Thirty Years Reporting on NASA's Earth Science Program

The Earth Observer

National Aeronautics and Space Administration

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Editor's Corner

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EOS Senior Project Scientist

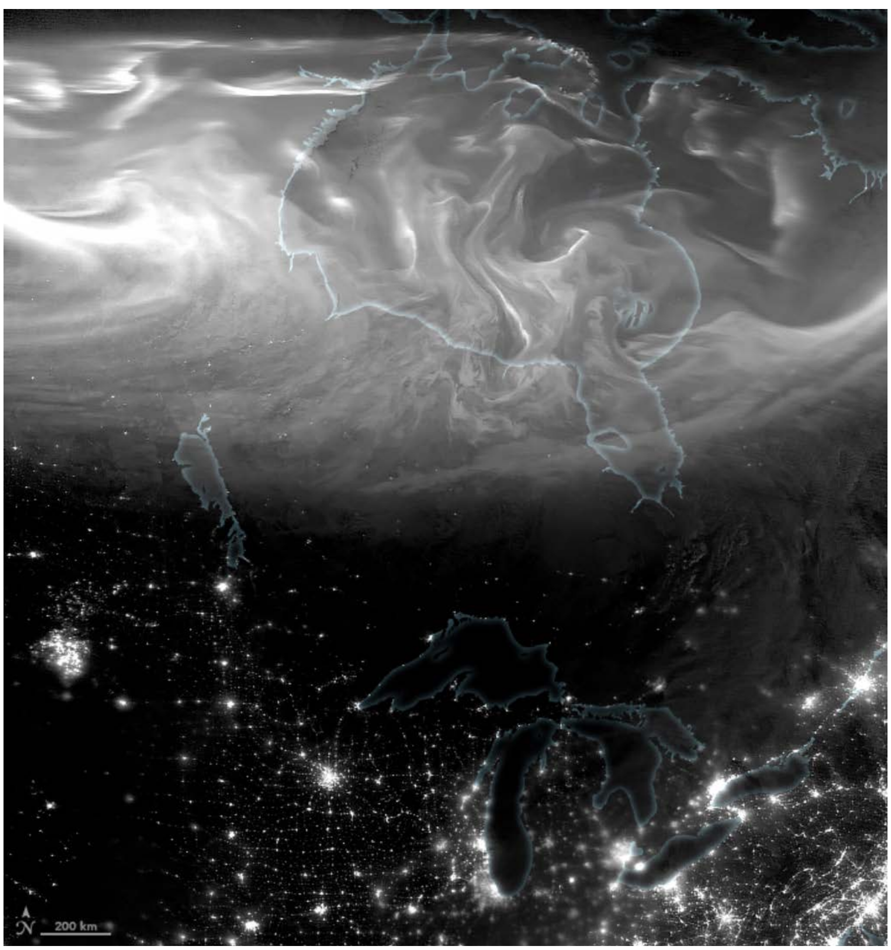
This issue of *The Earth Observer* marks the thirtieth anniversary of the publication of our first issue (March 1989)—shortly after the official beginning of NASA's Earth Observing System (EOS) Program. At that time, when the Internet was still in its infancy, print media was the best way to get the word out about the program, meetings, results, announcements, and the like to hundreds of interested researchers across the country and the world. Enter *The Earth Observer*!

Times have certainly changed since those early days, with digital media now allowing for instantaneous communication. Nevertheless, *The Earth Observer* has adapted over the years, maintaining its role for three decades. It is well known and respected throughout the global Earth science community, with around 5300 subscribers (including both print and digital, the latter being part of our 'Go Green' campaign)[1] around the world at last count. Now in **Volume 31**, the newsletter continues to live out the mission it had from its inception: to *report timely news from NASA's Earth Science Program*. The three-decade legacy is a tribute to the contributors and editorial staff who work hard to produce each issue—including the current one, which features a new thirtieth anniversary masthead and tagline.

On page 4 of this issue, our Executive Editor, **Alan Ward**, offers his perspective on the publication's evolution over the time he has been involved—which encompasses nearly two-thirds of *The Earth Observer*'s history.

[1] Any who are interested can opt to forego receiving the print issue. See back cover for details on how to "Go Green."

continued on page 2



NASA's *Earth Observatory* (EO) website (*https://earthobservatory.nasa.gov*) will celebrate its twentieth anniversary on April 29, 2019. Not unlike *The Earth Observer*, which celebrated its thirtieth anniversary in March 2019, EO was intended to help improve communications between Earth scientists and the general public. These two communication platforms work together to report NASA Earth Science. Images and stories originally published on the EO website are sometimes printed in the newsletter. An example is shown here. On March 28, 2019, a stunning *aurora borealis*—commonly known as the Northern Lights—made an appearance over Hudson Bay in Canada. The Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership satellite acquired this nighttime image of the dancing lights over North America. VIIRS has a *day-night band* that detects city lights and other nighttime signals such as auroras, airglow, and reflected moonlight. In this image, the sensor detected the visible light emissions that occurred when energetic particles rained down from Earth's magnetosphere and into the gases of the upper atmosphere. **Credit:** NASA's Earth Observatory

In This Issue

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

On a related note, the *Earth Observatory* website (*https://earthobservatory.nasa.gov*) celebrates its twentieth anniversary on April 29, 2019. The website was launched in anticipation of the Terra launch (which took place in December 1999).[2] The site was intended to improve communication between Earth scientists and the general public, taking advantage of Internet technologies, which were rapidly emerging at that time. Over the past two decades, it has become an outstanding platform for presenting compelling Earth science images and stories in ways the public and mainstream media can easily understand. The site has grown considerably since it began, becoming one of NASA's most popular websites. Its longevity and growth are due to the many dedicated individuals who have worked to produce content for the site over the years. A sincere thank you to the *Earth Observatory* team, past and present, for a remarkable job. *The Earth Observer* plans a more detailed feature article on the activities related to the *Earth Observatory*'s twentieth anniversary later this year.

These milestone anniversaries for *The Earth Observer* and *Earth Observatory* come during a season of milestones for NASA. Last year was the Agency's sixtieth anniversary, and also the sixtieth anniversary of the launch of Explorer 1—the first satellite launched by the U.S. This year the milestones continue. July will mark the fiftieth anniversary of the Apollo 11 Moon landing, and more specific to the realm of Earth science, December will mark the twentieth anniversary of the launch of EOS Terra.

This issue contains an article on another sixtieth anniversary milestone that, while somewhat lesser known, was foundational to the evolution of Earth science investigations as we know them today—the launch on February 17, 1959 of Vanguard II, which was the first meteorological satellite. The mission opened the pathway for the development of the early TIROS series of meteorological satellites, which was then followed by the Nimbus Program, which in turn led to the development of current high-performance satellites and instruments capable of observing Earth as a system (e.g., EOS). Vanguard's history is more than a story of satellite and rocket hardware development, however. It is also a human drama, as it encompasses the successes and failures of the efforts of scientists and engineers who envisioned this new frontier. The story involves national politics, budget uncertainties, military service rivalries, technological challenges, and scientific competition. For those curious to know more, turn to page 7 of this issue to read the story.

