Thirty Years Reporting on NASA's Earth Science Program

The Earth Observer

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Editor's Corner

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Terra, the first of three EOS flagship missions (later joined by Aqua and Aura), celebrated the twentieth anniversary of its launch on December 18, 2019. Having long exceeded its expected design life of six years, Terra is a tremendous feat of engineering, continuing to collect valuable data used for scientific advancement and everyday applications.

As Terra begins its third decade of operations, and thereby its data records become increasingly valuable for climate studies, all five sensors onboard (ASTER, CERES, MISR, MODIS, and MOPITT) continue to operate. Collectively, they provide complementary data about land surface, water, atmosphere, snow/ice, and Earth's energy budget. Many of the climate data records produced by Terra's instruments are the longest ever produced by a single satellite mission.[1] These data have transformed our understanding of Earth and its interconnected systems. To date, more than 20,000 publications using Terra data products have been produced, and the publication rate has steadily increased over the years.

There were two activities to recognize the twentieth anniversary of Terra. The first was a program in San Francisco on December 8, 2019 (the Sunday before the start of the Fall AGU Meeting) along with a Terra@20 session at AGU. The second was a reception on December 18, 2019, at GSFC, with a dinner later that evening in Greenbelt, MD. More information on the Terra activities at the Fall AGU will be included as part of *The Earth Observer*'s annual report on NASA's AGU Fall Meeting participation—planned for our January–February 2020 issue.

[1] For more information on the achievements of Terra's instruments 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*].

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NASA's Terra mission celebrated the twentieth anniversary of its launch on December 18, 2019. As Terra begins its third decade of operations, its data records are increasingly valuable for climate studies—which require long-term time series in order to detect trends. After twenty years, all five sensors onboard Terra (ASTER, CERES, MISR, MODIS, and MOPITT) continue to operate. Collectively, they provide complementary data about land surface, water, atmosphere, snow/ice, and Earth's energy budget. These data have been used for scientific advancement and a wide variety of practical applications. The graphic here gives some of the impressive numbers associated with the Terra mission. **Image credit**: NASA

In This Issue

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

On behalf of the broad Earth science and application community, congratulations to the current Terra Project Scientist, **Kurt Thome** [GSFC], and all the scientists, engineers, and other team members—past and present—who made this remarkable milestone possible.

The launch of Terra was the impetus for the development of the NASA Earth Observatory, or EO, (*earthobservatory.nasa.gov*) which made its debut about seven months before the launch, in April 1999—as was reported in this very newsletter.[2] When EO began, the Internet was still fairly young; blogs and social media sites were in their infancy. With the imminent launch of Terra and the subsequent EOS missions that would follow, NASA needed a way to tell the stories of our planet and our Earth science research and missions. With the vision of **Yoram Kaufman** (the second Terra Project Scientist), EO was born. The website has served that role admirably ever since.

The technology of science and the Internet has changed significantly in a generation, and the site has evolved and grown in order to keep pace with these advances. While the storytelling approach has changed some over the years, what has remained constant since the beginning is the attractive, newsworthy, and scientifically important images and stories that are routinely developed by the team. Of course, none of EO's success would be possible without the many scientists, engineers, communicators, data users, patrons, and friends inside and outside of NASA, who review content, suggest stories and images, and share scientific insights.

To celebrate their anniversary, the EO team has revisited notable *Images of the Day* with "EO On This Day" (*earthobservatory.nasa.gov/on-this-day*), which looks back at where Earth science was at the birth of the EO and EOS. Congratulations to EO's current Team, and to all who have contributed to its success over the years. Turn to page 4 to read about EO's twenty years of communicating NASA Earth Science.

We also have a status report from another of the EOS flagships in this issue. The twelfth Aura Science Team meeting was held August 27–29, 2019, in Pasadena, CA. What makes this meeting particularly newsworthy is that this year was the fifteenth anniversary of Aura's launch—July 15, 2019.[3] Several speakers reflected on the origins of the Aura mission (first known as EOS CHEM)[4] and the spirited debates across the Atlantic concerning its potential payload, which ended up being MLS, OMI, HIRDLS, and TES—the first two of which are still operational. Other presentations summarized the current status of Aura and its data products, plans for the end of the mission (from the Mission Operations Working Group), and discussions of many

[2] To be reminded of the world that was when EO made its debut, see "NASA Unveils Earth Observatory Web Space" in the March–April 1999 issue of *The Earth Observer* [**Volume 11**, **Issue 2**, pp. 17-18—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/mar_apr99.pdf#page=17*].

[3] See the Editorial of the July–August 2019 issue of *The Earth Observer* [**Volume 31**, **Issue 4**, p. 3] to learn more.

[4] To learn more about the evolution of EOS, including EOS-CHEM (Aura), 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*].

scientific discoveries from the following focus areas: tropospheric emissions and air quality, stratospheric ozone chemistry, dynamics, and trends; and climate observations and modeling. It was a successful meeting and a fitting tribute to 15 years of Aura observations. Please turn to page 9 to learn more.

Last but certainly not least, on November 2, 2019, at 1:59 PM UTC (9:59 AM EST), NASA's commercial cargo provider Northrop Grumman launched its twelfth resupply mission to the International Space Station (ISS) from Virginia Space's Mid-Atlantic Regional Spaceport at WFF. Known as NG-12 (but also dubbed the *SS Alan Bean*, to honor the Apollo and Skylab astronaut who died in May 2018), the flight carried seven CubeSats[5] including the Hyper-Angular Rainbow Polarimeter (HARP). HARP is a wide field-of-view imaging polarimeter designed for retrieving aerosol and cloud properties. The 3U CubeSat HARP is a NASA Earth Science Technology Office (ESTO) InVest project, with joint collaboration between the Earth and Space Institute at UMBC and the Space Dynamics Laboratory (SDL) at Utah State University.

HARP will simultaneously sample at 120 unique viewing angles, 4 visible and near-infrared wavelengths, and 3 unique polarization states. The polarization separation is done with a modified Phillips prism and wavelength selection via stripe-filter detectors—both are key to achieving polarization accuracy with no moving parts and miniaturization into a CubeSat payload. An airborne version (AirHARP), flown in a couple of NASA field deployments, was also developed to help refine algorithms that will be used on HARP data. HARP is expected to deploy from the ISS in late January. HARP is a precursor to HARP2, which is one of the two polarimeters that will fly on NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission that is currently under development. Congratulations to HARP PI, **Vanderlei Martins** [UMBC], and the entire team on a successful launch, and best wishes for a successful deployment and fruitful measurements.[6] ■

[5] Brief descriptions of all CubeSats on NG-12 can be found at *https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cygnusng12.*

[6] To learn more about HARP, see *https://www.nasa.gov/feature/goddard/2019/tiny-nasa-satellite-will-soon-see-rainbows-in-clouds.*

List of Undefined Acronyms Not Defined in Editorial and Table of Contents

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer [*Terra*]
CCD	Charge Coupled Device
CERES	Clouds and the Earth's Radiant Energy System [*Terra*]
EOS	Earth Observing System
GSFC	NASA's Goddard Space Flight Center
HIRDLS	High Resolution Dynamics Limb Sounder [*Aura*]
MISR	Multi-angle Imaging SpectroRadiometer [*Terra*]
MLS	Microwave Limb Sounder [*Aura*]
MODIS	Moderate Resolution Imaging Spectroradiometer [*Terra*]
MOPITT	Measurements of Pollution in the Troposphere [*Terra*]
OMI	Ozone Monitoring Instrument [*Aura*]
TES	Tropospheric Emission Spectrometer [*Aura*]
WFF	NASA's Wallops Flight Facility.

Celebrating 20 Years of NASA's Earth Observatory

Kevin Ward, NASA Earth Observatory, Science Systems and Applications, Inc., kevin.a.ward@nasa.gov

When the virtual doors of NASA's Earth Observatory (EO) website (*http://earthobservatory.nasa.gov*) first opened to the public in April 1999, who could have imagined the world that exists today? When the team published their first content, it is likely they had no idea that 20 years later the site would still be publishing—nor how different the world would be in just two decades.

When the site first went live in 1999, the Internet was still fairly young. Blogs, social media, and Google were in their infancy.[1] At that time, only about 3–5% of the world had Internet access; about 41% of American adults used the World Wide Web—most often to look at the weather. (By contrast, today (2019), 59% of the world's population (4.5 billion) have access to the Internet, including 90% of U.S. adults.) The founders of Facebook, Twitter, and Instagram had not yet moved out of their parents' homes. And the EO team was grappling with a fundamental question: *How should NASA tell the story of our planet and our Earth science research and missions?*

"56 Kbps modem access is today's recommended optimum" —First EO Annual Report, June 2000

Have I mentioned yet today how much I love @NASA EO?
—@_ColinS
Twitter user

The original content for EO was a collection of background fact sheets developed by the Earth Observing System (EOS) Project Science Office (now the Science Support Office) in preparation for the launch of the EOS flagship satellite, Terra. The website also offered a small sampling of stories about the ways NASA-funded scientists were studying Earth and how upcoming NASA missions were going to examine our climate and environment in new ways. The underlying model was—and still is—that of a popular science magazine targeting an audience that has often been described as the *science-attentive public*.

I'm afraid we haven't told you enough how vital you are to the country, and the world…Even when I don't access the site, I am comforted that you are there. ***—Ruth***

With the launches of Landsat 7 and Terra in 1999, the EOS program was off and running, and with more and more data available and topics to explore, EO was able to slowly progress from an occasional image-driven story, to a story each weekday in 2000, to the *Image of the Day* series by 2002. Data were still not widely available online in 2002; nevertheless, EO launched its *Natural Hazards* collection (*https://earthobservatory.nasa.gov/topic/natural-event*) that same year. This introduced a capacity for delivering near-real-time, news-driven imagery at a time when online browsing of satellite imagery was not routine.

In the mid-2000s, technology and data access evolved—more data became available online in near-real-time (e.g., MODIS Rapid Response),[2] more data were made free (e.g., Landsat), and bulk downloading became more routine—and the EO began to experiment with more compelling image-driven storytelling. The ever-lengthening data record provided more plentiful and timely imagery and was fodder for more-sophisticated data visualization. The presentations moved beyond simple snapshot images to telling stories of change over time, e.g., the *World of Change* series—see *NASA Earth Observatory Views "A World of Change"* on page 5—and to compiling global maps of key parameters (*https://earthobservatory.nasa.gov/global-maps*). Whether looking at the growth of cities, the recovery of Yellowstone National Park after wildfires, or the waxing and waning of the Antarctic ozone hole, writers and visualizers tapped the expanding data record to tell deeper Earth system science stories.

I just finished teaching a 400+ student course in environmental science and could NOT have done it without such great material from @NASA_EO
—@scottstgeorge
Twitter user

By 2010, the Earth Observatory was arguably the most prominent source of NASA satellite imagery of Earth to appear in the mass media. If you saw a satellite image

[1] To be reminded of the world that was when EO made its debut, see "NASA Unveils Earth Observatory Web Space" in the March–April 1999 issue of *The Earth Observer* [**Volume 11**, **Issue 2**, pp. 17-18—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/mar_apr99.pdf#page=17*].

[2] To learn more, see "NASA's Worldview Places Nearly 20 Years of Daily Global MODIS Imagery at Your Fingertips" in the July–August 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 4**, pp. 4-8—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/July-August%202018%20Color%20508.pdf#page=4*].

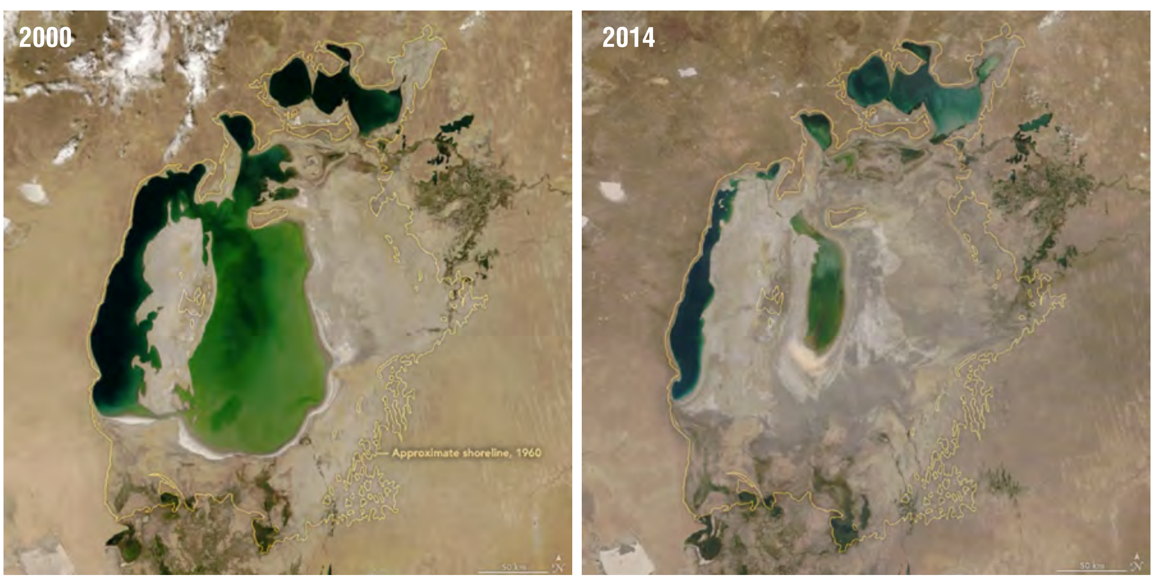
from NASA on television or social media, it most likely originated at the Earth Observatory. Examples include coverage of: The Indonesian tsunami in 2004; Hurricane Katrina in 2005; the Deepwater Horizon oil spill in the Gulf of Mexico in 2010; the eruption of Eyjafjallajökull volcano in Iceland in 2010; and the Tohoku (Japan) earthquake and tsunami in 2011—see **Figure 1** on page 6 for some examples. The Earth Observatory's iconic images and maps continue to appear in many publications and applications. Perhaps none is better known than the *Blue Marble*, and the more recent *Black Marble*—to learn more, see *Viewing Earth by Day and by Night: The Blue and Black Marbles* on page 7.

The Earth Observatory's iconic images and maps continue to appear in many publications and applications.

NASA Earth Observatory Views a "World of Change"

As the availability of Earth science data began to increase exponentially in the early 2000s, image-driven storytelling via the Earth Observatory became more sophisticated. The *World of Change* section made its debut in 2009. These two examples demonstrate how pairs (or, in some cases, time series) of images are used to highlight the changing Earth over time (e.g., changing ozone hole, changing coastline, changing water level, changing sea ice). See *https://earthobservatory.nasa.gov/world-of-change* to view the entire collection of World of Change stories.

Growing Deltas in Atchafalaya Bay. While the sea overtakes much of the delta plain of the Mississippi River, sediment from the Atchafalaya River continues to build two new deltas to the west as chronicled by these Landsat images from 1984 and 2017. **Image credit**: NASA Earth Observatory/USGS (*https://earthobservatory.nasa.gov/world-of-change/WaxLake*)



Shrinking Aral Sea. Once part of the fourth-largest lake in the world, the eastern lobe of the southern Aral dried up for the first time in modern history as seen in the right image from 2014. For comparison, the left image shows the extent of the lake in 2000. Both images come from the MODIS instrument on the Terra satellite. For comparison, the faint white lines in both images show the approximate location of the shoreline in 1960, showing that the Aral Sea has shrunk rather dramatically since then. **Image credit**: NASA Earth Observatory (*https://earthobservatory.nasa.gov/world-of-change/AralSea*)

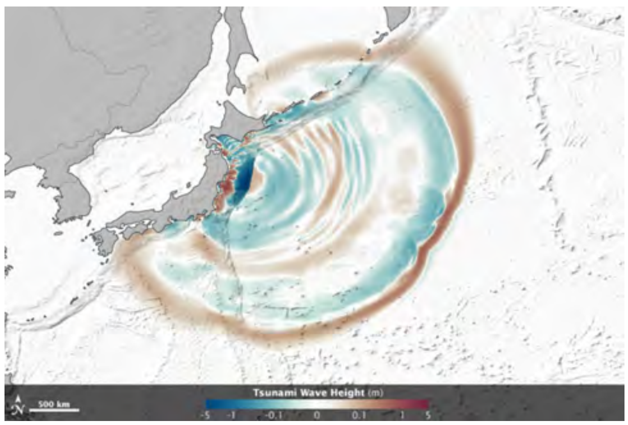


Figure 1. The Earth Observatory team's ability to rapidly turn satellite observations of natural events into news-driven stories was enabled by the continued growth of the EOS program and supporting data systems. These images show [*clockwise from top left*]: Hurricane Katrina, 2005; Eyjafjallajökull volcano, 2010; Tohoku/Sendai tsunami, 2011. **Image credit:** NASA Earth Observatory and Jeff Schmaltz [NASA's Goddard Space Flight Center—*MODIS Rapid Response Team*]

Around the same time, the EO team began experimenting with the distribution of images and stories via social media. The *NASA_EO* Facebook and Twitter accounts quickly grew when social media channels became the "new" media and users began using them as their news sources. EO's presence on Facebook grew to 5 million followers by 2014 and 8 million in 2016. The channel was then offered up to the wider NASA Earth science communications community and rebranded as *NASAEarth*. More than 10 million people now follow the page.

I started following EO in high school, 20 years ago. Thank you for all you, and NASA, do to create different perspectives for humanity.

—AJ

As the Earth Observatory moved into its second decade, data and imagery became much more accessible and browsable online as the costs of hard drives and bandwidth continued to decline. Satellite imagery became available to the public through browsable applications within just a few hours of acquisition.[3] This data availability, combined with the public's ability to download larger quantities of imagery directly, meant that the EO team had to continue to evolve. Why continuously produce images of natural events when news media, Earth science user communities, and the public could find their own without a filter?

What I love about NASA Earth is that they don't just say, "Here's a pretty picture." They educate us with full explanations of the photos.

—Rebekah

This change in the media landscape—the new paradigms by which the public finds and consumes news—has given the EO team space to think anew about the best ways to communicate NASA Earth science. No longer do team members feel compelled to chase every image of Hurricane X, Y, or Z, or every wildfire in the U.S. Instead, they now focus on telling deeper and more compelling stories that emphasize the uniqueness of NASA science, the breadth of the Agency's data sources, and the wealth of knowledge among NASA-funded scientists.

EO in its twentieth year continues to evolve (see **Figure 2** on page 8) and the team continues to hone its craft, upgrade its systems, and look for trends to better

[3] To learn more, see "NASA's Worldview Places Nearly 20 Years of Daily Global MODIS Imagery at Your Fingertips" in the July–August 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 4**, pp. 4-8—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/July-August%202018%20Color%20508.pdf#page=4*].

