeting_e2019/about.php

Undefined Acronyms Used in Editorial and Table of Contents

AC-VC	Atmospheric Composition Virtual Constellations
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and the Earth's Radiant Energy System
DSCOVR	Deep Space Climate Observatory
EPIC	Earth Polychromatic Imaging Camera
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
ESA	European Space Agency
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GOES	Geostationary Operational Environmental Satellite
ISRO	Indian Space Research Organization
LP DAAC	Land Processes Distributed Active Archive Center
LRI	Laser Ranging Interferometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NISTAR	National Institutes of Standard and Technology Advanced Radiometer
NOAA	National Oceanic and Atmospheric Administration
OCO	Orbiting Carbon Observatory
OMI	Ozone Monitoring Instrument
TIROS	Television Infrared Observation Satellite

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