Even as we celebrate our past history, NASA's Earth Science Division (ESD) must have a strong leadership team in place to guide our activities and ensure the achievement of future milestones. **Michael Freilich**, who had been the Director of the ESD since 2006, officially retired at the end of February.[3] A search to find Freilich's successor did not result in a selection. **Thomas Zurbuchen**, Associate Administrator for the Science Mission Directorate, noted that this is an important period of time when a strong team needs to be in place to implement the 2017 Earth Science Decadal Survey recommendations. In approximately one year, the call for candidates will be reopened. In

[2] See "NASA Unveils The 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] Freilich's retirement was announced in the Editorial of the September–October 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 5**, p. 3]. His accomplishments during his tenure as Director of the Earth Science Division were summarized in *https://science.nasa.gov/news-articles/nasa-earth-science-director-announces-retirement*.

the meantime, **Sandra Cauffman**, the ESD's Deputy Director since May 2016, will continue to serve as Acting ESD Director. In addition, **Paula Bontempi** has been appointed to serve as Acting Deputy ESD Director. At ESD since 2003, Bontempi has a background in ocean biology, biogeochemistry, and carbon cycle science, and is the program scientist for MODIS (Terra and Aqua), Suomi NPP, and PACE. My congratulations, and great appreciation, to Cauffman and Bontempi for taking on these roles in the coming year.

Some of our Earth-observing satellite missions achieve milestones of longevity, thereby ensuring continuity of crucial climate data records. One recent example is the Solar Radiation and Climate Experiment (SORCE), which marked the sixteenth anniversary of its launch in January 2019. Considering that the SORCE prime mission ended in 2008 and had to overcome technical challenges related to a failed reaction wheel, failed star tracker, and diminished battery power, it is nothing short of remarkable that SORCE survived long enough to overlap by more than a year with the Total and Spectral Solar Irradiance Sensor-1 (TSIS-1), which launched in 2017.

SORCE has maintained a *Day-only Operations* mode since 2014, essentially shutting down during each orbit's eclipse, only to awaken again when its solar panels are illuminated at every sunrise. In the same year, TSIS-1 was approved to fly on the ISS after several years of uncertainty following reconfigurations of the multi-agency NPOESS and JPSS programs. Once the decision to fly on ISS was made, NASA, NOAA and the Laboratory for Atmospheric and Space Physics at the University of Colorado moved with full purpose to ensure that TSIS-1 would reach orbit by late 2017. Thus, the events of 2014 were critical in maintaining continuity of the solar irradiance climate data record—now in its fifth decade (41 years)! In the event that SORCE did not continue until the launch of TSIS-1, the Total Solar Irradiance Calibration Transfer Experiment (TCTE), flying a SORCE Total Irradiance Monitor (TIM) spare, was launched on the U.S. Air Force's STPSat-3 in 2013 to mitigate a possible gap in total solar irradiance.

The achievements of SORCE are many. One of the major highlights is the establishment of a new value of total solar irradiance: 1361 W/m^2. Another is that SORCE initiated the first daily record of solar spectral irradiance. Moreover, surviving long enough to make the connection to TSIS-1 will be one of its lasting legacies. SORCE will end operations in January 2020, performing final experiments to gain additional insight into the performance of its radiometers. TCTE is planned to operate through the end of June 2019. Meanwhile, TSIS-1 will carry the solar irradiance record into the next decade and, almost simultaneously, into the next solar cycle.

Thus far, the TSIS-1 instruments that measure total and spectral irradiance have been performing as designed. Comparisons between the TSIS-1, SORCE, and TCTE Total Irradiance Monitors (TIM) show that they agree within their respective uncertainties, even though they were calibrated at the component level over a period of 15 years. The performance of the TSIS-1 Spectral Irradiance Monitor (SIM), the first rebuild of the trailblazing SORCE SIM, has been equally impressive. The changes in design of the TSIS-1 SIM, based on lessons learned from SORCE, appear to have achieved the expected results. It will be fascinating to see what these observations reveal during the early phase of the next solar cycle, since uncertainty abounds over how quiet the Sun has become—stay tuned.

The Orbiting Carbon Observatory-3 (OCO-3) is now at Cape Canaveral Air Force Base in Florida getting ready for launch as a part of the Commercial Resupply Service #17 (CRS17) to the ISS, scheduled for April 25, 2019. The OCO-3 payload was trucked from NASA/Jet Propulsion Laboratory in California to NASA's Kennedy Space Center in December 2018. Since then, the spacecraft has been integrated with the SpaceX Dragon Trunk. Now, OCO-3 waits with other cargo for the scheduled launch on the SpaceX Dragon cargo spacecraft on the Falcon 9 rocket. Once deployed on the ISS, the in-orbit checkout (IOC) for OCO-3 is expected to last no more than 90 days. The Level-1b (L1b) product will be released 90 days after the end of IOC and the Level-2 product 90 days after the L1b release.

OCO-3, flying the OCO-2 flight spare instrument, will extend the atmospheric carbon dioxide (CO_2) data record begun by OCO-2 in 2014 into the diurnal domain. The OCO-3 instrument was upgraded to include an agile Pointing Mirror Assembly that allows the instrument to operate in a *snapshot* mode to provide highly dense data coverage over an area of about 50 x 50 mi (80 x 80 km). In addition to CO_2, OCO-3 will provide Solar Induced Chlorophyll Fluorescence (SIF), a byproduct of photosynthesis. OCO-3 will leverage OCO-2 data processing and algorithms.

OCO-3 will be installed on the Japanese Experiment Module-Exposed Facility (JEM-EF) in site #3. Two other NASA instruments are already installed on JEM-EF—ECOSTRESS and GEDI. These three ISS instruments will offer an unprecedented view of ecosystems through near coincident retrievals of evapotranspiration, biomass structure, CO_2, and SIF. ■

Note: List of undefined acronyms from the *Editor's Corner* and the *Table of Contents* can be found on **page 39**.

A Thirtieth Anniversary Reflection from the Executive Editor

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

This issue marks the thirtieth anniversary of the release of the first issue of *The Earth Observer*. This is a remarkable achievement for a NASA publication. It's also a source of immense pride for me, because my entire professional career has been spent supporting work related to NASA Earth Science. More specifically, I've been reviewing content and occasionally contributing articles for *The Earth Observer* since 2001—and since 2006, I have been its executive editor. In that role, I not only edit every word that is published in the newsletter, in consultation with other members of the editorial team (and with the EOS senior project scientist as required), I also plan each issue and develop an overall vision for the publication.

As the executive editor, I wrote this personal perspective, but—clearly!—I don't do what I do alone. As noted above: I have the help of a talented team that currently includes four other editors and a designer. I want to extend kudos to the current team: to **Heather Hanson**, **Mitchell Hobish**, **Ernest Hilsenrath**, **Douglas Bennett**, and **Debbi McLean**; thanks to each of you for all you do![1] This team not only spends many hours researching articles we write ourselves, but many more hours editing contributions from other authors involved in various aspects of NASA Earth Science (e.g., research, applications, education), helping them transform rough drafts into publishable newsletter articles. One contribution that is specific to me is that each *Editor's Corner* must be meticulously researched, written, and fact checked, as it represents an official record of the highlights of NASA Earth Science at that given moment in time from the perspective of the EOS senior project scientist.[2] Much of the work our editorial team does is behind the scene and therefore "transparent" to readers, but without it the bimonthly publication of *The Earth Observer* would not be possible.