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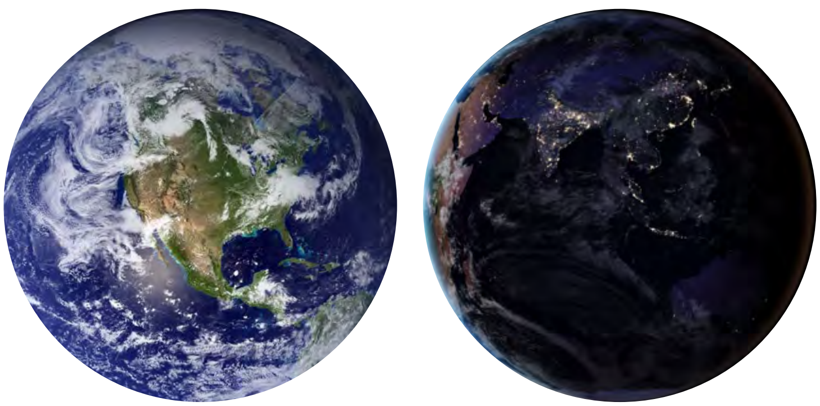
Viewing Earth by Day and by Night: The Blue and Black Marbles

The first images of Earth taken from space were grainy black and white images from the Television Infrared Observation Satellite (TIROS) series. It was not until the Apollo missions that the first full-color images of Earth were obtained. One such photograph was destined to become an icon. It was taken by the crew of Apollo 17 from a distance of about 45,000 km (28,000 mi) from Earth. This so-called *Blue Marble* image was the inspiration for later images of Earth compiled using satellite data that are described in this sidebar.

In 2002 NASA produced its first satellite-based *Blue Marble*, which was at that time the most detailed true-color image of Earth's surface ever produced. While it looks like a photograph, the image was built using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA's Terra satellite (launched in 1999). Scientists and data visualizers stitched together four months of observations of the land surface, coastal oceans, sea ice, and clouds to create a seamless mosaic of every square kilometer (0.39 square miles) of our planet. In October 2005 NASA released a newer version of the spectacular image collection that provided a full year's worth of monthly observations with twice the level of detail as the original. The collection is called the *Blue Marble: Next Generation* [shown in image, *left*]. Like its predecessor, it is a composite image that uses MODIS data, but unlike the original image, it includes data from MODIS on both Terra and Aqua (the latter of which launched in 2002).

NASA's *Black Marble* image of Earth at night came in 2012—about a year after the Suomi National Polar-orbiting Partnership (NPP) mission launched. (Suomi NPP is a partnership between NASA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Defense.) One of the instruments onboard is the Visible Infrared Imaging Radiometer Suite (VIIRS), which unlike MODIS on Terra and Aqua, can actually "see" visible light in the dark, courtesy of its *day-night band.* VIIRS can observe dim light down to the scale of an isolated highway lamp or fishing boat. It can even detect faint, nocturnal atmospheric light—known as *airglow*—and observe clouds lit by it.



The Earth Observatory's iconic images and maps continue to appear in many publications and applications. Shown here is the Blue Marble: Next Generation [*left*], published in 2005, and the Black Marble [*right*], published in 2012 and updated in 2016. **Image credit**: NASA Earth Observatory

While VIIRS was not the first instrument that allowed nighttime lights to be observed, the spatial resolution is six times better than previous instruments [e.g., the Operational Linescan System (OLS) onboard the Defense Meteorological Satellite Program (DMSP) satellites] and the resolution of lighting levels (*dynamic range*) is 250 times greater than its predecessors. In addition to those enhancements over OLS, unlike DMSP, Suomi NPP is a civilian mission and its images are much more readily available to scientists. The technological advances of VIIRS, combined with the much more rapid access to data, enabled scientists to create the first *Black Marble* images of Earth's nighttime lights in 2012 [shown in image, *right*], with an update in 2016.

The stories listed below were used to compile this summary. To learn more of the story of how these images were created and how they have evolved over time please visit:

- *https://earthobservatory.nasa.gov/features/BlueMarble*
- *https://earthobservatory.nasa.gov/features/BlueMarble/BlueMarble_history.php*
- *https://earthobservatory.nasa.gov/blogs/elegantfigures/2011/10/06/crafting-the-blue-marble*
- *https://earthobservatory.nasa.gov/features/IntotheBlack*
- *https://earthobservatory.nasa.gov/images/90008/night-light-maps-open-up-new-applications*

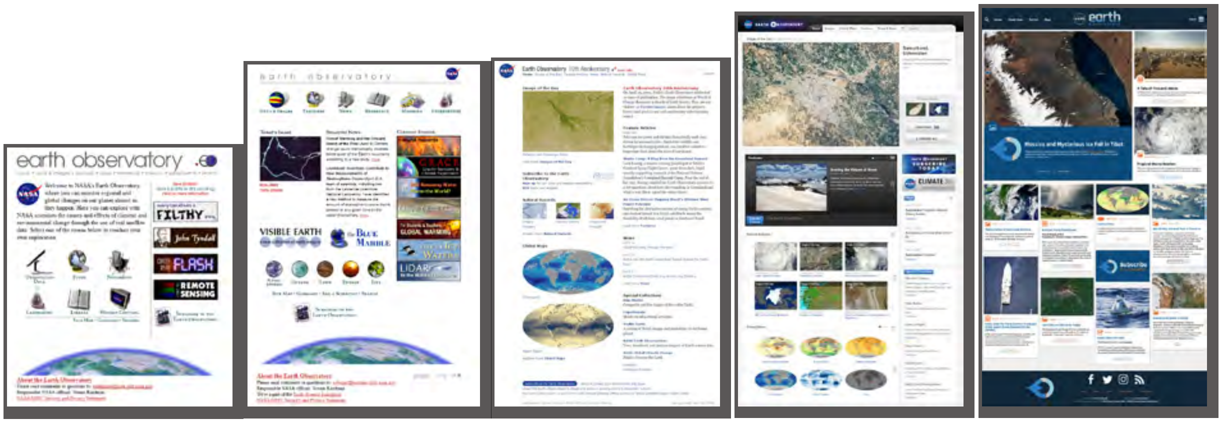


Figure 2. Through the years [*left to right*, front page screenshots from 1999, 2004, 2009, 2013, and 2019] the look and feel of the Earth Observatory website has evolved, but it continues to provide a home for stories and images about the environment, Earth systems, and climate that emerge from NASA's research, including its satellite missions, field research, and models. **Image credit**: NASA Earth Observatory

understand which communication techniques, data sources, and fundamental questions are worthy of pursuit. The fundamental question behind all of these efforts is: *What is the climate or Earth system science story that NASA is* ***best*** *positioned to tell?*

An anniversary is a time for looking back with fond remembrance, but it is also a moment to take those lessons and achievements and use them to grow into the future. The EO team has assembled a few resources on the website to celebrate the journey so far: Revisiting notable Images of the Day through "EO On This Day" (*https://earthobservatory.nasa.gov/on-this-day*); producing stories that look back at where Earth science was at the birth of the EO and EOS and how that science has matured. The team has also collaborated with NASA's Applied Sciences Program to produce an aesthetic and artistic view of the extensive EO image archive in the form of a new print and electronic book: *Earth* (*https://earthobservatory.nasa.gov/features/earth-book-2019*).

As EO begins its third decade, the EO team is grateful for the hundreds of people who have provided support over the years by providing scientific review, editorial content, or general encouragement. We particularly want to thank **Jack Kaye** [NASA Headquarters—*Associate Director for Research and Analysis for the Earth Science Division*] for his long-term support. While there are too many to name individually, the team especially wishes to thank the hardy supporters from various NASA centers, affiliated institutions, and organizations—especially those who dial in to our weekly editorial meeting and feed us far more story ideas than we can ever address. Our achievements have been a group effort, and we are the sum of many parts. We look forward to another decade and beyond. ■

I don't travel, so for me, you offer me views of the world I will never see any other way.
—Kathy

For most of my life I did not have access to the Internet. Given the amount of pseudo-science and worse on the Internet, it is important that the stories from NASA be well written and by competent, knowledgeable persons. That has not always been the case. Earth Observatory (via Facebook for me) is an exception, most of it being straightforward presentation and explanation of data.
—Anonymous

Summary of the 2019 Aura Science Team Meeting

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

Introduction

The 2019 Aura Science Team meeting took place August 27–29, 2019, in Pasadena, CA; NASA/Jet Propulsion Laboratory (JPL) hosted the meeting. Since the launch of Aura in 2004,[1] the Aura Science Team has convened on 12 occasions, on both sides of the Atlantic. The purpose of these meetings is to share recent scientific results, review calibration/validation activities and algorithm improvements, as well as to hear Working Group reports (e.g., Mission Operations and Data Systems). Of particular importance is the opportunity the meetings provide for face-to-face collaboration among the Aura instrument team members.

About 130 scientists attended, including representatives from the Netherlands, Finland, and Canada. The meeting covered 13 invited papers (where each speaker gave a 20-minute presentation), 53 contributed papers (10-minute presentations), and 45 posters. While every presentation is not summarized here, most of the presentations have been posted online at *https://avdc.gsfc.nasa.gov/?site=1072744097*.

This article reports on the broad range of results from Aura's four instruments, addressing Aura's main measurement themes: Tropospheric Emissions and Air Quality; Stratospheric Ozone Chemistry, Dynamics, and Trends; and Climate Observations and Models. A key topic for many of the presentations was measurement synergy among the instruments, with examples of how they contribute to Aura's three science themes.

Meeting Opening

Bryan Duncan [NASA's Goddard Space Flight Center (GSFC)—*Aura Project Scientist*] opened the meeting, welcomed attendees, and thanked JPL for organizing the event. He reviewed the agenda and ground rules for the presentations so that speakers were well aware of their responsibilities to ensure that discussions for all 66 papers fit into the three-day meeting. He also announced that time would be set aside during the morning session to recognize the Ozone Monitoring Instrument (OMI) international team for receiving the 2018 Pecora Group Award—see *OMI International Team Receives the 2018 Pecora Group Award* on page 10.

Kenneth Jucks [NASA Headquarters (HQ)—*Aura Program Scientist*] provided an update on Aura activities taking place within NASA HQ's Atmospheric Composition Focus Group. He reminded attendees that proposals for continued participation in the Aura Science Team were due shortly after the meeting. Jucks also listed the aircraft field campaigns that are conducting atmospheric composition measurements that complement Aura observations.[2] Finally, he reported on the status of NASA's Earth Science budget.

Retrospective and Mission Status

This being the fifteenth anniversary year for the Aura mission, in addition to the usual Instrument Principal Investigator (PI) and Working Group reports and science presentations, the speakers in this section of the meeting reflected on the beginnings of the mission. After 15 years of operations, two of the four original instruments are operating as planned, and continue to provide data for each of Aura's three main measurement themes, described above.

The Spacecraft Payload

Recounting the early days, **Mark Schoeberl** [Science and Technology Corporation—*Former Aura Project Scientist*] recalled how NASA justified the mission (called EOS-CHEM at that time) based on the success of the Upper Atmosphere Research Satellite (UARS) and the need to continue monitoring and understanding the chemistry and dynamics of stratospheric ozone. The evolution of the EOS-CHEM mission was steeped

[1] Read "Aura Celebrates Ten Years in Orbit" in the November-December 2014 issue of *The Earth Observer* [**Volume 26**, **Issue 6**, pp. 4-17—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/November-December_2014_color_508.pdf#page=4*].

[2] Examples of these campaigns can be found at *https://dcotss.org*, *https://www2.acom.ucar.edu/acclip*, and *https://espo.nasa.gov/ORACLES/content/ORACLES.*

Aura Science Team Meeting participants. **Photo credit:** Susan MacFadden in changing budgets, mission priorities, and HQ policies for formulation of the Earth Observing System.[3] The mission's instrument-selection process was arduous, but finally settled with compromises, in the early 1990s. The instrument complement, however, did not include an SBUV/TOMS[4] successor. After spirited negotiations across the Atlantic in 1998, the Netherlands agreed to provide the OMI to fly on EOS-CHEM, which eventually became known as Aura. The final Aura payload consisted of four instruments: HIRDLS, MLS, OMI,

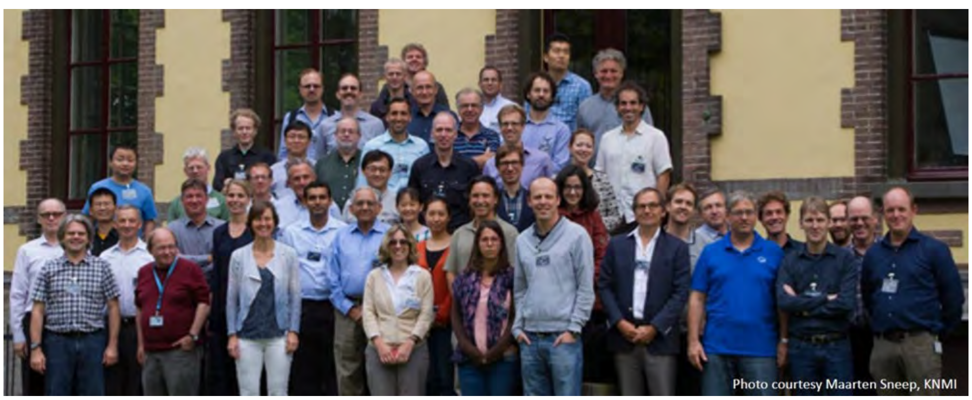
[3] To learn more, see "The Enduring Legacy of the Earth Observing System, Part II: Creating a Global Observing System—Challenges and Opportunities" in the May–June 2011 issue of *The Earth Observer* [**Volume 23**, **Issue 3**, pp. 4-14—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/May_June_2011_col_508.pdf#page=4*].

[4] SBUV/TOMS stands for Solar Backscatter Ultraviolet/Total Ozone Mapping Spectrometer, which flew on Nimbus 7. There were five TOMS instruments, four of which reached orbit on missions that launched between 1979 and 1996; the last satellite with TOMS onboard was Earth Probe, which failed in 2006.

OMI International Team Receives the 2018 Pecora Group Award

The Ozone Monitoring Instrument (OMI) international team received the *2018 Pecora Group Award* for its "sustained team innovation and international collaboration to produce daily global satellite data that revolutionized air quality, stratospheric chemistry, and climate research."

During a short presentation ceremony at the Aura meeting, **Sandra Cauffman** [NASA HQ—*Acting Division Director of the Earth Science Division*] presented the International OMI Science Team with the award.



The OMI Science Team won the *2018 Pecora Group Award*. This photo of the team was taken at the 2017 OMI Science Team Meeting, which was held in the Netherlands. **Photo credit:** Martin Sneep [KNMI]

The award citation notes: "The OMI team developed ground-breaking uses of satellite data and advanced atmospheric-constituent detection. The OMI team has developed innovative approaches to characterizing the atmosphere using satellite imagery. The OMI data and products are increasingly recognized as a gold standard resource for use in remote sensing applications."

The *William T. Pecora* Award is presented annually to recognize outstanding contributions by individuals or teams using remote sensing to understand the Earth, educate the next generation of scientists, inform decision makers or support natural or human-induced disaster response. The Pecora Award is sponsored by the U.S. Department of the Interior and NASA.

Further information about the OMI team's award can be found at *https://www.nasa.gov/feature/ozone-instrument-team-data-champion-receive-earth-observation-award.*

Information about the Pecora Award can be found at *https://www.usgs.gov/land-resources/national-land-imaging-program/pecora.*

and TES.[5] Of those, MLS and OMI are still producing excellent science data. These four instruments were designed to make key atmospheric composition observations that address Aura's three themes as listed in the Introduction.

The Instruments[6]

John Gille [National Center for Atmospheric Research— *HIRDLS U.S. Principal Investigator (PI)*] summarized how HIRDLS, during its four years of operations, provided new data on daily global changes of aerosol types and distributions—as well as 9 trace gases important to ozone chemistry at 1-km (0.62-mi) vertical resolution—despite an 80% blockage of the instrument's field of view from day one. These data revealed a wide range of small- and global-scale processes, especially in the upper troposphere and lower stratosphere (UTLS). Some examples included how planetary-scale waves (e.g., Rossby and Kelvin waves) and the quasi-biennial oscillation (QBO)[7] could affect the transport of stratospheric ozone.

Nathaniel Livesey [JPL—*MLS PI*] stated that MLS continues to perform as planned. The few anomalies over the past 15 years have had no effect on the expected performance or lifetime of MLS. Livesey demonstrated how MLS contributed to all three of Aura's major themes, using the data from 16 chemically and radiatively atmospheric gases along with the measurements of atmospheric temperature and geopotential heights. For example, definite signs point to an upper-stratospheric [35-50 km (~22–31 mi)] ozone recovery. However, in the lower stratosphere and in polar regions, strong interannual variability hampers detection of this recovery. Finally, Livesey reported that more than 1000 papers using MLS data have been published to date.

Pieternel Levelt [Koninklijk Nederlands Meteorologisch Instituut (KNMI, Royal Netherlands Meteorological Institute)—*OMI PI*] explained how OMI came to be included in the Aura payload and summarized OMI's impressive "firsts." OMI was the first Earth science instrument to employ a charge-coupled device (CCD) detector, which enabled simultaneous spectral measurements of Earth scenes from horizon to horizon with near-urban-scale spatial resolution. As an example, these features allowed OMI to collect images of global air quality (AQ) and regional changes over time. It was the first instrument to demonstrate how AQ improved over the western Northern Hemisphere and Western Europe from 2005 to 2014, and degraded over Asia during the same time frame. In another part of her presentation, Levelt talked about OMI's successor, the TROPOspheric Monitoring Instrument, or TROPOMI.[8] The instrument has better spatial resolution than OMI and can also measure carbon monoxide and methane, a greenhouse gas (GHG).

[5] HIRDLS stands for High Resolution Dynamics Limb Sounder; MLS stands for Microwave Limb Sounder; OMI stands for Ozone Monitoring Instrument; and TES stands for Tropospheric Emission Spectrometer.

[6] The TES PI chose not to participate in this section of the meeting since TES is no longer functioning. However, TES and its science results appear in presentations and posters throughout the meeting.

[7] The QBO is a quasiperiodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere, with a mean period of 28-to-29 months.

Tropospheric Emissions and Air Quality

Measuring tropospheric emissions is an emerging theme for space observations. Taking measurements in the troposphere and the boundary layer—previously a remote sensing challenge—is the main goal for OMI and TES. Fossil fuel burning is the primary source of tropospheric emissions that lead to poor AQ and climate change, although there are natural sources as well.

Daniel Jacob [Harvard University], the invited speaker for this section, opened his presentation with a video of former President Obama explaining how air pollution affects our planet.[9] He reviewed results derived from OMI nitrogen dioxide (NO_2) data—see **Figure 1**. More recent pollution measurements over China show an improvement in AQ, starting about 2013. The initial improvements were the result of China's strict clean air regulations. Jacob went on to say that TES global tropospheric ozone data show a midlatitude pollution belt, with the effects of biomass burning reaching the free troposphere. These data, in conjunction with atmospheric chemistry models, will enable interpretation of the measurements and allow projections of future tropospheric ozone and trace gas distributions from anthropogenic or natural perturbations. Jacob concluded his presentation by illustrating how a geostationary

[8] TROPOMI flies on the Copernicus Sentinel-5 Precursor satellite. The Sentinel-5 Precursor (S5P) is the first of the atmospheric composition Sentinels, launched on October 13, 2017, planned for a mission of seven years.

[9] This video can be found at *https://aura.gsfc.nasa.gov/science/feature-20160428.html*.

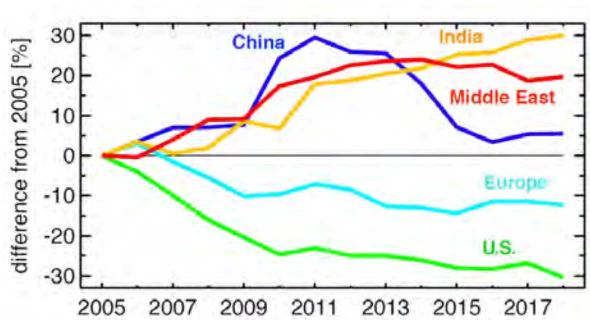


Figure 1. Regional trends in NO_2 emissions for the period 2005 to 2018. NO_2 is an ozone pollution precursor whose source is primarily fossil fuel burning. For the U.S. and Europe, NO_2 decreased while in most of Asia it increased. China showed a decrease after 2013 as a result of strict emission regulations. **Image credit:** Kazuyuki Miyazaki [JPL]

satellite constellation with AQ instruments onboard, to be launched in the 2020–2022 timeframe, will provide improved coverage of global air pollution and its emission sources.[10]

Subsequent presentations in this section revealed that OMI AQ trends do not agree with those measured by the U.S. Environmental Protection Agency (EPA). EPA reports indicate that pollution continues to decrease over the U.S., whereas OMI-observed decreases flattened in 2009. The likely reason for this is that the EPA measures emissions near the ground while OMI measures a column amount mostly from the boundary layer to the top of the atmosphere, meaning the air being sampled by the satellite and from the ground are not exactly the same. The discrepancy results from the fact that NO_2 continued to decrease below the boundary while no change has been detected above the boundary. Chemical–dynamic and radiative-transfer models are being used to better interpret the satellite data and, ultimately, to reconcile the differences.

Several presentations dealt with the formaldehyde–nitrogen dioxide ratio ($HCHO/NO_2$). Because these two gases are proxies for ozone-pollution precursors [i.e., volatile organic compounds and nitrogen oxides (NO_x)[11]], the ratio of the concentrations of these two compounds serves as a good indicator of ozone production efficiency in a given location, and thus can offer an idea of how its production might be mitigated. The technique is being further refined by improving the retrieval algorithms of ozone and its precursors, as explained by later speakers.

Improving trace-gas retrieval algorithms was a prevalent topic for this session and a recurring topic among the posters. These improvements include updated surface reflectivity tables and better air mass factors[12] in the presence of clouds and aerosols. One project in particular will result in updated data products, which will include algorithm traceability chains and error characterization that will enable single algorithms to be employed across similar instruments flying on different satellites.

Jessica Neu [JPL–*TES Deputy PI*] provided an overview of TES measurements and their legacy, as well as how the measurements complement OMI data. She pointed to the drastic changes in NO_x emissions over various regions of the globe. In addition, Neu discussed how TES provides a standard for tropospheric ozone measurements because of the instrument's long-term stability. By combining TES, MLS, and OMI data, she was able to demonstrate that change in mid-tropospheric ozone is largely controlled by a combination of emissions, long-range transport, downward transport from the stratosphere, and advection variations resulting from synoptic-scale events, e.g., El Niño. Finally, Neu described how combining infrared and ultraviolet measurements from other satellite missions [e.g., the Suomi National Polar-orbiting Partnership (NPP), National Oceanic and Atmospheric Administration-20 (NOAA-20), and European polar-orbiting weather satellites] will continue the TES legacy.

Stratospheric and Mesospheric Ozone Trends

The depletion of the ozone layer increases the amount of solar ultraviolet (UV) radiation that reaches the Earth's surface, harming human health as well as plants. As a complement to the global effort to monitor ozone, UV radiation measurements are also being conducted from the ground and space. One presentation showed biases between the erythemal dose rate (EDR)[13] derived from satellite UV radiation reflected from Earth's surface and the direct measurements of incoming radiation made from the ground. The study showed that an OMI-derived EDR climatology is statistically consistent with ground-based data. But a comparison with 31 ground stations indicated that OMI has a 7% positive bias—which is larger than the 6% surface measurement uncertainty. Nevertheless, OMI EDR is now incorporated into the Commission for Environmental Cooperation's health-tracking system.[14] In addition, the U.S. Centers for Disease Control and Prevention use NASA data to help the public better understand UV exposure.[15]

Michelle Santee [JPL] gave a presentation that exemplified Aura's second major theme (Stratospheric Ozone Chemistry, Dynamics, and Trends), stating that: "Conclusive verification that stratospheric ozone destruction is lessening in response to international controls on anthropogenic ozone-depleting substances (ODSs) enacted under the Montreal Protocol and its Amendments remains an atmospheric science imperative." This verification is ensured by the remarkable stability of the ozone measurements from Aura, with both MLS and OMI exhibiting little or no drift in

[10] To learn more about TEMPO, see "NASA Ups the TEMPO on Monitoring Air Pollution" 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*].

[11] NO_x is used to represent all oxides of nitrogen resulting from burning of fossil and agricultural fuels.

[12] Air mass factor defines the direct optical path length through Earth's atmosphere, expressed as a ratio relative to the path length at the zenith, taking into account atmospheric constituent spectroscopy.

[13] In medical science, erythemal dose rate refers to the amount of radiation which, when applied to the skin, makes it turn temporarily red (*erythematous*).

[14] The Commission for Environmental Cooperation was established by Canada, Mexico, and the U.S. to implement the North American Agreement on Environmental Cooperation, the environmental side accord to the North American Free Trade Agreement.

[15] To learn more, visit *https://earthobservatory.nasa.gov/images/145413/new-map-shows-risk-of-sunburn-across-the-us?src=ve*.

ozone relative to correlative ground-based observations. Along with monitoring ozone, any changes need to be explained by dynamics and chlorine chemistry. Several studies showed how MLS helped confirm that stratospheric chlorine is declining—consistent with the trend expected by compliance with the Montreal Protocol.

The decline in chlorine concentration in the lower stratosphere shows significant hemispheric asymmetries but is consistent with the different atmospheric dynamics in the Northern and Southern Hemispheres. OMI, along with other satellite data, shows no significant upward trend—yet—in global total ozone, as would be expected from the Montreal Protocol. However, an upward trend in upper stratospheric ozone is evident in studies using MLS data. Based on these results, global ozone trends appear to be headed into a recovery phase.

Detecting an ozone recovery in the lower stratosphere remains a challenge because of background atmospheric dynamics. One speaker took on this challenge by using hydrogen chloride (HCl), a reservoir for active chlorine in ozone chemistry, and nitrous oxide (N_2O), a tracer for dynamics, with a chemical model employing a multiple linear regression, and concluded that the length of the Aura dataset (i.e., since 2004) is still not long enough to conclusively extract an upward ozone trend from the background dynamics.

However, MLS data do show signs of a recovery of the Antarctic ozone hole—despite large, dynamically driven, year-to-year variations. Studies using satellite and model data of monthly ozone amounts show that the minimum ozone is occurring earlier where the changes are the largest—see **Figure 2**. These studies conclude that the Antarctic ozone hole began to recover in the early 2000s.

Satellite and ground-based data show a recent and significant increase in HCl starting around 2007 in the lower stratosphere of the Northern Hemisphere. That contrasts with the ongoing, monotonic decrease of near-surface source gases. Using model simulations, this trend anomaly can be attributed to a slowdown in the Northern Hemisphere atmospheric circulation, occurring over several consecutive years. This allows more aged air to be transported to the lower stratosphere, characterized by a larger relative conversion of source gases to HCl.

The Atmospheric Chemistry Experiment–Fourier Transform Spectrometer (ACE-FTS)[16] is a complementary mission to Aura that continues to monitor many gases (74 of them!) important to stratospheric ozone chemistry, particularly chlorofluorocarbons (CFCs), one of the sources of ozone-depleting substances (ODS). As stated earlier, the recovery of the stratospheric ozone layer relies on compliance with the Montreal Protocol mandate to phase out ODS such as CFCs. More than one presenter showed that the atmospheric concentration of trichlorofluoromethane (CFC-11) has declined substantially since the mid-1990s. Recent data from ACE-FTS, however, detected a striking increase in CFC-11 global trends after 2012, with more pronounced changes in the Northern Hemisphere than in the Southern Hemisphere. Strong indications are that the source is in eastern Asia.

Since the ozone trend is very small compared with natural atmospheric dynamic features described earlier, trend analysis requires very accurate data from a stable instrument. Two important effects that influence trend analysis are instrument calibration drift and a drifting satellite orbit. The Solar Backscatter Ultraviolet/2 (SBUV/2) instrument data provides the data mainstay for calculating ozone trends. The first satellite was the Backscatter Ultraviolet (BUV) instrument, which

[16] ACE-FTS is the main instrument on the Canadian SCISAT satellite.

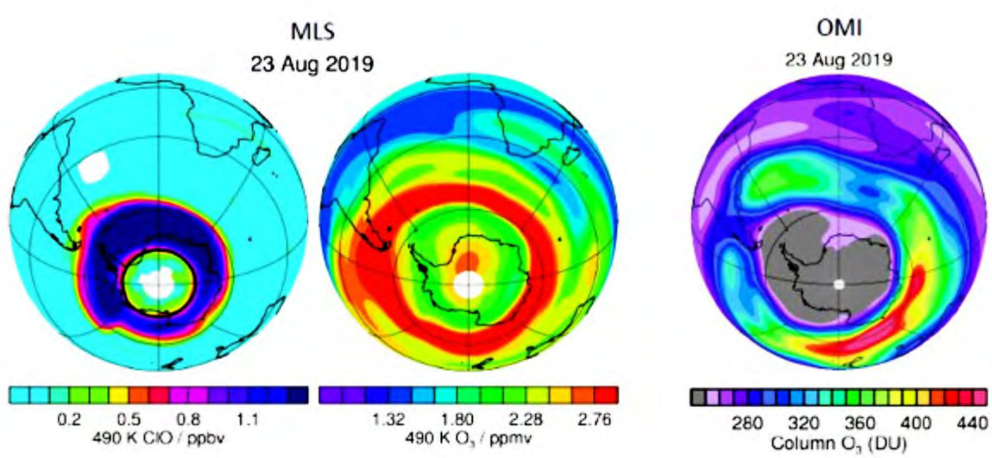


Figure 2. Images from MLS and OMI depict the 2019 Antarctic Ozone Hole as it was forming in late winter. The 490 K level is about 100 hPa (or mb) in the South Polar atmosphere. The image on the left shows that chlorine monoxide (ClO), which plays a key role in ozone depletion, is well established over the pole. The center image shows how ozone builds up during the winter months, but chlorine is beginning to catalytically destroy ozone. Column ozone in the right hand image clearly shows a developing ozone hole. **Image credit**: Michelle Santee [JPL]

launched in 1970 on Nimbus 4, followed by SBUV on Nimbus-7, launched in 1978. Subsequently, SBUV/2 instruments were flown on a series of NOAA polar-orbiting weather satellites, which collect ozone data to this day. The early NOAA satellite orbits drifted with respect to their Equator-crossing time. This affected the ozone retrieval algorithm and necessitated a correction, which was supplied by MLS ozone data, and will be applied to the entire nearly 50-year dataset. MLS ozone profiles were also used to correct for SBUV/2 errors due to changes in time of day and for improved algorithm *a priori* data.

Climate Observations

Many presentations dealt with the diverse aspects of climate change. Again, not all are summarized herein, but they appear online at the website mentioned in the Introduction. Of particular interest was how climate and AQ are interrelated and how the measurement of one could be used to infer the other. Because of the broad scope of this issue, this section is further divided into subsections to underscore the wide range of climate topics.

Upper Troposphere and Lower Stratosphere

The UTLS is a region in the atmosphere where coupled dynamical, chemical, and microphysical processes play essential roles in climate change. Water vapor, ozone, aerosols, and the amount and spatial distributions of cirrus clouds—all measured by Aura's instruments—are controlled by these coupled processes and have important effects on Earth's radiation budget, which in turn controls climate—a topic of intense study by the Aura science team.

In an invited presentation, **Andy Dessler** [Texas A&M University] showed how he used a linear regression model, Aura data, and chemistry–climate models (CCM) of tropical lower-stratospheric water vapor, to discover that the QBO, the Brewer–Dobson circulation,[17] and the tropical troposphere temperature variations were the major factors driving variability and trends of water vapor in the UTLS. After quantifying how these factors affect water vapor, Dessler concluded that there was little or no trend in water vapor in the tropical UTLS since 1980.

In a follow-on presentation, the speaker showed results of a study using data from several satellites, including MLS, and a maximum covariance analysis, that agreed with Dessler's finding concerning the major factors driving water vapor variability and trends. With convection included, however, the tropical central Pacific sea surface temperature (SST) becomes another driver of variability in tropical lower stratospheric water vapor on shorter timescales. The presented test case was for the "dry event" (a steep drop in water vapor at 83 hPa) of 2000, but was also applicable for the 2005 and 2015 events. In all three of these cases, when the central Pacific SST warmed, the tropical lower stratospheric humidity decreased.

Greenhouse Gas Emissions

Space measurements of GHG emissions and air pollutant sources have a lot in common. The chemistry and transport processes that affect AQ are modified by climate change. Conversely, air pollutants—particularly GHGs, ozone, and aerosols—are significant climate forcers. Moreover, climate forcers and air pollutants are often emitted from common sources, e.g., power plants. Consequently, measurements of climate change and AQ are inherently connected.[18]

There were presentations on two different methods used to derive carbon dioxide (CO_2) emissions from coal-fired power plants and from urban-scale sources (e.g., traffic), both using OMI observations of co-emitted NO_2. The EPA's reports on CO_2 emissions for individual U.S. power plants are based on fuel data and/or measurements at the stack. In the case of urban scales, EPA inventories are reported. Satellites [e.g., NASA's Orbiting Carbon Observatory–2 (OCO-2) and the Japan Aerospace Exploration Agency's Greenhouse gases Observing Satellite (GOSAT) and GOSAT-2 satellites] measure CO_2 directly from space. Sampling individual power plants and megacities, however, is difficult because of satellite viewing limitations. A technique that demonstrates how OMI NO_2 data and ground observations of NO_x, CO_2, and EPA inventories can provide a way to calculate CO_2 emissions from OMI measurements. More work remains to apply this method globally and validate the results.

Aerosols

Aerosols influence climate change through both direct radiative forcing, which includes the scattering of solar radiation and the absorption/emission of terrestrial radiation, and indirect radiative forcing, mainly by the effects of aerosols on cloud properties. Validation of OMI aerosol amounts and characteristics therefore remains a high priority. A study showed OMI and ground data single scattering albedos retrievals agree within 0.03 for aerosol optical depth values of 0.3 and larger. On a global scale, there is little or no trend evident from the 13-year OMI record—see **Figure 3**.

[17] The Brewer–Dobson circulation is a model of atmospheric circulation proposed by Alan Brewer in 1949 and Gordon Dobson in 1956, which attempts to explain why tropical air has less ozone than polar air, even though the tropical stratosphere is where most atmospheric ozone is produced.

[18] This notion was articulated in "A Space-Based Constellation Architecture for Estimating Atmospheric Carbon Dioxide and Methane Concentrations and Fluxes from Natural and Anthropogenic Sources and Sinks," a Committee on Earth Observation Satellites (CEOS) *white paper*, led by David Crisp [JPL].

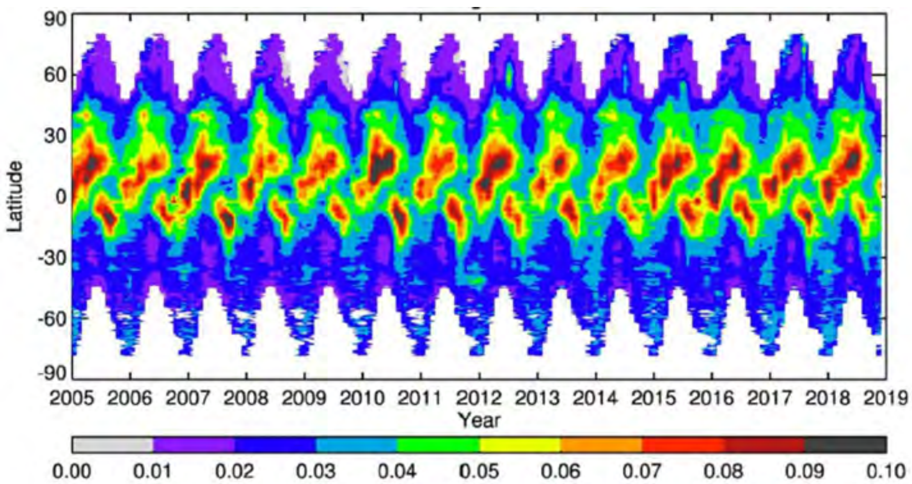


Figure 3. Global 13-year record of OMI Aerosol Optical Depth is shown as zonal averages as a function of time. The year-to-year variability is due to fires, dust, and changes in AQ. **Image credit**: Omar Torres [GSFC]

However, there are detectable trends over smaller geographical regions—e.g., over eastern Asia, where AQ has improved, and over northern Africa, where there has been increasing amounts of dust and fires, which tend to cancel each other in aerosol global zonal averages.

Volcanoes

Volcanic degassing is a precursor for the production of sulfate aerosols from sulfur dioxide (SO_2) and an input parameter for chemistry-climate models. Globally, OMI (and UV instruments on other satellites) has been used to quantify 90–100 volcanic SO_2 sources—many for the first time. The top 91 volcanic SO_2 sources appear in OMI data. Studies underway show that careful tracking of pre-eruptive SO_2 could lead to volcanic eruption forecasting and even "hazard maps." Global analysis of SO_2 emissions shows that volcanic emissions have remained constant while total SO_2 from power plants is decreasing.

Solar irradiance

Solar forcing plays a weak role in current global temperature trends. Model simulations, however, demonstrate that simulating regional climate changes requires the most accurate solar irradiance values. While the total and visible portion of solar irradiance changes are very small, solar ultraviolet spectral irradiances are the major contributor to chemistry and thermodynamic processes in the stratosphere. Climate model requirements for solar spectral irradiance stability and precision is at the edge of the capabilities of present instruments, e.g., OMI. Through careful analysis of long-term data records, solar variables, such as the 11-year and 24-day solar cycles, are being accurately captured. As OMI degrades and Aura's orbit decays, however, maintaining the solar irradiance data set will rely more on TROPOMI.

Using Climate–Chemistry Models to Predict Climate Change

The Coupled Model Intercomparison Project (CMIP) is a coordinated effort to understand past, present and future climate using multiple international models—see *http://www.wcrp-climate.org/wgcm-cmip*. CMIP has developed in phases, with CMIP6 well underway. The CMIP6 clouds and water-vapor simulations, based on observations from the Aura and A-Train[19] data, are being used to assess the model improvements from CMIP5 to CMIP6. Although overall performance of CMIP6 has improved, preliminary results show that model errors in the upper troposphere remain the largest—especially for clouds. In addition, CMIP6 models have a higher equilibrium climate sensitivity[20] than most of their counterparts in CMIP5. Long-term plans include identifying key physical mechanisms responsible for intermodel differences and applying new constraints from climate-sensitive observations to CMIP6 models to infer future climate changes in temperature and precipitation.