In many ways, the publication you hold in your hand—or perhaps you're scrolling through as a *.pdf* file on your computer or tablet—doesn't look much like **Volume 1**, **Issue 1** did in March 1989, shortly after the official beginning of NASA's Earth Observing System (EOS). (The **Figure** on page 5 shows how the look has changed over the years.) As challenging as developing the space flight hardware has always been, there was an equally large logistics issue that needed to be addressed at that time. A huge program involving hundreds of researchers strewn all over the nation—and eventually the globe—was trying to get off the ground, and they needed a means to communicate. The Internet, which we take for granted today, was in its infancy at that time. If you wanted to get the word out about upcoming meetings, results from those meetings, announcements, and the like, print media was still the way to go. Enter *The Earth Observer*!

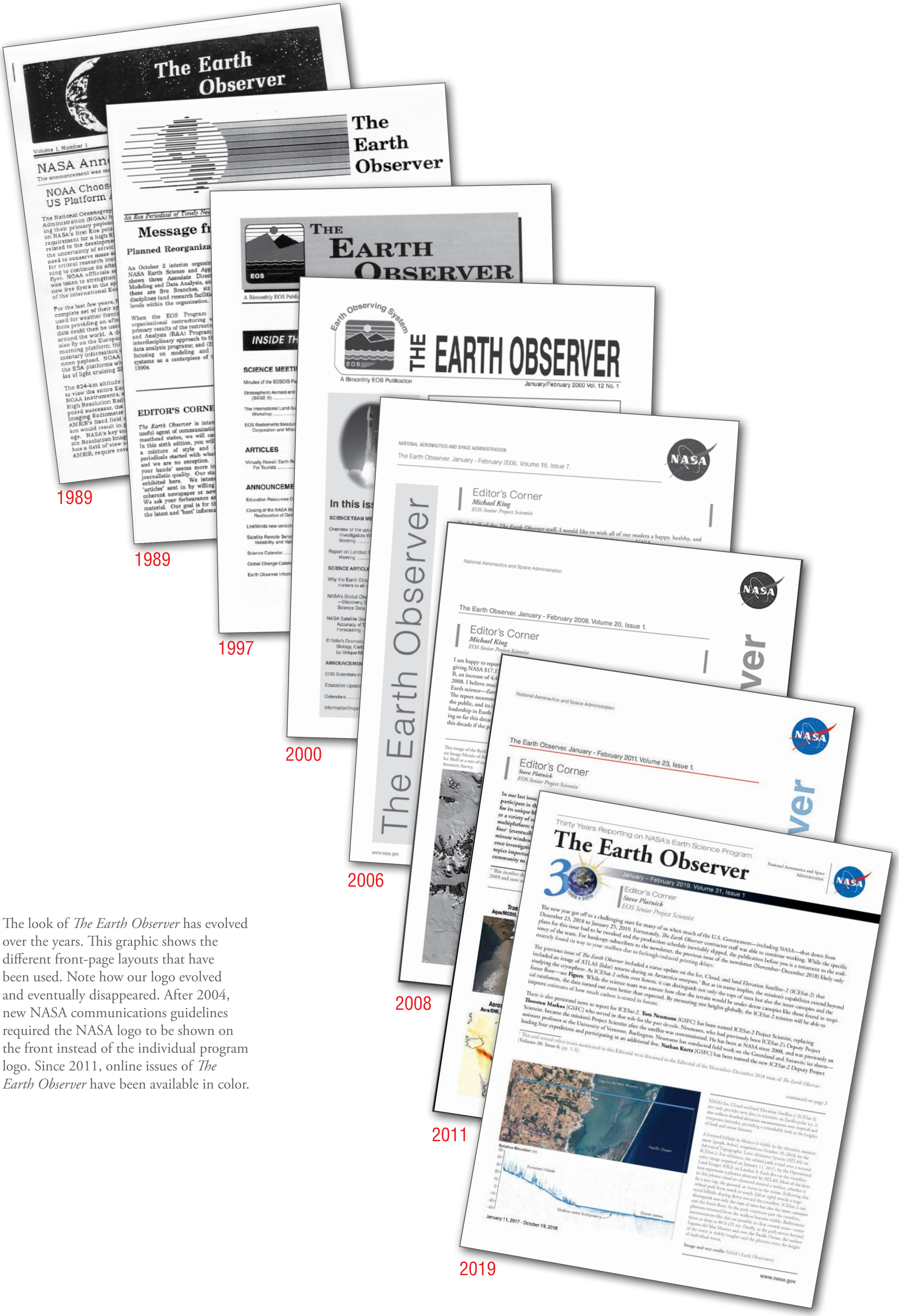
The full story of the intimately interconnected history of EOS and *The Earth Observer* was told in our twenty-fifth anniversary issue and need not be repeated here.[3] Instead, I will offer my own perspective on the publication's evolution over the time I have been involved—which encompasses about two-thirds of the newsletter's history. Thus, the reflections that follow don't necessarily represent NASA's official position on this publication. Rather, they are my own reflections based on my nearly 20 years of working on *The Earth Observer*.

When I made my first contribution to *The Earth Observer* in 2001, EOS was really just getting started. Terra had only launched a couple years earlier and the other flagship missions (Aqua and Aura) had not yet been launched. During my tenure, I've watched the EOS Program come of age. *The Earth Observer* has chronicled the establishment and now graceful aging of NASA's Earth-observing fleet of satellites and airborne and ground-based sensors. We continue to report on NASA Earth Science as we move beyond the Suomi NPP and Joint Polar Satellite System (JPSS) era, and into other endeavors such as Decadal Survey missions, including the Earth Venture element. We've reported on the launches of new (or recently launched) missions along the way, as well as on the remarkable scientific achievements of ongoing ones as, one by one, they exceeded their planned mission lifetime by many years and celebrated a decade or more in orbit. We've also reported on historical satellite missions and programs such as Nimbus and—on page 7 of this issue—Vanguard, which also encompasses Explorer and

[1] It is also fitting to acknowledge **Claire Parkinson** [NASA's Goddard Space Flight Center—*Aqua Project Scientist*], who conducts a final review of most issues prior to printing. We appreciate her ongoing contributions to the quality of *The Earth Observer*.

[2] The editorials (and old newsletters) were a major source of information for the article "A Trip Through Time via the Archives of The Earth Observer," which starts at the beginning in March 1989 and travels forward in time to March–April 2018, making several stops along the way to highlight what was going on at that time. You can read it in the March–April 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 2**, pp. 5-11—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Mar_Apr_2018_color%20508_0.pdf#page=5*].

[3] To read the full story, refer to "The Earth Observer: Twenty-Five Years Telling NASA's Earth Science Story" in the March–April 2014 issue of *The Earth Observer* [**Volume 26**, **Issue 2**, pp. 4-13—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Mar-Apr2014_508finalcolor.pdf#page=4*].



The look of *The Earth Observer* has evolved over the years. This graphic shows the different front-page layouts that have been used. Note how our logo evolved and eventually disappeared. After 2004, new NASA communications guidelines required the NASA logo to be shown on the front instead of the individual program logo. Since 2011, online issues of *The Earth Observer* have been available in color.