Working Group Reports

The reports from the Aura mission Working Groups resulted in considerable discussion among the science team members. The Mission Operations Working Group report had two parts: a report on the plans for Aura exiting the A-Train and an overall mission status update. The Data Systems Working Group report included updates on ground data systems, data preservation, and the status of NASA's Goddard Earth Sciences Data and Information Services Center (GES-DISC). The operations of Finland's *Sodankylä National Satellite Data Centre* (SNSDC) was also reported on during this working group meeting.

[19] Find out more about the A-Train at *https://atrain.nasa.gov*.

[20] The equilibrium climate sensitivity (ECS) is the temperature increase (in degrees Celsius) that would result from sustained doubling of the concentration of CO_2 in Earth's atmosphere, after Earth's energy budget and the climate system reach radiative equilibrium.

Topics covered in the Mission Operations report included current Aura spacecraft and instrument status, instrument performance and their trends, operational changes, and future spacecraft and instrument plans. Mission operations, including instruments, are all nominal. The leading issue was the implementation and effects of Aura leaving the A-Train constellation in 2021 in order to conserve fuel and lengthen the mission. The highest priority is maintaining the instruments' ability to preserve science and trend-quality long-term data records for as long as possible. After careful consideration, all parties agreed that Aura should remain in the A-Train until 2023. This will provide the best opportunity for collecting high quality data for the longest duration, with the goal to maintain operations to 2025 (approximately 19 years in the A-Train plus approximately 2–3 years at a lower drifting orbit).

The Data Systems Working Group report included a summary of each instrument team's Science Investigators Processing System (SIPS) data collection (version) status and product-level deliveries, as well as on converting its data formats (from HDF-EOS to NetCDF). OMI will switch from *ftp* to *https* for near-real-time data products; TES is beginning to deal with data preservation and end-of-data archiving; and the MLS Science Team will document the services they provided to users. Finally, there were side discussions on how OMI operations will be transferred to GSFC from KMNI. This needs to happen to allow KNMI to prioritize its resources toward TROPOMI operations.

Timo Ryyppö [Finnish Meteorological Institute's (FMI)[21]—*Director of the SNSDC*] talked about the Centre's fast delivery of remote-sensing products for scientific and commercial uses. The data center's high-performance computer arrays are capable of processing large amounts of satellite data into value-added products for various users. The Centre can instantly deliver Direct Readout products from OMI, the Ozone Monitoring Profiler Suite (OMPS),[22] and a host of other international environmental satellite instruments. One example is the Automatic Satellite Forest Fire Monitoring and Alert System.[23]

Summary

This was another successful meeting of the Aura Science Team. As usual, the plenary sessions provided an opportunity for participants to hear the updates on the status of the Aura satellite, its instruments, data systems, and the like, and to hear presentations on the latest science achievements under each of Aura's three themes. The Working Group reports covered ground-data systems status and mission operations. Not only that, falling as it did during the year of the fifteenth anniversary of Aura's launch, the meeting was also an opportunity to look back on what the mission has accomplished.

Aura's instruments—over the spacecraft's 15 years in orbit—have provided a deep understanding of the mission's three major themes. OMI and TES measurements of air pollution and its precursor gases revealed new information about AQ on urban, regional, and continental scales and their changes over time. Regarding stratospheric ozone trends, the Aura data record is now just long enough to reveal a signature of an ozone recovery over the backdrop of large, natural atmospheric variability in the upper stratosphere. OMI and MLS continue to monitor the chemistry and dynamics of the Antarctic ozone hole. HIRDLS, despite its short lifetime, provided new data on how chemically and radiatively active gases are influenced by small-scale and planetary waves in the stratosphere. The climate presentations underlined the importance of the UTLS region and its impact on the Earth's radiation balance. Climate forcers, such as the solar UV irradiances and aerosols, were also topics of particular interest because they influence health as well as climate. Several presentations demonstrated how Aura and A-Train data are being used for inputs and checks for international global models, such as the World Climate Research Project's CMIP. Finally, as an example of Aura synergy, presenters demonstrated how CO_2 emissions can be derived from OMI's NO_2 measurements, which has daily global coverage.

A testament to all Aura has achieved was the Pecora Group Award ceremony, described on page 10, which recognized OMI's outstanding contributions to atmospheric composition research and applications. In addition to looking to Aura's past and present, this meeting also looked toward the future—specifically, the plans for the eventual exit from the A-Train Constellation and the end of the Aura mission. The Mission Operations Working Group and the Science Team agreed that Aura should exit the A-Train in 2023—instead of 2021 as originally proposed—in order to conserve fuel and maximize Aura's lifespan, which is projected to end in 2025. The highest priority was preserving science-quality, long-term data records. The consensus was that each additional year of measurements enhances the value of Aura science. ■

[21] FMI is a partner in the OMI and provided some of the instrument hardware and data information services.
[22] OMPS flies on NASA's Suomi NPP and NOAA-20 satellites.
[23] The system is described at *https://pdfs.semanticscholar.org/7693/c5b9e2692f92e61e4433c58ebac5263b8714.pdf*.

Summary of the Fourth SWOT Science Team Meeting

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Introduction

NASA is partnering with the French space agency [Centre National d'Études Spatiales (CNES)], with contributions from two other international partners, to develop the Surface Water and Ocean Topography (SWOT) mission, scheduled to launch in 2021. The K_a-band Radar Interferometer (KaRIn), the main instrument onboard, will measure the elevation of water in two dimensions at unprecedented spatial resolution.

Data from SWOT will be used to make the first-ever global survey of Earth's surface water, providing essential information on large rivers, lakes, and reservoirs—along with high-resolution measurements of our global ocean. Thus, the mission will address key issues facing a warming planet such as the variability of fresh water resources. Moreover, its ocean data will help reveal the capacity of ocean circulation to regulate the rate of warming.

The fourth SWOT Science Team Meeting (STM) was held in Bordeaux, France, June 18-20, 2019.[1] The meeting was immediately preceded by the SWOT Ocean Calibration/Validation and Science In-Situ Campaigns and Hydrology Data Products workshops, which both took place on June 17. All three meetings are summarized here; the agenda and presentations for the meetings are available at *https://swot.jpl.nasa.gov/meetings.htm?id=22.*

These meetings were planned and convened by the mission's science leads: **Tamlin Pavelsky** [University of North Carolina, Chapel Hill] and **Jean-François Cretaux** [Centre National de la Recherche Scientifique/Laboratoire d'Études en Géophysique et Océanographie Spatiales, France] for hydrology, and **Rosemary Morrow** [CNES] and **Lee-Lueng Fu** [NASA/Jet Propulsion Laboratory (JPL)] for oceanography. Fu is also the SWOT Project Scientist.

This was the last meeting of the current SWOT Science Team (ST) whose funded projects will end by spring 2020. The next round of SWOT ST funding from NASA (U.S. proposals) and CNES (French, European, and international proposals) will support activities from April 2020 to April 2024. The focus for 2020-2024 ST projects will be prelaunch preparations and early scientific studies.

Mission and Instrument Status Update

NASA and CNES are jointly developing and managing SWOT, with contributions from the Canadian Space Agency (CSA) and the U.K. Space Agency (UKSA). The overall technology goal of SWOT is to set the standard for future operational altimetry missions. The SWOT flight system is nearing completion and preparing for the next phases of assembly, integration, and testing (AIT). **Figure 1** on page 18 provides an overview of the mission instruments.

The KaRIn instrument is a multinational effort comprised of components from NASA, CNES, UKSA, who will supply the duplexer for the radiofrequency unit, and CSA, who will supply a satellite radar component that generates pulses known as an Extended Interaction Klystron. The main elements of KaRIn are well underway. Moving forward, the focus will be on completing and preparing KaRIn for integration on the spacecraft.

Space Exploration Technologies (SpaceX) of Hawthorne, CA, will provide launch services for SWOT. Launch is targeted for September 2021 on a SpaceX Falcon 9 rocket from Vandenberg Air Force

[1] The third SWOT STM was held in Montreal, Canada, June 26-28, 2018, and was summarized in the September-October 2018 issue of *The Earth Observer* [**Volume 30, Issue 5**, pp. 31-34—*https://eospso.gsfc.nasa.gov/sites/default/files/eo_pdfs/Sep_Oct_2018_color_1.pdf#page=31*].

SWOT STM participants at the L'Agora du Haut Carré – Campus Talence, University of Bordeaux. **Photo credit:** CNES

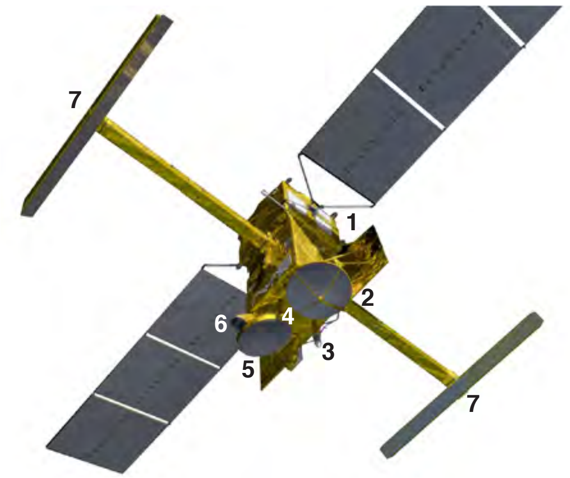


Figure 1. Visualization of the SWOT flight system elements as seen from below the observatory. The following summarizes the status of these elements as of June 2019. Provided by CNES, the spacecraft bus (1) was completed and nearly all hardware had been delivered for AIT to begin in fall 2019. Also from CNES, the Nadir Altimeter (2) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) instrument (3) were undergoing final testing. Built by NASA, the Laser Retroreflector Array (4) and Advanced Microwave Radiometer (5) had been completed and the X-band telecommunications antenna (6) had been delivered for AIT. The NASA-provided Global Positioning System Payload, which is located inside the spacecraft bus, was in final assembly and test. The KaRIn instrument is in the middle of the observatory, located between the two KaRIn reflectors (7) at the ends of the central mast. The text has more details on the components of KaRIn. **Image credit:** NASA/JPL

Base in California. As shown in **Figure 2**, SWOT will operate in two distinct orbits. The satellite will be in a one-day repeat orbit for about six months after launch. This *fast-sampling phase* will focus on achieving calibration/validation (cal/val) objectives and studying rapidly changing phenomena. The fast-sampling phase will be followed by a 21-day repeat orbit, nominally for 3 years. This science data collection orbit is designed to balance global coverage and frequent sampling while meeting SWOT's oceanography and hydrology objectives, as described below.

Calibration and Validation Efforts

With launch less than two years away, cal/val was a significant topic at this year's STM. Many SWOT team members are focused on postlaunch cal/val efforts. The initial one-day repeat orbit was chosen to significantly speed up the acquisition of calibration and performance validation data early in the mission. The spacecraft will be at an altitude that is only slightly lower [i.e., about 34 km (21 mi)] than the science data collection orbit. Thus, results and conclusions from the fast-sampling orbit will generally carry over into the subsequent mission phase.

Oceanography

The selection of SWOT oceanography cal/val sites has been guided by the mission requirement to be near a SWOT orbit crossover during the fast-sampling phase—see **Figure 3** on page 19. By virtue of being sampled twice per day, these crossover locations maximize the number of measurements and optimize the ability to collect coincident ground truth data. A region located about 300 km (186 mi) offshore of Monterey, CA, (referred to below as the "California Current" site) has been selected as a *primary* ocean cal/val site with another primary site in the western Mediterranean Sea. Both locations are indicated by stars in Figure 3.

> ***SWOT Oceanography Objective***
>
> - Characterize the ocean mesoscale and submesoscale circulation (15 to 200 km or about 9 to 124 mi, overall) at spatial resolutions approaching 15 km, or 9 mi.

In preparation for SWOT's post-launch cal/val campaign, an *in situ* field experiment will be conducted at the California Current site. The planned investigation includes objectives for both oceanography and geodesy (i.e., related to Earth's gravitational field, which affects sea surface height, SSH). Oceanographic data will include temperature and salinity at fixed depths from in-water mooring. In addition, profiles of temperature and salinity will be acquired using mobile instruments such as underwater gliders and sensors that move vertically along a wire, propelled by the ocean's wave motion (i.e., Wirewalker, Prawler).[2] Geodetic data will be collected to validate SSH measurements. These instruments will include ocean bottom pressure recorders, Global Positioning System (GPS)-equipped buoys arrayed along SWOT's ground track, and airborne lidar instruments.

[2] To learn more about these sensors, see *https://swot.jpl.nasa.gov/meetings_by_folder.htm?id=1013*.

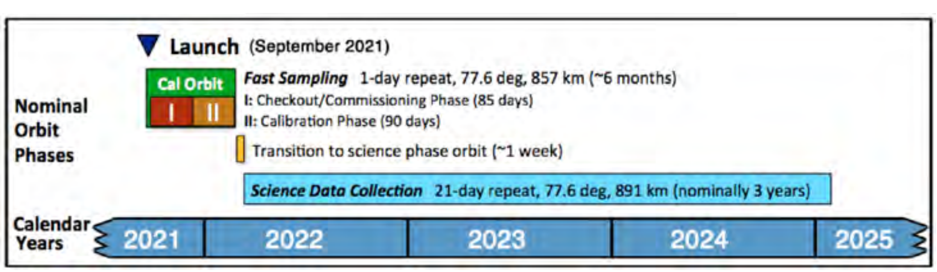
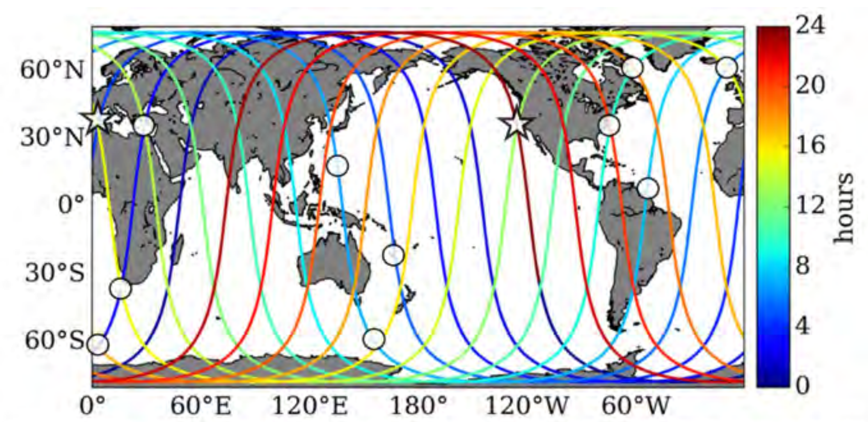


Figure 2. After SWOT launches, there will be an initial *checkout/commissioning phase* lasting about 85 days, followed by an approximately three-month *calibration phase in fast-sampling mode*. Once these two phases are complete, the satellite will be moved to a slightly higher altitude where it will stay for the remainder of the mission. It will take about a week to transition SWOT to *science data collection phase*. **Image credit:** NASA/JPL



Modified from d'Ovidio et al. (2019) Frontiers in Fine-Scale in situ Studies: Opportunities During the SWOT Fast Sampling Phase. Front. Mar. Sci. 6:168

Figure 3. This map shows the planned repeat orbit track during the cal/val phase, coded by time within the one-day repeat period. Stars indicate the location of SWOT's primary ocean cal/val sites including the "California Current" site, a location offshore of Monterey, CA, and another location in the western Mediterranean Sea. Circles indicate proposed *case study* sites, representing a variety of ocean regimes that address several SWOT scientific questions. **Image credit:** NASA/JPL

In addition to the two primary sites, the circles in **Figure 3** indicate regions that have been proposed as potential *case study* sites during the SWOT fast-sampling phase. By instrumenting multiple regions in both hemispheres, investigators will address a variety of scientific questions related to the ocean energy budget, exchanges at the ocean interface (e.g., atmosphere, ice) and balanced motions (e.g., eddies) versus unbalanced motions (e.g., internal gravity waves and internal tides). Instrumentation for these sites would likely consist of temperature and salinity sensors that are both moored and mobile (e.g., gilders, ship-based). Also, given the ties between ocean motion and patterns of life (e.g., chlorophyll) in some areas, several proposed experiments also have biophysical objectives. A core project of the World Climate Research Programme, Climate and Ocean—Variability, Predictability, and Change (CLIVAR) has endorsed the organization of this international series of multiple *in situ* sites during the fast-sampling phase. Overall, these studies have potential to advance the understanding of how fine-scale ocean dynamics impact ecological dynamics and the carbon cycle.

Looking beyond the fast-sampling phase, there was also a report on outcomes from the *SWOT Oceanographic Campaign Workshop*, which was held in October 2018. This group recommended having a separate, dedicated field campaign in the Gulf Stream region one to two years after the launch of SWOT. Its primary scientific focus would be on the small mesoscales that SWOT would resolve. The proposed activity would take place during the science data collection phase of SWOT (see Figure 2), allowing the scientific community time to assess SWOT data before trying to design and execute an *in situ* campaign.

J. Thomas Farrar [Woods Hole Oceanographic Institution—*S-MODE Principal Investigator*] provided an overview of a highly synergistic field campaign that is being funded as a NASA Earth Venture Suborbital Investigation known as the Sub-Mesoscale Ocean Dynamics Experiment (S-MODE). Centered at SWOT's California Current site, its goal is to test the hypothesis that kilometer-scale ocean eddies make important contributions to vertical exchange of climate and biological variables in the upper ocean. S-MODE is scheduled to have a one-month campaign in September 2021. While it is not specifically a SWOT cal/val activity, S-MODE could provide insights on SSH variability and dynamics that will be observed by SWOT.

Hydrology

The SWOT hydrology cal/val plan includes specific requirements for rivers, lakes, wetlands, and estuaries. Cal/val efforts will be conducted over many locations, as outlined in the **Table** on page 20. The rivers, lakes and wetlands listed represent a range of sizes, climate zones, physiographic characteristics, vegetation types (wetlands), and tidal conditions (estuaries).

For rivers, *Tier 1* sites will involve direct field measurements by SWOT validation team members while *Tier 2* sites will leverage existing measurement assets (e.g., U.S. Geological Survey stream gauges) with minimal additional field measurements. Note that the final suite of *Tier 2* sites is still to be determined; the minimum requirement is an in-water stage recorder with high-level position accuracy (Global Navigation Satellite System, GNSS) and hourly or better recording.

SWOT Hydrology Objectives

- Provide a global inventory of all terrestrial water bodies (lakes, reservoirs, wetlands) whose surface area exceeds 250 x 250 m (~820 ft by ~820 ft) and rivers whose widths exceed 100 m (~330 ft).
- At submonthly, seasonal, and annual time scales: Measure the global storage change in freshwater bodies; and estimate the global change in river discharge.

Similarly, the lakes and wetlands listed in the **Table** include *Tier 1* and *Tier 2* sites. Information from these locations will be complemented by a related NASA-funded effort, Lake Observations from Citizen Scientists and Satellites (LOCSS). LOCSS has engaged a network

Table. Locations of SWOT hydrology cal/val activities.

Rivers	Lakes and Wetlands	Coasts and Estuaries[+]
Tier 1	***Tier 1***	***Fast Sampling (1-day)****
Willamette River (U.S.)	Everglades Wetlands (U.S.)	Columbia /*Willamette Rivers (U.S.)
Garonne River (France)	Lake Tahoe & Sierra Lakes (U.S.)	*Connecticut River (U.S.)
Lower Mississippi River (U.S.)	Lower Mississippi Wetland (U.S.)	Gabon Estuary (Africa)
Connecticut River (U.S.)	Prairie Potholes (U.S.)	Guayas Estuary (Ecuador)
Tanana River (U.S.)	Yukon Flats Lake and Wetland (U.S.)	Mt. St. Michel/Normandy (France)
Peace River (Canada)	***Tier 2***	*Saint Lawrence Estuary (Canada)
Slave River (Canada)	Champlain/St. Pierre (U.S./Canada)	***Science Data Collection (21-day)***
Saint Lawrence River (Canada)	Lake Baikal (Russia)	*Everglades (U.S.)
Saskatchewan River (Canada)	Lake Chad (Central Africa)	Fraser River (Canada)
Sagavanirktok River (U.S.)	Lake Issykkul (Kyrgyzstan)	*Garonne/Gironde Estuary (France)
South America	Los Lagos (Chile)	Mackenzie Delta (Canada)
Tier 2 (To be Selected)	Peace-Athabasca Delta (Canada)	Magdalena (Colombia)
50-100 sites with the following:	***LOCSS (Citizen Science)***	*Mississippi Delta (U.S.)
• Stage recorder with high-level position accuracy (GNSS)	3 sites in Bangladesh and 3 in France	Seine Estuary (France)
• Hourly or better data recording	17 lakes in Illinois (U.S.)	Wax Lake Delta (U.S.)
	13 lakes in North Carolina (U.S.)	
	24 lakes in Washington (U.S.)	

[+] This column lists potential site locations.
* These locations are associated with Tier 1 sites for rivers, lakes, and wetlands.

of citizen scientists[3] that report lake height by reading simple gauges. The project also uses satellite images to determine the surface area of the lakes being monitored. By knowing the changes in both lake height and surface area, researchers can understand how the volume of water in a given lake is changing over time. By the time SWOT launches, LOCSS hopes to have a network of 100-200 regularly observed lakes worldwide that can be used for validation.

Coasts and estuaries are located at the nexus of land and sea, with phenomena that therefore have a large variety of spatial and time scales. These areas are complicated by seasonal variations (e.g., change in discharge and vegetation), tides, and events such as storm surges. Moreover, the shallow slope of many coasts and estuaries will present a measurement challenge for SWOT. Potential cal/val sites for coasts and estuaries (see Table above), parsed between the fast-sampling and science data collection orbits. Several of these locations are associated with *Tier 1* sites for rivers and wetlands, as shown by asterisks.

Overall Meeting Outcomes and Next Steps

SWOT's improved spatial resolution over today's ocean-observing satellite altimeters (e.g., Jason-3) will allow detection of features such as eddies with diameters of 10 to 20 km (6 to 12 mi). Work conducted by the STM over the past four years has affirmed the promise of SWOT to provide new opportunities to reveal dynamic processes at these scales over the global ocean.

SWOT will provide unprecedented opportunities to study how SSH signatures are related to the ocean's physical, chemical, and biological processes. SWOT is also expected to play a key role in studying the ocean climate system by revealing new information on the ocean's vertical transport of heat, carbon, and nutrients.

As NASA's first-ever global survey of Earth's surface water, a major goal for SWOT is to determine the storage and discharge rate of water on land. Work conducted by the ST has demonstrated that river discharge can be estimated from SWOT alone with acceptable accuracy. ST efforts have contributed to readying SWOT data on lake height, extent, and storage changes for assimilation into global hydrology models. The development of *a priori* databases for rivers and lakes is well underway; however, there are major efforts ahead to set up these databases prior to the SWOT launch (e.g., extent of lakes, separation between lakes and artificial reservoirs). Other ongoing work will focus on harmonizing river and lake algorithms and products.

The final meeting of the current SWOT ST solidified many of the upcoming cal/val efforts. It also demonstrated the current capabilities of—and future plans for—data products and high-resolution models (e.g., ocean tides). The project reported significant progress on flight hardware with KaRIn development being the critical path towards maintaining the SWOT launch schedule. The overall project continues to be challenging, as to be expected with the development of cutting-edge technology. SWOT teams expressed their excitement as they look forward to the next phase of the mission, preparing for launch and post-launch activities.

The next SWOT STM will likely be held in the U.S. during the last two weeks of June 2020. ■

[3] To learn about another example of citizen science, see "Globe Observer: Citizen Science in Support of Earth System Science" in the November–December 2017 issue of *The Earth Observer* [**Volume 29**, **Issue 6,** pp. 16-21—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Nov_Dec_2017_color_508.pdf#page=15*].

Summary of the 2019 NASA Weather and Air Quality Forecasting Workshop

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Workshop Rationale and Overview

The NASA Weather and Air Quality Applications Workshop was an invitation-only event organized by NASA's Global Precipitation Measurement[1] (GPM) Applications Team. The workshop was held July 22-23, 2019, at the Earth System Science Interdisciplinary Center[2] (ESSIC) in College Park, MD. The workshop brought together 40 experts from NASA, the National Oceanic and Atmospheric Administration (NOAA), U.S. Naval Research Laboratory (NRL), European Centre for Medium-Range Weather Forecasts (ECMWF), Environment and Climate Change Canada (ECCC), Japan Meteorological Agency (JMA), Japan Aerospace Exploration Agency (JAXA), Colorado State University, University of Oklahoma, and Pennsylvania State University. In a series of scientific sessions, panels, and breakouts, participants discussed how existing NASA satellite products could be better leveraged for numerical weather prediction (NWP) modeling activities and air quality (AQ) forecasting efforts, and outlined future needs for NASA's next-generation satellite estimates.

This workshop served as the first engagement with the NWP and AQ communities to discuss the utility and opportunities for future measurements, including those that may be taken as part of the proposed combined Aerosol and Clouds, Convection, and Precipitation (ACCP) Designated Observable (DO), which was identified as a high-priority observation by the National Research Council's (NRC) Second (2017) Earth Science Decadal Survey.[3] The ACCP DO is described further in the summary of Day Two, beginning on page 24, below. The four main objectives of the workshop were to:

- Understand how GPM data products are currently assimilated in NWP modeling and opportunities for future applications;
- explore barriers and solutions related to the assimilation of satellite observations into NWP models and opportunities for AQ forecasting;
- assess how future measurements from the ACCP concept study may be utilized by the NWP and AQ forecast community; and
- increase awareness of the needs of the NWP and AQ forecast community for future research developments and collaboration.

With a range of experts onhand and dedicated breakout sessions to enable discussion, the workshop provided a framework for rich dialogue on the use and application of satellite observations in weather and AQ forecasting communities, as well as guidance for future NASA mission planning. This report summarizes highlights from the workshop. For more information about the meeting and to view the meeting agenda, visit *https://pmm.nasa.gov/nwp-workshop*.

DAY ONE

The first day of the workshop began with opening plenary presentations that offered an overview on the status of NASA Applied Sciences, GPM mission elements, and NWP and AQ forecasting activities at NOAA. The remainder of the day was dedicated to three panels highlighting activities in NWP and AQ forecasting. Each panelist had 10-15 minutes to present their research. The panelists then jointly discussed opportunities and challenges of using NASA Earth observations within their fields of study. The floor was then opened for discussion among the workshop participants.

Opening Plenary

Dalia Kirschbaum [NASA's Goddard Space Flight Center (GSFC)—*GPM Deputy Project Scientist for Applications*] and **Phil Arkin** [ESSIC—*ESSIC Deputy Director* and *Senior Research Scientist*] began with welcoming remarks on behalf of both the GPM Applications Team and ESSIC.

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[1]GPM is co-led by NASA and the Japan Aerospace Exploration Agency (JAXA), and includes more than 20 additional international partners. To learn more about GPM, see "GPM Core Observatory: Advancing Precipitation Measurements and Expanding Coverage" in the November–December 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 6**, pp. 4-11—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Nov_Dec_2013_final_color*.pdf#page=4]. and "The Global Precipitation Measurement (GPM) mission's scientific achievements and societal contributions: reviewing four years of advanced rain and snow observations," available at *https://doi.org/10.1002/qj.3313*.

[2] ESSIC is a joint center between the University of Maryland's Departments of Atmospheric and Oceanic Science, Geology, and Geographical Sciences.

[3] This review sought to identify the key scientific questions and gaps in current Earth science research and applications and the observations recommended to address them. To read the report, see "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space," at *https://science.nasa.gov/earth-science/decadal-surveys*.

John Haynes [NASA Headquarters (HQ)—*Program Manager for Applied Sciences Program for Health and Air Quality Applications*] spoke next, and offered a broad perspective on the use of NASA Earth observations for real-world precipitation and AQ applications and opportunities to expand relevant research and operational activities. **Scott Braun** [GSFC—*GPM Project Scientist*] provided an overview of the GPM mission and mission updates, including spacecraft and instrument status, GPM algorithm updates, and current activities related to GPM applications science. **George Huffman** [GSFC—*GPM Deputy Project Scientist*] described GPM data product levels and gave a status update of the release of Version 06 of the Integrated Multi-satellitE Retrievals for GPM (IMERG),[4] announcing that it includes precipitation data from 2000 through the present—see **Photo 1**.

Photo 1. During the Open Plenary session, **George Huffman** presented an overview of GPM data product levels and gave a status update on the release of Version 06 of IMERG. **Photo credit**: Dalia Kirschbaum [GSFC]

Ivanka Stajner [NOAA/National Weather Service (NWS) and NOAA/Environmental Modeling Center (EMC) at the National Centers for Environmental Prediction (NCEP)] and **Shobha Kondragunta** [NOAA/National Environmental Satellite, Data, and Information Service (NESDIS)/Center for Satellite Applications and Research (STAR)] presented an overview of NOAA's current AQ products and modeling activities for AQ forecasting, which included the status of emerging operational and research AQ products from NOAA, NASA, the European Space Agency (ESA), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) for various model applications.

Panel One: Numerical Weather Prediction Activities within the U.S.

Emily Berndt [NASA's Marshall Space Flight Center (MSFC)/Short-term Prediction Research and Transition Center (SPoRT)] facilitated the first panel, which consisted of four panelists from operational and research agencies within the U.S., highlighting current activities in assimilating NASA datasets within their agencys' NWP modeling activities.

Kevin Garrett [NOAA/NESDIS/STAR] presented information on the assimilation of NASA satellite data—including the GPM Microwave Imager (GMI)—to initialize NWP and forecasting models for operations at NOAA/NESDIS/STAR, and showed an example of how retrievals from the GMI have helped provide guidance for short-term weather prediction and forecasting of precipitation.

Will McCarty [GSFC/Global Modeling and Assimilation Office (GMAO)] described the impacts on the Goddard Earth Observing System (GEOS) model analyses and forecasts from assimilating all-sky radiances from the GMI instrument. He explained that in 2018, all-sky GMI observations in near real-time were implemented into the GEOS Forward Processing (FP) system's algorithm, which increased the types of variables analyzed (e.g., hydrometeors such as liquid cloud, ice cloud, rain, and snow). McCarty then noted that the assimilation of GMI into the GEOS system made significant positive impacts on GEOS forecasts, especially for lower tropospheric water vapor, temperature, and winds.

Joshua Cossuth [NRL] described the current NWP systems and data assimilation schemes used by the NRL for operational global weather prediction. He placed emphasis on the importance of satellite microwave data for the Navy's environmental prediction systems, used for NWP operations.

Yanqui Zhu [NOAA/NCEP/EMC] presented information on the status and progress of all-sky radiance assimilation in NCEP's global weather prediction system to help improve weather modeling, and showed an example of how NOAA's Advanced Microwave Sounding Unit (AMSU) improves their system's temperature and relative humidity analyses and forecasts.

Panel One Discussion Summary

Following the first panel—see **Photo 2**—three questions were primarily discussed:

- What data are the highest priority for assimilation?
- In cases where new datasets need to be assimilated, what are the new datasets and tools that need to be developed?
- How long does it take to integrate satellite data into operational systems?

The panelists agreed that microwave observations are still the most utilized observations and provide valuable

[4] Technical documentation for IMERG V06 can be viewed at *https://pmm.nasa.gov/sites/default/files/document_files/IMERG_V06_release_notes_190503.pdf*.

information for assimilation systems. There was discussion about the need to assimilate aerosol information as well as directly assimilate GPM's Dual Frequency Precipitation Radar (DPR) data into models. The panel emphasized the importance of developing new innovative measurements that add value to existing assimilation data such as vertical wind profiles and the need to create model flexibility to add new datasets that help improve model parameterizations. The panelists concluded that data users will have to come up with a customized approach to integrate satellite data into their systems to meet specific needs. The panel noted that incorporating data from new sensors is highly dependent on the type of data, calibration and biases of the data products, and availability to resources used to bring in and test new data.

Photo 2. Yanqui Zhu (speaking) responds to a question from the audience during the Numerical Weather Prediction Activities within the U.S. panel discussion. Other panelists included [*left to right*] **Joshua Cossuth**, **Will McCarty**, and **Kevin Garrett**. **Photo credit:** Dalia Kirschbaum [GSFC]

Panel Two: Numerical Weather Prediction Activities outside the U.S.

Patrick Gatlin [MSFC] moderated Panel Two of NWP Forecasting Activities, which was intended to give participants an international perspective on current activities in assimilating NASA datasets and other relevant products within their agencys' NWP modeling and forecasting activities.

Yasutaka Ikuta [JMA] provided an overview on how data from GPM's DPR and GMI instruments are assimilated within JMA's NWP systems. Ikuta described the use of the DPR's three-dimensional observations, stating that it is a valuable resource for determining initial conditions for JMA's Meso-Scale Model (MSM), which helps improve forecasts for mesoscale convective systems.

Alan Geer [ECMWF] described ECMWF's current and future activities using satellite-based cloud and precipitation data in their global weather forecasting activities. He described many satellite products that are helping to provide initial conditions for operational forecasts and improving forecast quality by tuning and developing microphysics and convection parameterizations.

Marco Carrera [ECCC] described current assimilation activities of space-based remote sensing for operational NWP at ECCC—see **Photo 3**. Carrera noted that the IMERG product has significant potential to improve the ECCC Canadian Precipitation Analysis (CaPA) that combines precipitation gauge observations with a short-range NWP precipitation forecast in areas not covered by radar or gauge observations. He concluded with a discussion about the challenges in implementing satellite data into NWP systems, including data latency and volume, quality control and bias correction, and quantification in improvement to NWP systems such as evaluation metrics.

Photo 3. Marco Carrera presented an overview of current assimilation activities of space-based remote sensing for operational NWP at ECCC. **Photo credit:** Dalia Kirschbaum [GSFC]

Panel Two Discussion Summary

After this panel, the questions raised for discussion included:

- What other space-based datasets are currently being assimilated besides radiances?
- For passive microwave (PMW) observations, are all-sky or clear-sky observations assimilated?
- How does the assimilated data improve the data products provided?
- What will be the opportunities and challenges for the assimilation of satellite observations into NWP models in the next 5 to 10 years?

The panelists discussed that the assimilation of radar data (e.g., from DPR) is planned or currently in testing phases for some of their agency's modeling activities, but noted potential challenges with assimilating radar, e.g., processing limitations for bringing in three-dimensional precipitation datasets. There was also discussion that JMA, ECMWF, and ECCC are working toward a plan to assimilate all-sky radiances in the near future. The panel further emphasized that assimilating brightness temperature data from the GMI helps improve their agency's forecasts. Discussion concluded with panelists emphasizing the need and opportunity for measuring snow using K_u- and K_a-band radar observations.

Panel Three: Air Quality Forecasting Activities

Shobha Kondragunta facilitated the third panel, during which panelists presented current activities in assimilating NASA datasets within their agencys' AQ modeling activities.

Ivanka Stajner described new and upcoming NASA satellite datasets of interest to assimilate within the Unified Forecast System[5] (UFS) to improve AQ forecasting. She explained that NOAA currently uses Aerosol Optical Depth (AOD) data from the Moderate Resolution Imaging Spectroradiometer (MODIS)6 within their AQ forecasting activities for volcanic and fire emissions and aerosol dust. Stajner noted that challenges in assimilating these data relate to uncertainties in aerosol properties like composition and the planetary boundary layer (PBL) height and processes. She concluded that to address these uncertainties and improve air quality forecasts going forward, additional observations—including detecting aerosol height, size, composition, and optical properties—are needed.

Keiya Yumimoto [Kyushu University/JMA] presented information on the aerosol data assimilation system currently used by JMA, the Himawari-8[6]/MODIS AOD hybrid assimilation system. He stated that JMA's future plans are to assimilate lidar data to provide vertical profiles during the night to improve AQ forecasting.

Anton Darmenov [GSFC/GMAO] described current and future GMAO plans for aerosol forecasting and data assimilation. He emphasized that, to improve AQ forecasting, high-resolution (i.e., <1 km) polarimetric observations—with good global spatial and temporal coverage and aerosol vertical information—need to be addressed.

Amy Huff [formerly Pennsylvania State and now NOAA/NESDIS/STAR] described using satellite observations to support U.S. operational AQ forecasting, including identifying the location and transport of fire/dust plumes with satellite data to produce accurate operational forecasts. She concluded by pointing out that satellite product requirements for AQ operational forecasting and applications should include the highest possible spatial and temporal resolution (~5 km or less, ~1 hr or less), low latency, and geostationary or a morning overpass to support an early afternoon deadline for issuing forecasts.

[5] UFS is a comprehensive, community-based Earth modeling system, designed as both a research tool and as the basis for NOAA's operational forecasts. See *https://ufscommunity.org*.
[6] Himawari-8 is one in a series of JMA geostationary weather satellites.

Panel Three Discussion Summary

Following the third panel, the questions raised for discussion included:

- Is precipitation relevant for AQ Forecasting?
- Which data/products are needed for AQ forecasting applications?
- How do workshop participants want to work with NASA to assimilate ACCP?

The panelists noted that it is essential to use satellite data within global models because these models help produce accurate AQ forecasts. The discussion addressed the relevance of incorporating precipitation data into AQ forecasts, noting that while precipitation is important to define initial conditions for aerosol states, precipitation data are not yet incorporated into operational AQ models. The panelists further communicated the need to better constrain aerosol precursor pollutants to initiate models for AQ forecasting and applications. The panel concluded with a discussion describing planned future efforts and how they relate to the ACCP study, which includes unifying NOAA's data assimilation with NASA products, generating reanalysis data, and developing real-time aerosol forecasts.

DAY TWO

Day two of the workshop began with an overview of the ACCP study concept, followed by two thematic breakout sessions with discussions focused on potential applications of weather and AQ forecasting.