TIROS[4] in its story, and the pioneering role that each of these programs played in laying the groundwork for EOS and the missions and programs that build on its rigorous scientific and technical heritage. There have also been articles that look ahead to preview future missions, or give an overview of both current and future Earth observing capabilities from a particular vantage point (e.g., geostationary orbit).

As noted earlier, EOS wasn't simply a satellite-based program. *The Earth Observer* has also reported on complementary ground elements, describing results from field campaigns and other ground-based observation programs over the years. A favorite article of mine was the report on the FIFE and BOREAS campaigns,[5] on the occasion of a meeting held to mark the twenty-ninth anniversary of FIFE'87.[6] I was the lead author on an article we published that combined a historical summary of FIFE and BOREAS with a summary of the meeting. We've also published feature articles on more-general topics, such as Earth Science Mission Operations,[7] responsible for keeping the fleet flying safely, and Earth Science Data Operations,[8] which includes the Earth Observing System Data and Information System (EOSDIS). There have also been shorter tutorial articles published on EOSDIS applications, such as Worldview and the Global Imagery Browse Service, to better inform our readership of the vital supporting role these activities play in providing timely access to Earth science data and information, which is critical to the success of NASA's research endeavors.

Perhaps the series I take the most personal pride in is our *Perspectives on EOS* series, which ran from 2008 through 2011.[9] It really didn't begin with a series in mind; it started with an article that I wrote for the newsletter's twentieth year, and grew organically into a compendium of recollections and memories from key members of the EOS program. It is often said that history is the telling of a personal story, and that was certainly true with these articles, as the storytellers had actually lived them. We were fortunate to get contributions from the likes of **Dixon Butler**, **Piers Sellers**, **Michael King**, and **Ghassem Asrar**, all of whom played prominent roles in the early history of EOS. One of our hopes in compiling these articles was that lessons learned in making EOS a reality could be applied by those tasked with implementing new missions through today and into the future. Feedback we have received on those articles indicates that we attained that objective. If ever someone endeavors to write an official history of EOS, these articles, combined with other content from our newsletter, could prove to be a valuable resource.

Meeting summaries and workshop reports have been part of *The Earth Observer* from the very first issue, and remain so today—see several examples in this issue beginning on page 19. In the early days, when Internet access wasn't as widespread as it is today, the newsletter printed meeting minutes almost verbatim. At that time, a printed summary was the most efficient—and often the only—way to get the word out about the results of the meeting. The problem was that meeting minutes don't make for the most interesting newsletter articles. If you aren't a member of the science team or an expert on the workshop's subject matter, you could quickly lose interest. Today, details of virtually every meeting are readily available online and printing pages of summary are no longer economically or environmentally justifiable. Thus, we focus on "telling the story" of each event, providing a high-level summary with more-detailed reporting on individual presentations as deemed appropriate. We always include a URL that interested readers can follow to find more detailed information. This is clearly a viable approach, as some of the teams who reported in those first issues in 1989 are still contributors to our newsletter today.

While much has changed aesthetically and in terms of content in 30 years, *The Earth Observer*'s core commitment remains the same as it was with that very first issue: *To report timely news and events from NASA's Earth Science Program.* As has been the case for the past three decades, the future will inevitably require us to learn to navigate new modes of communication (e.g., we've experimented with an *iBook* version of the newsletter and ways to get more of our material posted online). Regardless of communications medium, our core commitment to telling compelling stories about NASA Earth Science remains the same. It has been my honor to serve as executive editor for a baker's dozen of years, and I look forward to seeing what comes next for *The Earth Observer* as we begin our fourth decade. I think it's been a good run so far—but I hope our best is yet to come! ■

[4] TIROS stands for Television Infrared Observation Satellite.
[5] FIFE stands for First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment, with campaigns to the Kansas prairie in 1987 and 1989; BOREAS stands for Boreal Ecosystem–Atmosphere Study, a joint U.S.-Canadian endeavor with preparatory activities in 1993 and field deployments to Western Canada in 1994 and 1996.
[6] See "Reflections on FIFE and BOREAS: Historical Perspectives and Meeting Summary" in the January–February 2017 issue of *The Earth Observer* [**Volume 29**, **Issue 1**, pp. 6-23—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Jan-Feb%202017%20color%20508.pdf#page=6*].
[7] See "Earth Science Mission Operations, Part I: Flight Operations—Orchestrating NASA's Fleet of Earth Observing Satellites" in the March–April 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 2**, pp. 4-13—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Mar_Apr_2016_508_color.pdf#page=4*].
[8] See "Earth Science Data Operations: Acquiring, Distributing, and Delivering NASA Data for the Benefit of Society" in the March–April 2017 issue of *The Earth Observer* [**Volume 29**, **Issue 2**, pp. 4-18—*https://eospso.gsfc.nasa.gov/sites/default/files/eo_pdfs/March%20April%202017%20color%20508.pdf#page=4*].
[9] The *Perspectives on EOS* series of articles has been compiled as a single volume and is available at *https://eospso.nasa.gov/earthobserver/new-perspectives-eos*.

The Vanguard of Earth-Observing Satellites

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Introduction

It is a season of milestones for NASA. Last year (2018) was the sixtieth anniversary of the agency's founding. It was also the sixtieth anniversary of the launch of Explorer 1, the first satellite to transmit scientific data from space. Just ten years after Explorer 1, in 1968, NASA flew Apollo 7, the first crewed Apollo flight in our race to the Moon.

Other significant NASA anniversaries are taking place in 2019 as well. The first manned lunar landing by Apollo 11 riveted the world 50 years ago this July. And a new era of Earth-science observatories came online with the launch of Terra, the first of NASA's Earth Observing System (EOS) flagship satellites, 20 years ago this December.

This article is written on the occasion of a lesser-recognized, but still significant, milestone happening in 2019: the sixtieth anniversary of the launch of Vanguard II on February 17, 1959. The successful launch of this mission laid the foundation for the way we collect Earth science data from space. The mission opened the pathway for the development of the first meteorological satellites, which were then followed by modern high-performance satellites and instruments capable of observing Earth as a system of interrelated geophysical and biological disciplines. Despite the tribulations of the U.S.'s initial efforts to reach space, the development and success of Vanguard pointed the way by which we build, test, launch, and operate satellites to this day. Therefore it's appropriate that this article appear in the thirtieth anniversary issue of *The Earth Observer*, which has dedicated to reporting on the progress and accomplishments of NASA Earth Science since its inception in March 1989.

This article is written on the occasion of a lesser-recognized, but still significant, milestone happening in 2019: the sixtieth anniversary of the launch of Vanguard II on February 17, 1959.

Vanguard's history is more than a story of satellite and rocket hardware development. It is also a human drama, as it encompasses the successes and failures of the efforts of scientists and engineers who envisioned this new frontier. The story involves national politics, budget uncertainties, military service rivalries, technological challenges, and scientific competition. Unfortunately, space available in *The Earth Observer* permits only this shortened story of Vanguard, which focuses on its role as a pioneer for the development of Earth-observing satellites. There are, however, excellent sources which lucidly recount Vanguard's story in more detail. This author relied heavily on these sources, which are listed in the *Acknowledgments* at the end of the article, and highly recommends them to those who wish to know "the rest of the story."

The Space Frontier: Rocket Early History

The greater part of the Vanguard story unfolds at the dawn of the space age as NASA [specifically, Goddard Space Flight Center (GSFC)] was being established. However, the story actually begins late in the nineteenth century when Konstantin Tsiolkovskiy, a Russian scientist, showed by means of the laws of motion the feasibility of using a reactive force to propel a rocket into space above the pull of Earth's gravity. His most important work, published in 1903, was *Exploration of Outer Space by Means of Rocket Devices*, in which he described how a multistage rocket, using liquid oxygen and hydrogen as fuel, could put a satellite into orbit around Earth.

A few decades later, in 1929, Romanian-born Hermann Oberth worked out similar formulas and subsequently published a book titled *The Rocket into Planetary Space,* which explained how rockets could escape Earth's gravitational pull. After receiving a patent for his rocket design, Oberth launched his first rocket on May 7, 1931 near Berlin, Germany. At that time, Oberth became a mentor to a young assistant by the name of Wernher von Braun. Von Braun would go on to play a prominent role as a pioneer in American rocketry, as described here.

While these studies were virtually unknown in the English-speaking world, around the same time, Robert H. Goddard independently demonstrated, in his Clark University laboratory in Worcester, MA, that rocket propulsion would function in a vacuum. In 1917 he received a grant from the Smithsonian Institution to continue his experiments. Under this grant the Smithsonian published Goddard's report, *Method of Reaching Extreme Altitudes*. Although his grant ended, he continued his research at Clark University to develop a rocket that could reach the ionosphere. As Goddard's research was successful, he showed how rockets could be used not only for atmospheric research, but also as ballistic missiles and for space travel.

Between the world wars, Goddard showed his work on rocketry to the U.S. Army but was turned away, since the Army at that time failed to grasp the military application of large rockets. After World War II, the U.S., now recognizing the value of rocket missiles from the success of the German V-2 bombardment of London during the war, began its missile development using captured V-2 rockets. Wernher von Braun and other German technicians who immigrated to the U.S. (1945) after the war and settled in to work at the Army Ordnance Proving Ground at White Sands, NM, became key players in this effort.

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During the period from 1945 to 1955, the development of rocket missiles continued while U.S. and German scientists and engineers began experiments that replaced warheads with scientific instruments intended to explore the upper atmosphere. This effort was led by the Naval Research Laboratory (NRL). Initially, the tests were conducted using V-2 rockets; however, the supply was running out, so the Navy began developing specifications for a new *sounding rocket* to study the upper atmosphere.

Army–Navy Competition: First in Orbit

Although the Army's priority was missile development, while the Navy's was scientific investigation, competition developed between the Army and Navy, who both strived to be the first to put a satellite into orbit. By the mid-1950s, rockets were reaching heights of 100 km (~62 mi) with increasingly more sophisticated control and guidance systems—but not nearly high enough to achieve orbit. In the interim, the National Academy (NA)[1] and the National Science Foundation (NSF) debated how an Earth-orbiting satellite would benefit science. The likes of Homer Newell, William Pickering, John Townsend, Milton Rosen,[2] and the legendary James Van Allen became strong links between the scientific community and the U.S. Department of Defense, which was overseeing all rocket development efforts at the time.

Understanding the origins and structure of the ionosphere was a priority for both the NA and NSF. In the 1950s, the ionosphere could only be probed by sounding rockets from fixed locations, whereas it was becoming increasingly clear even at these early stages that global measurements were needed. After almost a decade of scientific and technical development and political debate, top-level government officials acknowledged that developing and launching satellites were in the national interest. In January 1955 a NA special study group, the Subcommittee on the Technical Feasibility of a Long Playing Rocket (i.e., a satellite), began evaluating the rocket-satellite schemes being developed by both the Army (called Explorer) and the Navy (called Vanguard).

In early 1955 NRL proposed the Vanguard satellite system, titled *A Scientific Satellite Program*. The Vanguard proposal was based on a civilian launch vehicle, the Viking, developed by the Glenn L. Martin Company (now Lockheed-Martin) and intended to

[1] Now the National Academies of Sciences, Engineering, and Medicine.
[2] These individuals eventually served as an Associate NASA Administrator, Director of NASA/Jet Propulsion Laboratory, Director of NASA's Goddard Space Flight Center, and NASA Headquarters Launch Vehicle Director, respectively.

meet all of the goals of the International Geophysical Year (IGY)[3] measurements using scientific satellites. The proposed payload was highly innovative for that time, and was controlled by unique spacecraft support systems (e.g., power, telemetry, command) that turned out to be the precursors of systems employed on current satellites.

In the meantime, the Army was pursuing its own mission, led by von Braun, to orbit a satellite using a descendent of the German V-2 military rocket developed by the Army Ballistic Missile Agency (ABMA) in Huntsville, AL. In order to meet the science objectives of IGY, the ABMA team asked James Van Allen, who was interested in conducting a worldwide survey of the cosmic-ray intensity above the atmosphere, to join in the effort.

In order to make a decision on which mission to fly, an endorsement had to be made by the NA. In addition, because launching an instrument-carrying Earth-orbiting satellite would be expensive and because contributions to the IGY would require sharing information with other nations, approval of the plan had to come directly from the president, but first required approval by the National Security Council (NSC). The Council imposed two conditions on the plan selection: First, the plan must show peaceful purposes of the effort; and second, that it must not interrupt development of military ballistic missiles. Because NRL's goal was to build a rocket only for atmospheric research, it was clear that only the Navy's Vanguard mission could meet those two criteria.

On July 28, 1955, the White House announced that President Eisenhower had approved plans for the U.S. to go ahead with the launch of an Earth-orbiting satellite as part of this country's participation in the IGY. Subsequently, the Army put their proposed Explorer mission on the shelf—for the time being. The Navy's marching orders were to place their Vanguard satellite in orbit during the IGY, accomplish a scientific experiment in orbit, and track the satellite and ensure its orbit was maintained. The condition that the Navy employ rockets used for scientific research rather than military missiles was still an NSC requirement.

On July 28, 1955, the White House announced that President Eisenhower had approved plans for the U.S. to go ahead with the launch of an Earth-orbiting satellite as part of this country's participation in the IGY.

Vanguard: Development, Test, and Failure

Once NRL was chosen to lead the program, it scrambled to form a team—180 members at the peak activity—to build and test the spacecraft, instruments, and their supporting systems. A major task was to write the specifications for the Viking launch vehicle. Glenn L. Martin Corporation was selected, since they were already manufacturing rocket vehicles for the NRL sounding rocket program. The development complexity, establishing the funding source, and the politics behind the selection resulted in enormous pressure on NRL to successfully launch a satellite. In response to this pressure, the team included experienced scientists from NRL and engineers from both NRL and Glenn L. Martin. The schedule required a launch by the end of 1958, coinciding with conclusion of the IGY. Concurrently the NA, through the IGY Satellite panel, was finalizing the selection of the scientific instruments for space flight.

Because there were no suitable civilian satellite-launching facilities, NRL constructed the first complete facility in Cape Canaveral, FL, in 1957. The planned Vanguard launch vehicle consisted of three stages and utilized upgraded but proven rockets used for atmospheric research soundings.[4] An important innovation of the first stage Viking rocket, first tested by Robert Goddard, was its ability to steer with a dual-axis gimbal during the thrust phase. Gimbaled first-stage guidance is now universally employed on all launch rockets since Vanguard.