ACCP Overview

The 2017 Earth Science Decadal Survey (referenced in the Workshop Rationale/Overview) provides an outlook for the next priority research areas and observations, and also outlines notional missions to make those observations. Among these missions are five *designated observables* (DO) to be implemented as cost-capped medium- and large-size missions directed or competed at the discretion of NASA. Two of these DOs—Aerosols (A) and Clouds, Convection and Precipitation (CCP)—have been designated as having high priority.[7] Furthermore, the 2017 Decadal Survey recognized the science merit in combining the A and CCP DOs. Consequently, a NASA ACCP study is currently being conducted to explore observing system architectures that would allow the A and CCP DOs to be combined to satisfy the scientific objectives of each DO and enable applications. The goal of the ACCP study is to define science goals and enabled applications to outline the geophysical parameters needed, the desired capabilities

[7] The other three designated observables identified by the Decadal Survey are mass change, surface biology and geology, and surface deformation and change.

associated with those parameters, and the observing systems approaches necessary to achieve them.

Members of the ACCP team provided the workshop participants with a brief overview of the ACCP study,[8] including the Science and Applications Traceability Matrix (SATM),[9] and ACCP-enabled applications. **Felix C. Seidel** [NASA HQ] provided a snapshot of the 2017 Decadal Survey, including the DOs; he also described the current *Program of Record* from NASA and its partners. **Vickie Moran** [GSFC—*ACCP Study Coordinator*] provided details about the ACCP status and science plan for the next several years, including information about the ACCP study team and ACCP science objectives. **Scott Braun** [GSFC] presented the ACCP SATM, including instrument architecture concepts, technology needed for the study, and the value framework approach used to determine relative impact of science objectives, applications, and cost/risk assessments. Lastly, **Ali Omar** [NASA's Langley Research Center (LaRC)] and **Emily Berndt** explained ACCP architecture elements and enabled applications envisioned by the suite of ACCP observations. These include—but are not limited to—severe storm forecasting and modeling, aerosol and precipitation interaction in modeling and forecasting, aviation industry and safety, agricultural modeling and monitoring, and disaster monitoring, modeling and assessment.

Breakout Sessions

In the afternoon, two breakout sessions convened, discussing instrumentation and observations for the ACCP study, and latency, data access, assimilation potential, and enabling applications within the ACCP Study. The goals for these sessions were not only to address the needs, opportunities, and barriers to the adoption and use of potential observations from the ACCP suite of products within these application communities, but also to provide feedback on the SATM. Summaries of the discussion in each breakout are provided below.

Breakout One

During the first breakout session, participants were divided into two groups: an Aerosols working group and a Clouds, Convection, and Precipitation working group. Some of the questions posed to each group were:

- How do workshop participants anticipate modeling systems will look when ACCP launches?
- To what extent do workshop participants envision using any of the proposed classes of instruments (radiometer, polarimeter, lidar, etc.)?
- What spectral information or instrument types excite workshop participants?
- What are the limitations of using SmallSat and CubeSat information in operational modeling schemes?

In response, the Aerosol working group noted a wide variety of variables that would be valuable to the community and are addressed within the ACCP study. Specifically, participants generally agreed that improvement in aerosol speciation, shape, size, composition, and polarization is needed and important for AQ modeling. There also needs to be an overall improvement in collecting aerosol chemical and physical information. The group then commented that the level of detail needed for the AQ forecasting community is within the PBL at heights around 100 m to 500 m (~328–1640 ft). The group also noted that the co-location of cloud and aerosol measurements on the same platform or constellation is important for assimilating aerosol data in the vicinity of clouds.

The CCP working group discussed how future modeling systems may evolve, citing plans for global models with 3-5 km (~2-3 mi) resolution within the next 5-8 years that focus on coupling atmosphere and ocean processes. There was also discussion of operating single model hydrometeors and mass flux convection schemes, with an emphasis on better parameterizing fluxes to represent convection. The group then described that particle size distribution using radar data such as from DPR in their assimilation schemes is of high interest for advancing NWP performance. The CCP working group also discussed the potential limitations in using SmallSat or CubeSat observations within their model, highlighting questions about the accuracy of observations, including consistency in calibration, noise, drifting issues, and longevity of the measurements. This is an area of active interest to better understand the capabilities and limitations of instruments onboard smaller satellites.

Breakout Two

During the second breakout session, participants were divided into four evenly distributed groups to encourage discussion. Some of the questions posed in each of the four groups were:

- How frequently do workshop participants need the data? What additional benefits/impacts could workshop participants have with improved latency?
- What is the minimum revisit time needed?
- What level/error of uncertainty is acceptable?
- What scale and resolution is needed?

[8] For more information about the ACCP study, visit *https://science.nasa.gov/earth-science/decadal-accp*.

[9] For the complete review of SATM, visit *https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/ACCP_SATM_Release_A_Final_0.pdf.*

- How do workshop participants envision the data they are assimilating will improve products that they provide?
- In which region do the NWP and AQ community really need data?

This breakout promoted productive discussions in each group through sharing across the NWP and AQ forecasting communities. There was strong agreement that aerosol and precipitation data latency of one to one-and-a-half hours is optimal for Level 1 and 2 products, with several workshop participants noting that the minimum revisit time needed is every half hour. The operational weather forecasting community indicated that the lowest latency is optimal for direct assimilation. Participants also agreed there needs to be improvement in capturing the surface latent heat flux and sensible heat flux for the lower boundary condition of a model and the height of the PBL, as well as consistent ways to characterize error and uncertainty of observations for data assimilation. Lastly, participants emphasized that more observations are needed under clouds and in the polar regions where aerosols and cloud interactions are not well constrained.

Conclusion

Overall, the workshop achieved its objectives. It provided a forum for communication between applied users from the operational and research NWP and AQ Forecast communities, and NASA scientists. The workshop also provided the first opportunity to discuss future NASA mission planning on ACCP. The meeting enabled participants to receive feedback from the community about the most significant gap areas as well as opportunities to advance modeling capabilities. The workshop identified key tenets of current and future applications regarding the importance of specific data variables and products, the availability of specific data formats and latency, the importance of effective error and uncertainty characterization, and defining orbit and sub-orbital needs for these communities. These workshop results will help to improve current data products and services developed by the GPM science team and will help to define and guide how the observations made from ACCP will be used by the applications communities. A summary table highlighting workshop results and findings can be viewed at *https://pmm.nasa.gov/nwp-workshop*. ■

Kudos to 2019 Pecora Award Recipients

NASA's Terra Team received the *2019 Pecora Group Award* in recognition of the significant contributions this group has made in all areas of Earth science, leading to a wide range of scientific impacts. Terra data have been used by multiple federal agencies for volcanic ash monitoring, weather forecasting, forest fire monitoring, carbon management, and global crop assessment. To date, there have been about 20,000 publications using Terra products—with a steady increase over time. The Terra Team was recognized for developing innovative techniques to characterize the environmental status and health of our planet.

Representing the Terra Team at the October 7 award ceremony in Baltimore, MD, were [*left to right*] **Michael Abrams** [NASA/Jet Propulsion Laboratory]; **James Drummond** [Dalhousie University]; **Robert Wolfe** [NASA's Goddard Space Flight Center]; and [*far right*] **Vince Salomonson** [University of Utah, *retired*]. **Marie-Josee Bourassa** [Canadian Space Agency] represented one of NASA's international partners on Terra. **Photo credit:** NASA

Not pictured, **Thomas R. Loveland** [U.S. Geological Survey's (USGS) Earth Resources Observation and Science (EROS) Center] received the *2019 Pecora Individual Award* in recognition of his outstanding contributions to the field of Earth science as a leading USGS scientist and chief scientist at EROS. Loveland has devoted his career to understanding how the Earth's surface is changing through mapping and monitoring land cover and land use. He led the development of innovative monitoring programs and produced exciting new land cover and land use change products. Of particular relevance to NASA, Loveland co-led the NASA–USGS Landsat Science Team from 2006–2016, and steered efforts to improve the Landsat satellite missions.

Congratulations to Loveland and the entire Terra Team!!

For more information, see *https://www.nasa.gov/feature/terra-mission-team-land-cover-scientist-honored*. A description of the Pecora Award can be found on page 10 of this issue.

Summary of the Sixth GEDI Science Team Meeting

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Introduction

The sixth Global Ecosystem Dynamics Investigation (GEDI) Science Team Meeting (STM) was held at the University of Maryland, College Park (UMD), August 6-8, 2019. **Ralph Dubayah** [UMD—*GEDI Principal Investigator (PI)*] convened the meeting. There were 30 GEDI science team members and collaborators in attendance. The main objectives of the meeting were to discuss GEDI data processing pipelines, data product dictionaries, data release timeline, data product performance compared to expectations—and to set priorities for the next six months regarding data processing—public release of data, documentation, and scientific publications. The following summary presents the highlights of the meeting. Those who wish to find out more details about the specifics of this meeting can contact the authors at the email addresses listed above. More information on the GEDI mission can be found at *http://gedi.umd.edu*.

Day One

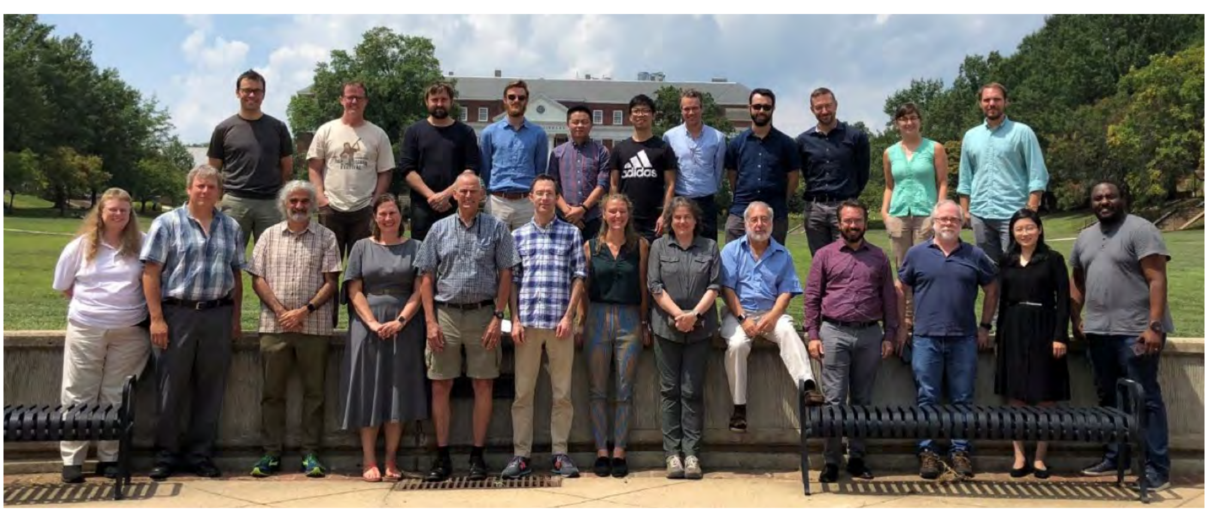
On the first day of the meeting, the PI and other representatives provided reports on the status of the GEDI mission, including a detailed update on the status of GEDI data product development.

GEDI Mission Status

Ralph Dubayah reviewed the history of the GEDI mission to date. It was originally scheduled for launch on the Space-X CRS-18 mission, but was accelerated to the Space-X CRS-16 mission, which launched on December 5, 2018. After launch, GEDI was successfully installed on the Japanese Experiment Module-Exposed Facility (JEM-EF) of the International Space Station (ISS). On-orbit checkout phase was completed on April 18, 2019, after which science data collection started. In just the first three months of data collection the instrument collected approximately 500 million high-quality *lidar waveform*[1] measurements over land. These numbers already far surpass the number of waveforms from the Ice, Cloud, and land Elevation Satellite (ICESat) mission[2] used in previous global scale biomass maps. GEDI's dense sampling is expected to support the best available international estimates of forest biomass. The **Figure** on page 28 shows an example of GEDI's sampling in Brazil [*left*] and an example of a GEDI waveform [*right*] collected over a complex tropical forest canopy.

Tony Scaffardi [NASA's Goddard Space Flight Center (GSFC)—*GEDI Mission Operations Manager*] explained the daily dynamics of mission operations at the GEDI Science and Missions Operation Center (SMOC), located at GSFC. The SMOC sends commands to the GEDI instrument and is responsible for the reception of data collected by GEDI. Scaffardi and his team have sorted through a number of challenges since the initial powering of the lidar instrument. These have included unexpected resets (most likely from radiation events), star tracker blindings caused by sunglint off the ISS structure and its robotic arms, and data dropouts, among others. He reported that despite these, the SMOC is now smoothly operating in nominal science collecting phase.

[1] For an explanation of how GEDI uses these *lidar waveforms* to measure canopy structure, see the "Summary of the Second GEDI Science Team Meeting" in the November–December 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 6**, p. 32—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Nov-Dec%202016%20color%20508.pdf#page=31*].
[2] NASA's ICESat mission launched in 2003 and ended in 2009.



Participants of the sixth GEDI Science Team Meeting. **Photo credit**: Ken Jucks [NASA Headquarters]

Bryan Blair [GSFC—*GEDI Deputy Principal Investigator* and *Instrument Scientist*] reported that the GEDI instrument is performing well. The beam dithering unit, creating eight laser tracks from the four laser beams, is performing flawlessly as are the pointing control mechanisms, which optimize the spatial coverage of the GEDI measurements.

Once a week, **Scott Luthcke** [GSFC] and other members of the GEDI science team evaluate potential Reference Ground Tracks (RGTs) that GEDI may hit. GEDI has the ability to point towards (or target) specific locations of interest to achieve more uniform coverage. RGTs are chosen each week to maximize the spread of GEDI's measurements and to hit areas of interest, such as large areas covered with airborne lidar to perform validation activities.

John Armston [UMD] reported on the current status of the high-quality GEDI waveform measurements collected over calibration and validation sites and explained how a team at UMD has developed a tool to colocate GEDI waveforms with airborne lidar data from GEDI's airborne simulator—the Land Vegetation and Ice Sensor (LVIS)—and from other airborne laser scanning (ALS) data. Validation of footprint-level height and cover estimates with these colocated datasets reduces spatial uncertainty and allows prelaunch footprint-level biomass calibrations to be evaluated and updated.

GEDI Data Product Development

The GEDI data products discussed during this session are summarized in the **Table** on page 29.

GEDI Level-1A (L1A) data products contain ungeolocated waveform parameters, and are generally not made publicly available. **Scott Luthcke** leads the waveform geolocation effort for the L1B product. He explained challenges associated with GEDI's star trackers, which relate to the operations of the ISS. Resolution of these challenges has required significant Science Team effort. Locational accuracy has also been improved through vicarious comparison with recent LVIS acquisitions.

Michele Hofton [UMD] leads the GEDI L2A data product development. She explained that the data product contains the corrected and smoothed received GEDI waveforms. Ranging determines the highest and lowest detected modes and uses this information to provide canopy height, ground elevation, and returned energy percentiles (also known as relative height metrics). The identification of the ground-return elevation is essential in this processing step as it determines the accuracy of canopy height and other data products.

Hao Tang [UMD] leads the processing of the GEDI L2B data products. This data product uses the L1B and L2A data products to compute canopy cover and vertical profile metrics.

Luthcke also leads the processing effort for L3 data products. The L3 data maps will contain 1-km^2 (~0.4-mi^2) gridded land surface metrics using optimal interpolation with locally determined covariance (kriging) in 100-m (~328-ft) subgrids. The grid for the data product has been established and the canopy structure and topography metrics will be imputed in the grid during data collection over the nominal two-year mission.

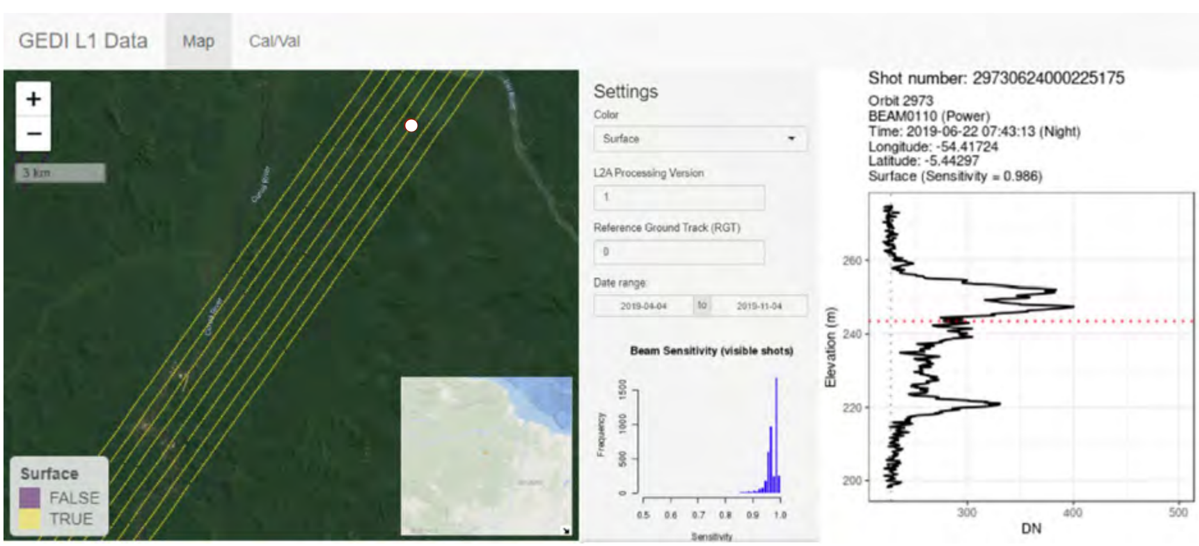


Figure. The image on the left shows GEDI tracks (diagonal lines) across a tropical forest in Eastern Brazil—shown on the small inset map at the bottom. Close inspection will reveal that the yellow "lines" are actually composed of dots, each indicating an individual GEDI waveform that reached the surface; small "gaps" in the line indicate *false surfaces*, where waveforms failed to reach the surface. The white dot on the fifth ground track [*top right*] shows the location where the sample Level-1B waveform, shown on the right, was obtained. The solid black curve in the graph on the right depicts the amount of returned energy along the elevation profile as a digital number (DN). The red dotted line on the graph shows the surface elevation from TanDEM-X. **Image credit**: Suzanne Marselis, John Armston, Ralph Dubayah [all from UMD]

Table. Summary of GEDI's data products, algorithm theoretical basis documents (ATBDs), ATBD authors, and product leads.

ATBD #	ATBD Title	Data Products Addressed	ATBD Authors/Product Leads
Level-1A-2A	Transmit and Receive Waveform Interpretation and Generation of L1A and L2A Products	1A-TX: Transmitted waveform parameters 1A-RX: Received waveform parameters 2A: Elevation and relative height (RH) metrics	**Michelle Hofton** [GSFC] **James Bryan Blair** [GSFC]
Level-1B	Geolocated Waveforms	Geolocated waveforms	**Scott Luthcke** [GSFC] **Tim Rebold** [GSFC] **Taylor Thomas** [GSFC] **Teresa Pennington** [GSFC]
Level-2B	Footprint Canopy Cover and Vertical Profile Metrics	Footprint canopy cover and vertical profile metrics	**Hao Tang** [UMD] **John Armston** [UMD]
Level-3	Gridded Land Surface Metrics	Gridded L2A and L2B metrics	**Scott Luthcke** [GSFC] **Terence Sabaka** [GSFC] **Sandra Preaux** [GSFC]
Level-4A	Footprint Above Ground Biomass	Footprint above-ground biomass density	**Jim Kellner** [Brown University] **Laura Duncanson** [UMD] **John Armston** [UMD]
Level-4B	Gridded Biomass Product	Gridded above-ground biomass density	**Sean Healey** [U.S. Forest Service (USFS)] **Paul Patterson** [USFS]
Demonstration Products	NA	Prognostic ecosystem model outputs	**George Hurtt** [UMD]
		Enhanced height/biomass using fusion with the German Aerospace Center (DLR) TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X) Mission	**Lola Fatoyinbo** [GSFC] **Wenlu Qi** [UMD]
		Enhanced height/biomass using fusion with Landsat	**Matt Hansen** [UMD] **Chenquan Huang** [UMD]
		Biodiversity/habitat model outputs	**Scott Goetz** [Northern Arizona University (NAU)] **Patrick Jantz** [NAU]

The L1B, L2A, L2B, and L3 data products from the first two months will be released to the public by late fall 2019. The L4A and L4B (footprint and gridded biomass data products) are scheduled to be released approximately 18 months after on-orbit checkout, but data for specific areas will likely be released sooner.

Day Two

The second day began with updates on a variety of topics of interest including the selection of new Regions of Interest (ROI) for GEDI, the status of the GEDI algorithm theoretical basis documents (ATBDs) and GEDI User Handbook, and discussion of plans for L4 data product processing. The remainder of the day was spent discussing updates on some of the planned applications for GEDI data, once the data become publicly available.

Selecting New Regions of Interest

Ralph Dubayah started the second day of the meeting with a discussion regarding the selection and inclusion of new ROIs that can be targeted through RGT selection and the GEDI pointing system. GEDI will collect science data along the RGTs.

Algorithm Theoretical Basis Documents and User Handbook

The ATBDs and the GEDI user handbook are now in their near-final format. These documents will be published on the GEDI website when the initial GEDI data products are released. The ATBDs contain full algorithm descriptions of each GEDI data product, whereas the user handbook contains a full summary of the mission, status, and data products. Ancillary data product descriptions will also be finalized in the following months by **John Armston**, **Hao Tang**, and **Jamis Bruening** [UMD].

Update on Plans for Level 4 Data Processing

The processing of L4A and L4B biomass data products will commence once the L2A and L2B processing pipelines are finalized. **James Kellner** [Brown University] discussed the development of the footprint-level L4A GEDI data products, wherein the world is stratified into regions—by continental region and/or plant functional type—with footprint biomass estimators selected for each combination of these strata. The prelaunch calibration of the footprint biomass estimators is currently being finalized, with each estimator using one to four explanatory variables to estimate Above Ground Biomass Density (AGBD). Models are tested for their geographic transferability to ensure that accurate predictions can be made outside of the areas in which the model was calibrated. **Sean Healey** and **Paul Patterson** [both from the U.S. Forest Service] updated the science team on the development of the gridded L4B GEDI biomass product. The L4B product will be created using a combination of hybrid and hierarchical model-based methodologies that have been published in peer-reviewed journals. The GEDI along-track biomass estimates are treated as cluster samples and the uncertainty in both sampling and footprint-level biomass estimates are accounted for. **Jamis Bruening** and **John Armston** have been working on an urban mask that can be used to filter biomass estimates in order to limit confusion between buildings and trees, which can artificially inflate biomass values.

GEDI Applications Presentations

Data from GEDI can be used for many data applications. For some of these applications, demonstrative products are created by the GEDI team such as shown in the table of data products on page 29.

George Hurt [UMD] and his team have been working to prepare the Ecosystem Demography (ED) model to ingest data for model initialization. The intent is to use GEDI data to initialize ED and enable global carbon modeling at 1-km resolution.

Matt Hansen [UMD] and his team are working toward implementing canopy height maps created from GEDI footprint-level measurements and Landsat/Sentinel imagery, along with quantifying biomass change using the amount of time that has passed since the forest disturbance from a 30-year disturbance history map.

Scott Goetz and **Patrick Jantz** [both from Northern Arizona University (NAU)] have used ICESat waveforms over Colombia to calculate groups of distinct forest structure for purposes of habitat delineation. This work has been done in preparation for the higher-resolution GEDI data. **Patrick Burns** [NAU] is using canopy structure information from simulated GEDI waveforms to model the distribution of bird species found in the forests of northern California.

Lola Fatoyinbo [GSFC] and **Wenlu Qi** [UMD] continue the collaboration with the Deutsches Zentrum für Luft- und Raumfahrt (DLR) [German Aerospace Center] to explore the fusion of GEDI and TanDEM-X[3] products to create higher resolution height and biomass maps—see Figure on page 28. The initial exploratory collaboration has now been expanded and finalized to produce global, high-resolution [25-100-m (~82-328-ft)] maps of canopy and biomass. Work is underway to build out the required computing infrastructure and to finalize algorithmic approaches.

Peter Boucher and **Crystal Schaaf** [both at University of Massachusetts, Boston] are studying the use of simulated GEDI data to locate the impacts of an invasive insect (the hemlock woolly adelgid) on canopy structure in New England. They found that full-waveform lidar data are particularly efficient for early detection of the insect, as it first affects the mid-canopy layer, making the identification of early signs of destruction difficult to detect with remote spectral imagery.

John Armston reported on the continued development of the GEDI Forest Structure and Biomass Database and highlighted how the collection of post-launch LVIS full-waveform lidar data in Costa Rica and in the U.S. can be used to validate the incoming GEDI waveforms. Additionally, **James Kellner** collected drone lidar data in La Selva, Costa Rica, during a GEDI overpass. Resulting data can be used to validate the GEDI simulator created by **Steven Hancock** [University of Edinburgh]. This simulator has been used to develop the GEDI biomass algorithms.

[3] TanDEM-X stands for TerraSAR-X (or TSX-1) add-on for Digital Elevation Measurement, which is a high-resolution interferometric synthetic aperture radar (SAR) mission. TanDEM-X is a joint venture of DLR and two private German companies via a public–private partnership consortium.

Day Three

The third day started with a plenary discussion (led by the PI) on the topics of science publications and reducing the validation of GEDI waveforms, and closed with summaries from each breakout session.

Closing Plenary

Ralph Dubayah led a discussion of the data release logistics. He also discussed publication of several peer-reviewed manuscripts explaining the data processing methods and/or describing the results obtained using the first GEDI data products. Another important point of discussion was the colocation tool, that has been created and tested primarily by **Steven Hancock** and **Carlos Silva** [UMD]. The tool optimizes the correlation of LVIS or simulated GEDI waveforms with real GEDI waveforms. This is of paramount importance in understanding GEDI's geolocation accuracy and the validation of the GEDI canopy structure information.

Laura Duncanson [UMD] informed the GEDI science team that the Committee on Earth Observation Satellites' (CEOS) Land Product Validation (LPV) Biomass Protocol is in the early stage of being written. Drafts will soon be circulated for internal review, after which external review and publication will take place. When completed, this protocol will be a good practice guide to the biomass model calibration and product validation at a global (or near global) scale. **David Minor** [UMD] and Duncanson have also advanced on the development of the Multi-Mission Analysis and Algorithm Platform (MAAP), a growing publicly available dataset of calibration and validation datasets for upcoming spaceborne biomass missions.

Breakout Sessions

The meeting closed with breakout sessions in which the data processing and release plan were detailed by the data product leads, the GEDI handbook was edited for publication upon data release in late fall 2019 by various members of the science team, and a public outreach plan was drafted under guidance of **Ralph Dubayah**.

Conclusion

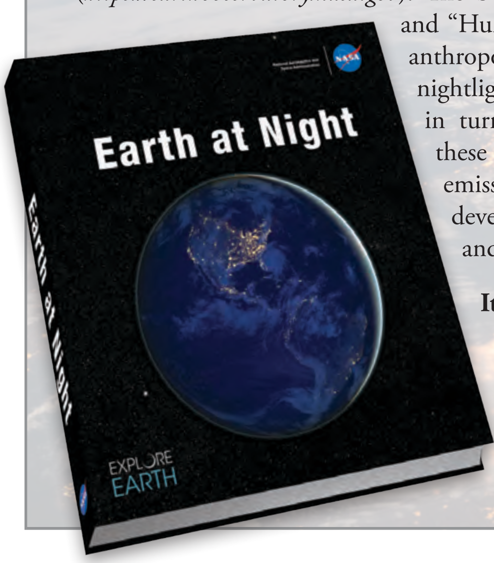
The GEDI Science Team Meeting resulted in a common understanding of the current status of the GEDI mission and a detailed plan for the activities of the next six months. Most importantly, the GEDI data processing pipelines were discussed in detail, the data processing schedule was finalized, and the first data products were reviewed by the GEDI team. The next GEDI Science Team Meeting will be scheduled for spring 2020. ■

NASA's New *Earth at Night* Book Reveals Our Planet in a Whole New Light

An exploration of Earth at night and how and why scientists study our planet during nighttime hours.

Even enshrouded in darkness, our planet has dazzling stories to tell! NASA's new 200-page book shows how humans and natural phenomena light up the darkness, and how and why scientists have observed Earth's nightlights for more than four decades using both their own eyes and spaceborne instruments.

Many of the images and captions used in the book originally appeared on NASA's *Earth Observatory* website (*https://earthobservatory.nasa.gov*). The book is divided into two main sections: "Nature's Light Shows" and "Human Light Sources." These sections feature images of natural and anthropogenic light sources respectively. They illustrate how scientists use nightlight data to study our changing planet and how decision makers, in turn, can use the knowledge gained for public benefit. Some of these applications include forecasting a city's energy use and carbon emissions, eradicating energy poverty and fostering sustainable energy development, providing immediate information when disasters strike, and monitoring the effects of conflict and population displacement.



It is an engaging and fascinating story; allow your eyes to adjust to the darkness and enjoy the adventure!

A **free** eBook version of *Earth at Night* can be downloaded at *https://www.nasa.gov/connect/ebooks/earthatnight_detail.html*

NASA Study Shows Human Activities Are Drying Out the Amazon

Esprit Smith, NASA/Jet Propulsion Laboratory, esprit.smith@jpl.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.

A new NASA study shows that over the last 20 years, the atmosphere above the Amazon rainforest—shown in the photo below—has been drying out, increasing the demand for water and leaving ecosystems vulnerable to fires and drought. It also shows that this increase in dryness is primarily the result of human activities.

Aerial view of the Amazon rainforest. **Photo credit**: Marcio Isensee e Sá/Adobe Stock

Scientists at NASA/Jet Propulsion Laboratory (JPL) analyzed decades of ground and satellite data over the Amazon rainforest to track both how much moisture was in the atmosphere and how much moisture was needed to maintain the rainforest system.

"We observed that in the last two decades, there has been a significant increase in dryness in the atmosphere as well as in the atmospheric demand for water above the rainforest," said lead study author, **Armineh Barkhordarian** [JPL]. "In comparing this trend to data from models that estimate climate variability over thousands of years, we determined that the change in atmospheric aridity is well beyond what would be expected from natural climate variability."

So, if it's not natural, what's causing it?

Barkhordarian said that elevated greenhouse gas levels are responsible for approximately half of the increased aridity. The rest is the result of ongoing human activity—most significantly, the burning of forests to clear land for agriculture and grazing. The combination of these activities is causing the Amazon's climate to warm—as illustrated in the **Figure** on page 33.

When a forest burns, it releases particles called *aerosols* into the atmosphere—among them, black carbon, commonly referred to as soot. While bright-colored or translucent aerosols reflect radiation, darker aerosols absorb it. When the black carbon absorbs heat from the sun, it causes the atmosphere to warm; it can also interfere with cloud formation and, consequently, rainfall.

Why it matters: The Amazon is the largest rainforest on Earth. When healthy, it absorbs billions of tons of carbon dioxide (CO_2) a year through photosynthesis—the process plants use to convert CO_2, energy, and water into food. By removing CO_2 from the atmosphere, the Amazon helps to keep temperatures down and regulate climate.

But it's a delicate system that's highly sensitive to drying and warming trends.

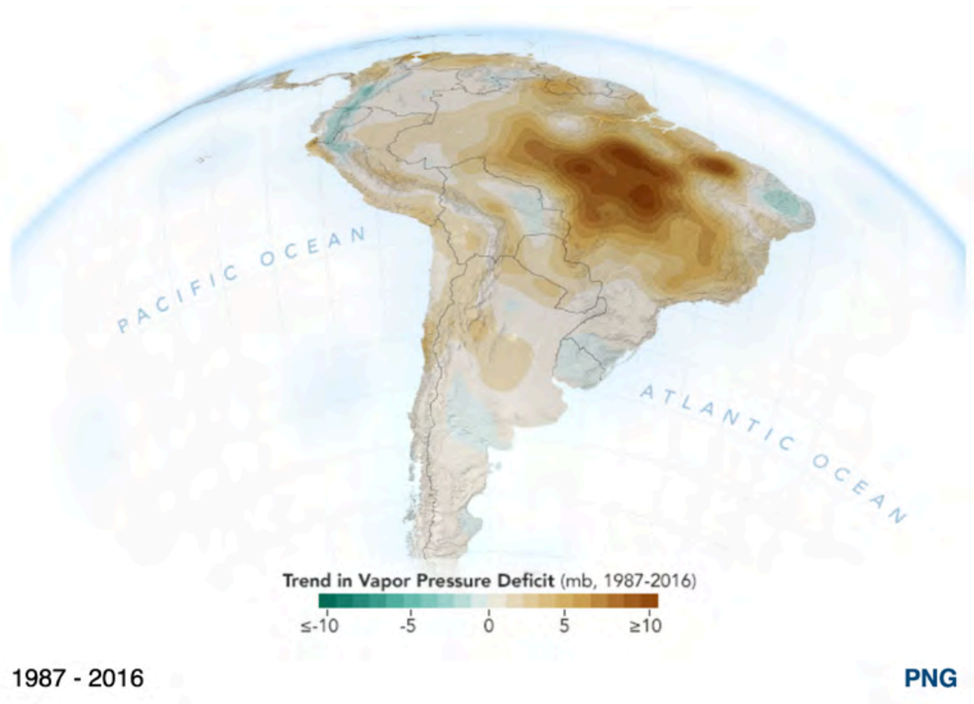


Figure. The map above shows the decline of moisture in the air over South America from 1987 to 2016, particularly across the south and southeastern Amazon, during the dry-season months (August through October). Using data from NASA's Atmospheric Infrared Sounder (AIRS) on the Aqua satellite and other instruments, the researchers calculated the *vapor pressure deficit* (VPD)—the difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated. When VPD increases, the amount of moisture in the air relative to its capacity is reduced and the air is drier. **Credit**: NASA Earth Observatory

Trees and plants need water for photosynthesis and to cool themselves down when they get too warm. They pull in water from the soil through their roots and release water vapor through pores on their leaves into the atmosphere, where it cools the air and eventually rises to form clouds. The clouds produce rain that replenishes the water in the soil, allowing the cycle to continue. Rainforests generate as much as 80% of their own rain, especially during the dry season.

But when this cycle is disrupted by an increase in dry air, for instance, a new cycle is set into motion—one with significant implications, particularly in the southeastern Amazon, where trees can experience more than four to five months of dry season.

"It's a matter of supply and demand. With the increase in temperature and drying of the air above the trees, the trees need to transpire to cool themselves and to add more water vapor into the atmosphere. But the soil doesn't have extra water for the trees to pull in," said study co-author **Sassan Saatchi** [JPL]. "Our study shows that the demand is increasing, the supply is decreasing and if this continues, the forest may no longer be able to sustain itself."

Scientists observed that the most significant and systematic drying of the atmosphere is in the southeast region, where the bulk of deforestation and agricultural expansion is happening. But they also found episodic drying in the northwest Amazon—an area that typically has no dry season. Normally always wet, the northwest has suffered severe droughts over the past two decades, a further indication of the entire forest's vulnerability to increasing temperatures and dry air.

If this trend continues over the long term and the rainforest reaches the point where it can no longer function properly, many of the trees and the species that live within the rainforest ecosystem may not be able to survive. As the trees die, particularly the larger and older ones, they release CO_2 into the atmosphere; and the fewer trees there are, the less CO_2 the Amazon region would be able to absorb—meaning an important element in Earth's climate regulation would essentially be lost.

The study, "A Recent Systematic Increase in Vapor Pressure Deficit Over Tropical South America," was published in *Scientific Reports* (*https://www.nature.com/articles/s41598-019-51857-8*). The science team used data from NASA's Atmospheric Infrared Sounder (AIRS) instrument aboard the Aqua satellite. ■

in the news

2019 Ozone Hole Is the Smallest on Record Since Its Discovery

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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.

Abnormal weather patterns in the upper atmosphere over Antarctica dramatically limited ozone depletion in September and October 2019, resulting in the smallest ozone hole observed since 1982, NASA and National Oceanic and Atmospheric Administration (NOAA) scientists have reported.

The annual ozone hole reached its peak extent of 6.3 million mi^2 (16.4 million km^2) on September 8—see **Figure** below—and then shrank to less than 3.9 million mi^2 (10 million km^2) for the remainder of September and October, according to NASA and NOAA satellite measurements. For comparison, during years with "normal" weather conditions, the ozone hole typically grows to a maximum area of ~8 million mi^2 (~20.7 million km^2) in late September or early October.

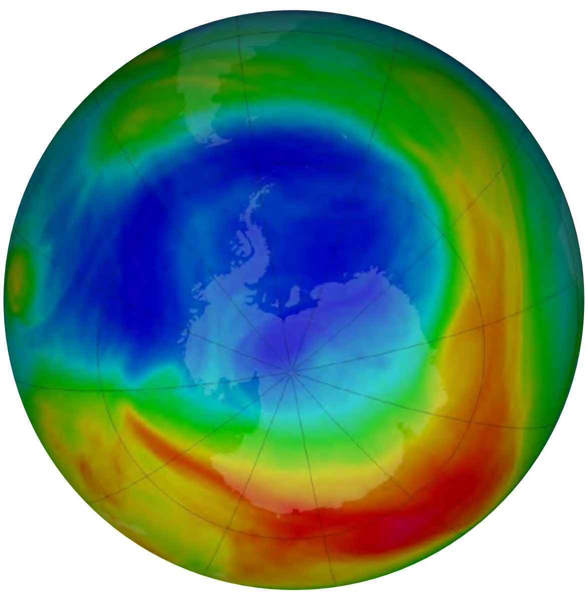

Figure. The 2019 ozone hole reached its peak extent of 6.3 million mi^2 (16.4 million km^2) on September 8. Abnormal weather patterns in the upper atmosphere over Antarctica dramatically limited ozone depletion this year, making this year's areal extent the smallest on record since the ozone hole was discovered in 1982. **Image credit:** NASA

"It's great news for ozone in the Southern Hemisphere," said **Paul Newman** [NASA's Goddard Space Flight Center (GSFC)—*Chief Scientist for Earth Sciences*]. "But it's important to recognize that what we're seeing this year is due to warmer stratospheric temperatures. It's not a sign that atmospheric ozone is suddenly on a fast track to recovery."

Ozone is a highly reactive molecule comprised of three oxygen atoms that occurs naturally in small amounts. Roughly 7 to 25 mi (11 to 40 km) above Earth's surface, in a layer of the atmosphere called the stratosphere, the ozone layer is a sunscreen, shielding the planet from potentially harmful ultraviolet radiation that can cause skin cancer and cataracts, suppress immune systems, and also damage plants.