[3] The IGY (1957-1958) was established to allow scientists around the world to take part in a series of coordinated observations of various geophysical phenomena. By the close of the activity, 67 countries had become involved. IGY activities spanned much of the globe including the North to the South Poles. The measurement campaigns were timed to coincide with the high point of sunspot activity in the Sun's eleven-year cycle.

[4] The three stages consisted of the Viking, Aerobee, and solid-fuel rockets. They were built by Glenn L. Martin, Aerojet General, the Johns Hopkins University's Applied Physics Laboratory, and the Atlantic Research Corporation, respectively. The second and third stages were used extensively during the IGY, where NASA and its predecessors were the primary users, for atmospheric research.

Another key component of the program was the satellite tracking system. NRL was already putting a system in place called Minitrack. It was initially operated by NRL, and had stations around the world that are still functioning. Minitrack was the first network to provide downrange instruments with the capability to determine a satellite's orbit. It was the predecessor to the current Spaceflight Tracking and Data Network (STDN), which began operations in the late 1970s and is managed and maintained at GSFC to this day.

NRL established a series of test flights called Test Vehicles, or *TVs*, beginning with TV-0. Each flight was designed to determine the performance and reliability of the vehicle and spacecraft. For example, the TV-0 objectives were to evaluate the satellite subsystems and the overall performance of the launch operations. The successful flight launched in December 1956, and reached an altitude of 78 km (48 mi), achieving nearly all of the engineering objectives. A further example, TV-3, using the complete three-stage launch system, was to place a 2-kg (4.4-lb) satellite into orbit to determine atmospheric density and the shape of Earth. Unfortunately, one second after launch the first stage lost thrust, and the entire vehicle fell back on the launch stand and exploded. The TV-3 Backup was also unsuccessful one minute after launch, when the vehicle control system failed.

At this time, Vanguard's story intersected with—and was changed by—a story unfolding on the other side of the world—the unexpected successful launch of a satellite by a U.S. adversary.

Each of the fourteen Vanguard launches revealed problems, despite careful testing of the of the launch and payload components. After each frustrating failure, NRL instituted further quality control inspections and tests—forerunners of today's procedures. At this time, Vanguard's story intersected with—and was changed by—a story unfolding on the other side of the world—the unexpected successful launch of a satellite by a U.S. adversary.

Sputnik: Launch Shocks the World

While the world's leading scientists debated the possibilities of spaceflight and the U.S. deliberated on missile defense versus meeting IGY science objectives, the country then known as the Union of Soviet Socialist Republics (USSR) orbited the world's first artificial satellite, Sputnik, on October 4, 1957. Sputnik I was an aluminum sphere about the size of a beach ball. It weighed 84 kg (185 lb)—much heavier than America's planned Vanguard satellites, with weights ranging from a few kilograms to 24 kg (53 lb). Sputnik, which means "traveling companion" in Russian, orbited Earth once every 96 minutes and remained in orbit until January 1958.[5] Amateur radio operators could easily pick up the distinctive beeping signals it continually broadcast.[6]

The successful launch by our Cold War adversary took America by surprise; suddenly the possibility of an intercontinental missile strike seemed much more a reality. President Eisenhower called for calm; he stated that the Soviet satellite was not a threat—and that the launch of a U.S. satellite was imminent.

History changed on that day in October. While the Sputnik launch was a single event, it was the beginning of new political, military, technological, and scientific era. The launch marked the start of the Space Age and what became known as the U.S.–USSR Space Race. Immediately after the Sputnik launch, the U.S. Department of Defense reacted to the subsequent political alarm by approving funding for another satellite project to insure a prompt response by the U.S. to the Soviet achievement. As a parallel effort to Vanguard, Wernher von Braun and his U.S. Army team were directed to resume work on their Explorer project.

[5] Sputnik 2 was the second spacecraft launched into Earth orbit, on November 3, 1957. It was the first to carry a living animal—a Soviet space dog named Laika—who died a few hours after the launch.

[6] You can hear a recording of Sputnik's signal at *https://history.nasa.gov/sputnik/sputnik.wav*.

Explorer: The U.S. Quickly Catches Up

The Army team consisted of the ABMA Jupiter-C rocket program, based in Huntsville, AL, and the California Institute of Technology's Jet Propulsion Laboratory (JPL) in Pasadena, CA. JPL designed and built the Explorer satellite, while ABMA modified the Jupiter-C to the so-called civilian Juno launch vehicle. The ABMA and JPL completed this modification and building the Explorer 1 payload, respectively, in 84 days. Unannounced to the public, the Juno rocket was launched from Cape Canaveral and successfully put the Explorer I satellite into orbit on January 31, 1958.

Unannounced to the public, the Juno rocket was launched from Cape Canaveral and successfully put the Explorer I satellite into orbit on January 31, 1958.

The Explorer 1 payload included an instrument to measure cosmic rays, designed and built under the direction of James Van Allen of the University of Iowa. But it did not have a tape data recorder, so only real-time data when the satellite was over a ground station were retrieved. George Ludwig (a GSFC pioneer), of Iowa's Cosmic Ray Laboratory, built the omnidirectional Geiger-Müller tube to detect cosmic rays, which unexpectedly was saturated most of the time once in orbit. The payload also included sensors to monitor micrometeorite impacts and measure temperatures throughout the payload. **Figure 1** is an illustration of the science payload as attached to the rocket launcher's fourth stage.

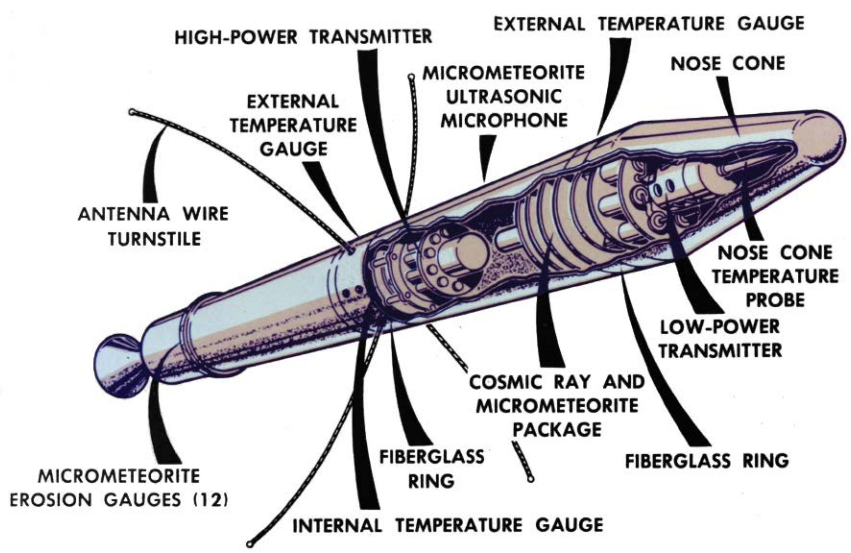

Figure 1. Illustration of Explorer 1. The satellite weighed 13.4 kg (29 lb). **Image credit:** U.S. Army/JPL/NASA

Although the USSR beat the U.S. in placing a satellite into orbit, Explorer I was the world's first satellite to return scientific data from space. Explorer 2, similar to Explorer 1, was launched on March 5, 1958, but the fourth stage of the Juno rocket failed to ignite. Explorer 3 was successfully launched just 21 days later, on March 26, 1958, and operated until June 16. Explorer 3 solved the mystery of the saturated Geiger counter on Explorer 1. The data collected during the mission concluded that the Explorer 1 Geiger counter had been saturated by strong radiation coming from a region of previously unknown charged particles trapped in space by Earth's magnetic field. Subsequent satellites further explored this region and found two distinct "belts" of charged particles. These are now known as the *Van Allen Radiation Belts*, and their discovery was considered to be one of the outstanding discoveries of the IGY.