The Antarctic ozone hole forms during the Southern Hemisphere's late winter as the returning sun's rays start ozone-depleting reactions. These reactions involve chemically active forms of chlorine and bromine derived from man-made compounds. The chemistry that leads to their formation involves chemical reactions that occur on the surfaces of cloud particles that form in cold stratospheric layers, leading ultimately to runaway reactions that destroy ozone molecules. In warmer temperatures, fewer polar stratospheric clouds form and they don't persist as long, limiting the ozone-depletion process.

NASA and NOAA monitor the ozone hole via complementary instrumental methods.

Satellites, including NASA's Aura satellite, the NASA–NOAA Suomi National Polar-orbiting Partnership (NPP) satellite, and the NOAA-20 satellite, measure ozone from space. The Aura satellite's Microwave Limb Sounder also estimates levels of ozone-destroying chlorine in the stratosphere.

At the South Pole, NOAA staff launch weather balloons carrying ozone-measuring "sondes," which directly sample ozone levels vertically through the atmosphere—a time lapse of a sonde launch is shown in the photo on page 35.[1] Most years, at least some levels of the stratosphere, the region of the upper atmosphere where the largest amounts of ozone are normally found, are completely devoid of ozone.

[1]Ozonesonde launches are not limited to the Antarctic. To read about a network of sonde launches in the tropics and subtropics, see "SHADOZ at 20 Years: Achievements of a Strategic Ozonesonde Network" in the September–October 2019 issue of *The Earth Observer* [**Volume 31**, **Issue 5**, pp. 4-15—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Sep_Oct_2019_color_508.pdf#page=4*].

This time-lapse photo from September 9, 2019, shows the flight path of an ozonesonde as it rises into the atmosphere over the Amundsen–Scott South Pole Station. Scientists release these balloon-borne sensors to measure the thickness of the protective ozone layer high up in the atmosphere. **Photo credit**: Robert Schwarz/University of Minnesota

However, according to **Bryan Johnson** [NOAA's Earth System Research Laboratory], "This year, ozonesonde measurements at the South Pole did not show any portions of the atmosphere where ozone was completely depleted."

While seeing such a small ozone hole is unusual, it is not without precedent. In fact, this is the third time in the last 40 years that weather systems have caused warm temperatures that limit ozone depletion, said **Susan Strahan** [GSFC /Universities Space Research Association]. Similar weather patterns in the Antarctic stratosphere in September 1988 and 2002 also produced atypically small ozone holes, she said.

"It's a rare event that we're still trying to understand," said Strahan. "If the warming hadn't happened, we'd likely be looking at a much more typical ozone hole."

There is no identified connection between the occurrence of these unique patterns and changes in climate.

The weather systems that disrupted the 2019 ozone hole are typically modest in September, but this year they were unusually strong, dramatically warming the Antarctic's stratosphere during the pivotal time for ozone destruction. At an altitude of about 12 mi (20 km), temperatures during September were 29 °F (16 °C) warmer than average, the warmest in the 40-year historical record for September by a wide margin. In addition, these weather systems also weakened the Antarctic polar vortex, knocking it off its normal center over the South Pole and reducing the strong September jet stream around Antarctica from a mean speed of 161 mph (261 kph) to a speed of 67 mph (109 kph). This slowing vortex rotation allowed air to sink in the lower stratosphere where ozone depletion occurs, where it had two impacts.

First, the sinking warmed the Antarctic lower stratosphere, minimizing the formation and persistence of the polar stratospheric clouds that are a main ingredient in the ozone-destroying process. Second, the strong weather systems brought ozone-rich air from higher latitudes elsewhere in the Southern Hemisphere to the area above the Antarctic ozone hole. These two effects led to much higher than normal ozone levels over Antarctica compared to ozone hole conditions usually present since the mid 1980s.

As of October 16, 2019, the ozone hole above Antarctica remained small but stable and was expected to gradually dissipate in the coming weeks.

Antarctic ozone slowly decreased in the 1970s, with large seasonal ozone deficits appearing in the early 1980s. Researchers at the British Antarctic Survey discovered the ozone hole in 1985, and NASA's satellite estimates of total column ozone from the Total Ozone Mapping Spectrometer confirmed the 1985 event, revealing the ozone hole's continental scale.

Thirty-two years ago, the international community signed the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. This agreement regulated the consumption and production of ozone-depleting compounds. 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. The ozone hole over Antarctica is expected to gradually become less severe as *chlorofluorocarbons*—banned chlorine-containing synthetic compounds that were once frequently used as coolants—continue to decline. Scientists expect the Antarctic ozone to recover back to the 1980 level around 2070.

To learn more about NOAA and NASA efforts to monitor the ozone and ozone-depleting gases, visit:

- *https://ozonewatch.gsfc.nasa.gov*
- *https://www.cpc.ncep.noaa.gov/products/stratosphere/polar/polar.shtml*
- *https://www.esrl.noaa.gov/gmd/dv/spo_oz* ■

NASA Views California's Kincade Fire from Space

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EDITOR'S NOTE: This story combines information and imagery from two primary sources. For more information, visit: *https://earthobservatory.nasa.gov/images/145805/kincade-fire-grows-overnight* and *https://www.nasa.gov/feature/jpl/californias-kincade-fire-burn-scar-seen-from-space.*

Residents of California live with the ever-present threat of wildfires, particularly from late spring until near the end of the calendar year, when winter rains normally arrive. The single most destructive fire for 2019 (as of this writing) has been the Kincade Fire, which struck in the heart of California wine country (Sonoma County) in late October and lasted into early November.

The fire began on October 23, and spread rapidly due to the combination of high winds [some gusts as high as 70 mph (113 kph)] and low humidity. It was finally declared contained on November 6, after it scorched 120 mi^2 (310 km^2, 77,758 acres), displaced more than 180,000 residents, and damaged or destroyed more than 400 structures. While four firefighters were injured fighting the blaze, remarkably no one was killed. The cause of the fire is unconfirmed.

NASA satellites are useful tools for studying fires. Observing from the vantage point of space, satellites can pinpoint the locations of active fires, and track the resulting plumes of smoke. Particularly in remote areas, satellites are often the first to alert officials to the presence of a wildfire. The images and data they beam back from space can be analyzed to help inform decision makers about the progress of fires and, after the flames are extinguished, to study the impact they had on ecosystems in the fire's path. The two images shown here give two examples of how NASA satellite are used to study fires: to monitor the growth of the fire and to observe the burn scar left behind.

The first image—shown in **Figure 1**—comes from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) satellite. It was obtained in the early afternoon of October 29, when the Kincade Fire was only about 30% contained. At that time the fire was still growing, with much of the new activity on the eastern side of the fire.

The second image—shown in **Figure 2**—comes from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument onboard NASA's Terra satellite. Whereas VIIRS places the Kindcade Fire in its broader context, ASTER focuses in on the area most directly impacted by the fire, and gives an idea of the extent of the damage. Thousands of scorched acres are visible in this image, which was obtained at 11:01 AM Pacific Standard Time (2:01 PM Eastern Standard Time) on November 3, 2019—at which point the blaze was about 80% contained. The burned area appears dark gray in ASTER's visible channels. *Hotspots*, where the fire is still smoldering, appear as white dots in ASTER's heat-sensing, thermal infrared channels. The town of Healdsburg, CA, is in the center of the image, which covers an area of about 24 x 25 mi (39 x 40 km).

Figure 1. This image, created using data from VIIRS onboard Suomi NPP, shows the Kincade Fire burning on October 29, 2019. **Image credit:** NASA Earth Observatory

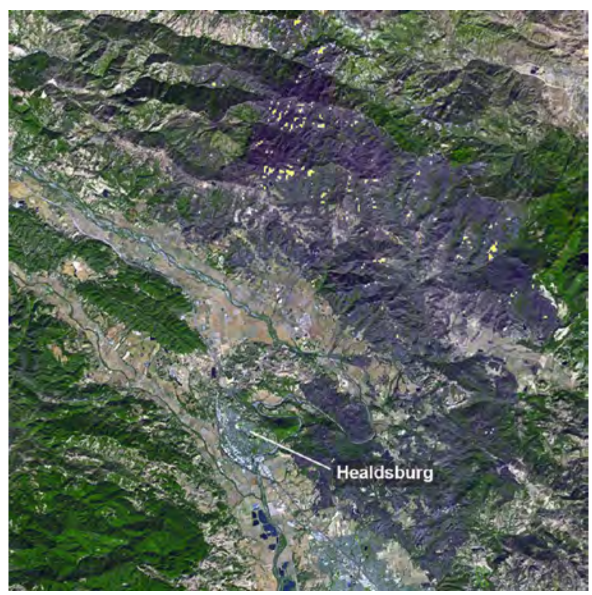


Figure 2. A large burn scar (darker area) can be seen from space where the Kincade Fire has burned through Sonoma County, CA. The image was taken on November 3, 2019, by the ASTER instrument aboard NASA's Terra satellite. **Image credit:** NASA/Jet Propulsion Laboratory-Caltech

NASA Earth Science in the News

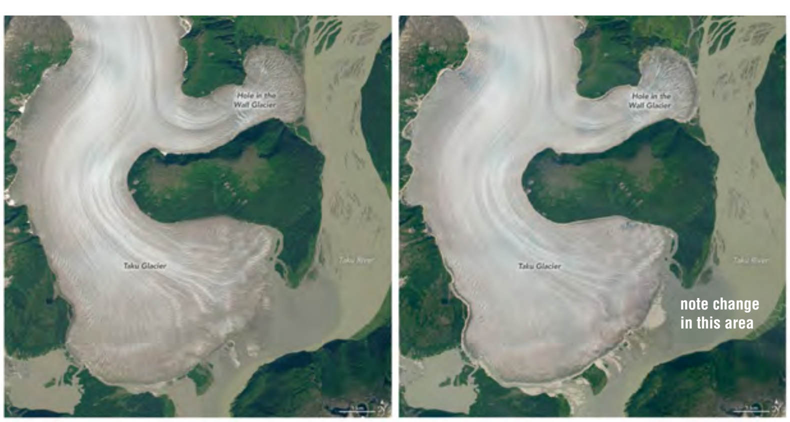
Samson Reiny, NASA's Goddard Space Flight Center, Earth Science News Team, samson.k.reiny@nasa.gov

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

The World's Thickest Mountain Glacier Is Finally Melting, and Climate Change Is 100% to Blame, November 5, *livescience.com*. Massive and meaty, the Taku Glacier in Alaska's Juneau Icefield was a poster child for the frozen places holding their own against climate change. As the largest of 20 major glaciers in the region and one of the single thickest glaciers in the world (it measures 4860 ft, or 1480 m, from surface to floor), Taku had been demonstrably gaining mass and spreading farther into the nearby Taku River for nearly half a century, while all of its neighboring glaciers shrank. Now, it appears those glory days are over. In a new pair of satellite photos shared by NASA's Earth Observatory, the slow decline of Taku Glacier has finally become apparent—see **Figure 1**. Taken in August 2014 and August 2019, the photos show the icy platforms where the glacier meets the river retreating for the first time since scientists began studying Taku in 1946. While the shrinkage is subtle for now, the results are nonetheless shocking. According to glaciologist **Mauri Pelto** [Nichols College, Massachusetts], who has studied the Juneau Icefield for three decades, Taku was predicted to continue advancing for the rest of the century. Not only have these signs of retreat arrived about 80 years ahead of schedule, Pelto said, but they also snuff a symbolic flicker of hope in the race to understand climate change. Of 250 mountain (or *alpine*) glaciers that Pelto has studied around the world, Taku was the only one that hadn't clearly started to retreat. "This is a big deal for me because I had this one glacier I could hold on to," Pelto told NASA. "But not anymore. This makes the score climate change: 250 and alpine glaciers: 0."

*__NASA Says Humans Are Drying Out the Amazon and Increasing the Threat of Fires__, November 7, *cnn.com*. A newly-released NASA study has found the atmosphere over the Amazon rainforest in South America has been drying out over the past 20 years—and that human activity is the primary cause. Scientists at NASA/Jet Propulsion Laboratory (JPL) looked at decades' worth of ground and satellite data to track the amount of moisture in the air over the Amazon and the amount of moisture needed to maintain the rainforest system. "We observed that in the last two decades, there has been a significant increase in dryness in the atmosphere as well as in the atmospheric demand for water above the rainforest," **Armineh Barkhordarian** [JPL] said in a statement. She is the lead author of the study, which was published last month in the journal *Scientific Reports*.[1] Barkhordarian's team compared the data to climate models that estimated climate variation over thousands of years, and in her words, "We determined that the change in atmospheric aridity is well beyond what would be expected from natural climate variability." The study found that the *vapor pressure deficit*, which measures the difference between the amount of air that is in the atmosphere and the maximum amount of moisture it can hold, has gone up, particularly across the south and southeastern Amazon, during the dry season months of August through October. Elevated greenhouse gas levels are responsible for about half of the increased aridity, according to Barkhordarian. Human actions such as burning forests

[1] To read the paper, visit *https://www.nature.com/articles/s41598-019-51857-8*.



August 20, 2014 **August 9, 2019**

Figure 1. These natural-color images show the Taku Glacier on August 20, 2014, and August 9, 2019. The images were acquired by the Operational Land Imager on Landsat 8. Though subtle, the changes are most visible at the boundaries between the glacier and river. **Credit:** NASA Earth Observatory

to clear land for farming and grazing are responsible for the rest of the change.

NASA Flew Gas Detectors Above California, Found 'Super Emitters,' November 6, *bloomberg.com*. Over the course of three years, NASA flew a plane carrying gas-imaging equipment above California and made a discovery that surprised even the state's own environmental agencies: A handful of operations are responsible for the vast majority of methane emissions. In a report published in *Nature*,[2] scientists estimated that 10% of the places releasing methane—including landfills, natural gas facilities, and dairy farms—are responsible for more than half of the state's total emissions. And a fraction of the 272,000 sources surveyed—just 0.2%—account for as much as 46%. The report doesn't identify these so-called "super emitters," but notes that landfills give off more methane than any other source in the state. NASA's equipment found that a subset of these landfills were the largest emitters in California and exhibited "persistent anomalous activity." The study marks the first time anyone has ever carried out a systematic survey across California of methane—a greenhouse gas that's 25 times more potent than carbon dioxide in trapping heat and contributing to global warming. The release of methane has been a continual challenge for California, which has some of the most aggressive goals in the nation for curbing emissions and slowing the impacts of climate change. NASA's aircraft made dozens of flights across 10,000 mi^2 (25,900 km^2) from 2016 through 2018. Landfills accounted for 41% of the source emissions it identified, manure management 26%, and oil and gas operations 26%.

[*]**South Pole's Ozone Hole Shrinks to Smallest since Discovery**, October 22, *apnews.com*. The ozone hole near the south pole this year is the smallest since it was discovered—but it is more due to freakish Antarctic weather than efforts to cut down on pollution, NASA reported.This fall, the average hole in Earth's protective ozone layer is 3.6 million mi^2 (9.3 million km^2). That's down from a peak of 10.3 million mi^2 (26.6 million km^2) in 2006. This year's hole is even smaller than the one first discovered in 1985. "That's really good news," NASA scientist **Paul Newman** [NASA's Goddard Space Flight Center] said. "That means more ozone over the hemisphere, less ultraviolet radiation at the surface." Earth's ozone layer shields life on the surface from harmful solar radiation, but man-made chlorine compounds that can last in the air for 100 years nibble at the ozone, creating thinning and a gap over the Southern Hemisphere. The hole reaches its peak in September and October and disappears by late December until the next spring in the Southern Hemisphere. The 1987 international Montreal Protocol—the only United Nations treaty ratified by every country on Earth—banned many of the chlorine compounds used in refrigerants and aerosols. The ban resulted in a slightly smaller ozone hole in recent years, but this year's dramatic shrinking isn't from those efforts, Newman said. "It's just a fluke of the weather," said atmospheric scientist **Brian Toon** [University of Colorado]. Chlorine in the air needs cold temperatures in the stratosphere and clouds to be converted into a form of the chemical that eats ozone, Newman said. The clouds go away when it warms up. But this September and October, the southern *polar vortex*—which just like the northern one is a swirl of cold high-speed winds around the pole—started to break down. At 12 mi (20 km) high in the atmosphere, temperatures were 29 °F (16 °C) warmer than average. Winds dropped from a normal 161 mph to about 67 mph (259 kph to 108 kph), NASA reported. This is something that happens on occasion, occurring in 1988 and 2002, but not this extreme, Newman said.

Our Planet Is Having Its Second-Warmest Year on Record in 2019, October 16, *washingtonpost.com*. This year there is no powerful El Niño lurking in the tropical Pacific Ocean to add extra heat to the ocean and atmosphere, but the relentlessly accumulating greenhouse gases in the atmosphere, plus natural climate variability, have helped to push 2019 toward record warmth anyway. Through September, which the National Oceanic and Atmospheric Administration (NOAA) reported was the hottest such month on record globally, the year ranks as the second warmest since instrument records began in the late nineteenth century. The odds slightly favor that 2019 will end up being the second-warmest year—coming in behind 2016. However, it is possible it will slip slightly in ranking to third or fourth warmest, according to NOAA projections. Matching analyses by the Copernicus Climate Change Service and NASA, NOAA found September featured exceptional warmth worldwide, particularly in North America and the Northern Hemisphere overall.

[*]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**.* ■

[2] To read the paper, visit *https://www.nature.com/articles/s41586-019-1720-3*.

Earth Science Meeting and Workshop Calendar

NASA Community

January 27–31, 2020
2020 Sun-Climate Symposium, Tucson, AZ
http://lasp.colorado.edu/home/sorce/news-events/meetings/2020-scs

May 11–14, 2020
ABoVE Science Team Meeting, Fairbanks, AK
https://above.nasa.gov/index.html

Global Science Community

January 12–16, 2020
American Meteorological Society 100th Annual Meeting, Boston, MA
https://annual.ametsoc.org/2020

February 16–21, 2020
Ocean Sciences Meeting, San Diego, CA
https://www.agu.org/Ocean-Sciences-Meeting

April 25–26, 2020
USA Science and Engineering Festival, Washington, DC
https://usasciencefestival.org/2020-expo

May 3–8, 2020
EGU General Assembly 2020, Vienna, Austria
https://www.egu2020.eu

May 24–28, 2020
JpGU-AGU Joint Meeting, Chiba, Japan
http://www.jpgu.org/meeting_e2020

June 24–July 4, 2020
Asia Oceania Geosciences Society, Hongcheon, South Korea
http://www.asiaoceania.org/aogs2020/public.asp?page=home.html

August 15–22 2020
43rd Scientific Assembly of the Committee on Space Research and Associated Events COSPAR 2020, Sydney, Australia
https://www.cospar2020.org/index.php

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Articles, contributions to the meeting calendar, and suggestions are welcomed. Contributions to the calendars should contain location, person to contact, telephone number, and e-mail address. Newsletter content is due on the weekday closest to the 1st of the month preceding the publication—e.g., December 1 for the January–February issue; February 1 for March–April, and so on.

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