Vanguard: Finally, a Success

While the Sputnik and Explorer launches took place, NRL continued to improve the Vanguard rocket systems with a series of test launches. Concurrently, the capabilities of science payloads became more sophisticated for investigating the space environment. For example, improved instruments were developed to measure variations in the intensity of solar X-ray and Lyman-α radiation and to explore Earth's magnetic field. There were also plans to deploy an expandable sphere to measure the upper-atmospheric density.

Figure 2. Vanguard I launch, March 17, 1958. **Image credit:** Naval Research Laboratory

TV-4 launched on March 17, 1958,[7] see **Figure 2**—with engineering and science objectives similar to those for the failed TV-3 mission described earlier on page 10. Once in orbit, TV-4 was renamed Vanguard I and was the second U.S. satellite, after Explorer 1, which had launched three months earlier, as noted previously. A picture of Vanguard I Backup appears in **Figure 3.** The primary purpose of the launch, which was to test the performance of the Vanguard rocket, was clearly achieved as the orbit of the small sphere was remarkably stable. Although orbiting this small 2-kg (4.4-lb) satellite was far from the final objective of a 20-kg (44-lb) instrumented satellite, the confidence placed in Project Vanguard was justified.

Further objectives for Vanguard were to evaluate satellite thermal parameters and to check the life of solar cells in orbit. Probably the most notable science contribution was the discovery that Earth is not a sphere, but shaped like a pear. Scientists also were able to study and measure the density of the atmosphere in a region some 750 km (466 mi) above Earth. Vanguard I provided extensive measurements of air density variations associated with solar activity changes and the first quantitative data on how solar radiation pressure affects a satellite's orbit.

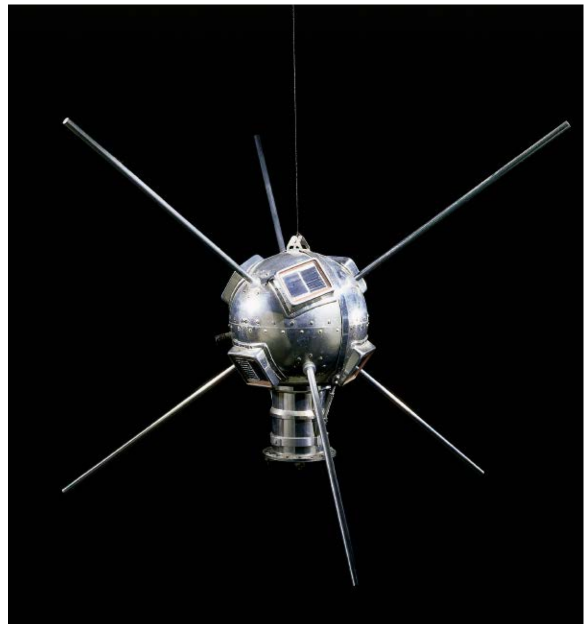

Figure 3. Vanguard I Backup on display at the Smithsonian Institution's National Air and Space Museum (NASM). **Image credit:** NASM

[Vanguard II evaluated] satellite parameters and to check the life of solar cells in orbit. Probably the most notable science contribution was the discovery that Earth is not a sphere, but shaped like a pear.

Civilian U.S. Space Science: NASA Takes Responsibility

About six months after the launch of Sputnik I, the President's Science Advisory Committee and the President's Advisory Committee on Governmental Organization recommended the establishment of a civilian agency to direct nonmilitary space activity. President Eisenhower sent a message to Congress on April 2, 1958, which stated that "…aeronautical and space science activities sponsored by the U.S. should be conducted under the direction of a civilian agency except for those projects primarily associated with military requirements." As a result of this message, and after lengthy congressional hearings, Congress enacted the National Aeronautics and Space Act,[8] (*Public Law 85-568*), and signed it into law on July 29, 1958. This law established the National Aeronautics and Space Administration, now so familiarly known as NASA, to replace the earlier National Advisory Committee for Aeronautics (NACA), which had been in place since March 3, 1915. It also incorporated several other government agencies that dealt with civilian space research and aeronautics into the new agency—which was given full responsibility for conducting scientific exploration of space for peaceful purposes.

The initial implementation of this responsibility was assigned to the newly created GSFC, which started a management and engineering infrastructure to develop a scientific satellite program. This included taking over and completing the Vanguard program

[7] To see how much a launch event has changed since 1958, and how much it has not, watch the video at *https://www.nrl.navy.mil/vanguard50/vanguard_launch.mp4.* **Note:** Video may not play on some web browsers.

[8] The entire text of the law can be found at *https://history.nasa.gov/spaceact.html.*

from NRL and then initiating a meteorological satellite program. In addition, as NASA was assuming the responsibility for the peaceful purposes of space activities, a number of Department of Defense programs were transferred to GSFC in 1959. Among them were the meteorological and communications satellites under development by the Army Signal Corps Engineering Laboratories (SCEL),[9] in Fort Monmouth, NJ. To further consolidate NASA's space science program, JPL, which designed, built, and operated the first five Explorer satellites of the series, turned the project over to GSFC in 1960.

Vanguard II: Precursor to Meteorological Satellites

The NA Space Panel continued to provide guidance for selecting instruments to either fly on Vanguard or Explorer. The criteria required that the instruments be compatible with mission objectives that included the expected orbit, the available spacecraft resources to operate the instruments, and their technical maturity. The Panel set up a hierarchy of "packages" containing an array of instruments to facilitate selection on when to fly and on which platform, Explorer or Vanguard.

Two instruments, pertinent to future Earth science missions, were considered for Vanguard II. The first was an optical cloud mapper, which was a scanner for meteorological observations, prepared by William G. Stroud of the SCEL. Its primary objective was to measure the global distribution and movement of cloud cover and to relate it to the large-scale meteorological features of the Earth. The basic data were the contrast between sunlight reflected from cloud, sea, and land masses mapped out as the satellite spun on its axis. Two photocells would look out in opposite directions at a known angle to the spin axis of the satellite. The signals from the photosensitive cells would be stored on an on-board analog tape recorder. A switch would turn the instrument off during the night and turn it on again when the satellite reemerged from darkness.

To further consolidate NASA's space science program, JPL, which designed, built, and operated the first five Explorer satellites of the series, turned the project over to GSFC in 1960.

The other instrument was proposed by Verner E. Suomi of the University of Wisconsin. The objective of his experiment, known as *Radiation Balance of the Earth*, was to measure the longwave radiation emitted from Earth, the shortwave radiation reflected from Earth, and direct sunlight impinging on the Earth. Harry Wexler[10] of the U.S. Weather Bureau (USWB), who had submitted a somewhat similar but more complicated experiment, supported Suomi's proposal as scientifically important and technically feasible. Suomi's instrument consisted of four small thermistors mounted on the ends of the satellite antennas: one sensor would be sensitive only to longwave radiation emitted by Earth's surface; the second, sensitive to other types of radiation; and the third and fourth sensors sensitive only to shortwave radiation reflected from Earth.

The Panel decided to fly the optical cloud mapper on Vanguard II and the Radiation Balance experiment would fly on Explorer 7,[11] which launched in October 1959. The Explorer 7 Earth radiation measurement became the precursor of NASA's Earth Radiation measurements that continue to this day with NASA's research satellites and the operational satellites of the National Oceanic and Atmospheric Administration (NOAA).

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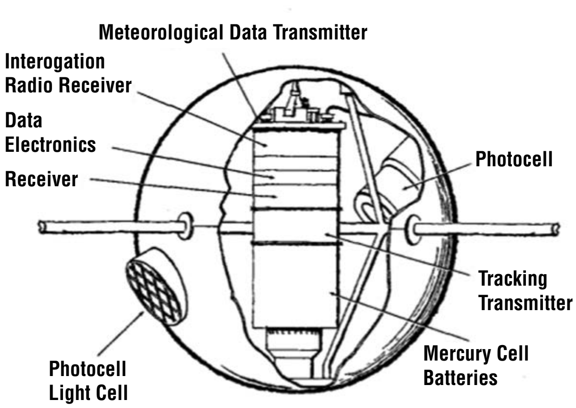
[9] The Army's Signal Corps Engineering Laboratories (SCEL) contributed the complete electronics package for Vanguard II including solar cell batteries. They also played an important role in the International Geophysical Year (IGY) with their upper air research and measurement of winds and temperatures using sounding rockets. SCEL scientists and engineers were also responsible for developing instruments that were to fly on future meteorological satellites.

[10] Harry Wexler was the Chief Scientist for what was then the U.S. Weather Bureau. He was a pioneer in weather research and was Chief Scientist for IGY Antarctica expedition. He also lectured on nuclear winter and ozone depletion in the 1960s, and discussed the use of weather satellites with Arthur C. Clarke, the originator of the concept of geosynchronous communications satellite orbits.

[11] The Radiation Balance instrument operated as planned, but did not have access to a data storage unit. For the data received, the measurements showed that large-scale outward radiation flux can be related to large-scale weather features. Eventually the data were used to estimate heating and cooling of the atmosphere.

...Vanguard II became known as the forerunner of the seminal Television and InfraRed Observation Satellite (TIROS) mission, discussed later.

Vanguard II was launched by NRL under the direction of GSFC on February 17, 1959.[12] This was the first full-scale Vanguard mission, with a 0.51-m (20-in) diameter sphere weighing 9.5 kg (21 lb)—see **Figure 4**. The satellite is still in orbit to this day. Vanguard II's orbit was perfect, giving the satellite a long lifetime in space. The support systems, electrical power (from batteries and solar cells), tape recorder, and telemetry all operated as planned. The cloud cover sensor system worked well, indicating extensive detail the variations of the reflected Earth radiation received by the satellite. But the data proved difficult to analyze because the satellite developed a large precession (likely because of a misalignment of the separation device in the third stage as the satellite was ejected into orbit) that caused it to move erratically, thereby constantly shifting its attitude relative to Earth. Although the scientists were unable to make a complete map of Earth's cloud cover, the experience gained from the flight led to much-more-capable meteorological satellites and their instruments. As a result, Vanguard II became known as the forerunner of the seminal Television and InfraRed Observation Satellite (TIROS) mission, discussed later.



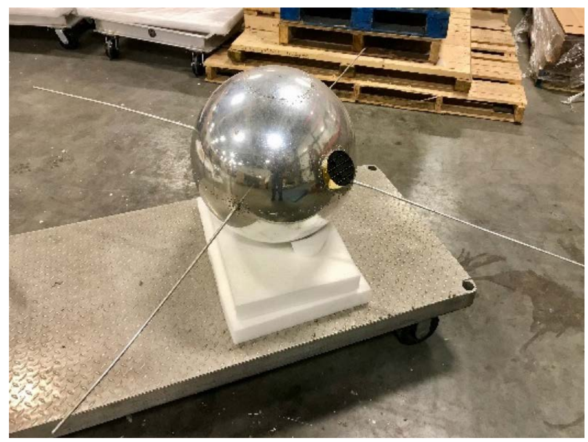


Figure 4. The diagram [*left*] shows the Vanguard II payload. The photo [*right*] shows the Vanguard II backup, which is stored in a warehouse at GSFC. **Image credits:** Diagram—NASA; Photo—Paul Newman [GSFC]

As the three Vanguard satellites are still orbiting with their drag properties essentially unchanged, their data form a viable and important baseline of atmospheric density distribution to this day.

Vanguard II also carried instruments to measure Earth's magnetic fields and incident solar X-rays. Because of its symmetrical shape and drag properties, changes in the satellite orbit enabled the calculations of upper atmospheric densities as a function of altitude, latitude, season, and solar activity. As the three Vanguard satellites are still orbiting with their drag properties essentially unchanged, their data form a viable and important baseline of atmospheric density distribution to this day.

Vanguard III was launched on September 18, 1959, and put the 22.7-kg (50-lb) satellite into the planned orbit of 377-km (234-mi) apogee and 517-km (321-mi) perigee. The satellite carried several scientific instruments, including an NRL-contributed instrument to measure solar X-rays, as well as three GSFC-contributed instruments to measure magnetic fields, micrometeoroid impacts, and satellite temperatures. The ionization chambers from NRL were saturated most of the time because of the high apogee of the satellite. This result enabled scientists to refine their determinations of the lower edge of what later became known as the inner Van Allen radiation belt (discovered by Explorer I) when the chambers came out of saturation as the satellite approached perigee. GSFC's magnetometer worked well; it showed there were systematic variations from the predicted fields. The micrometeoroid experiment was successful as well.

Although Vanguard III remains in a stable orbit, the satellite stopped transmitting on December 11, 1959, about two months after launch. As this mission used the last of the seven launch vehicles procured by the Navy for the IGY, and since NASA decided not to procure more, Project Vanguard came to an official end shortly after this flight.

[12] To watch a video that describes one of Vanguard II's mission objective and its launch, visit *https://www.youtube.com/watch?v=1Azape1hQuE*.

Many of the early experiments from both Explorer and Vanguard missions were follow-ons from initial discoveries of the Van Allen belt characteristics and their interaction with Earth's magnetic field. Explorer 6 carried five instruments that were to measure various types of solar radiation and magnetic fields and to televise Earth's cloud cover.[13] The mission only lasted about two months, but was likely the first space mission to explore "Sun-weather" phenomena. The pictures of Earth from orbit were fuzzy—but the first ever, which in and of itself makes them noteworthy.

Vanguard and Explorer were truly pioneering missions for future Earth science exploration. They demonstrated that a satellite orbiting Earth provides a unique perspective that can reveal interrelationships of geophysical parameters on a global scale. From a technological and organizational view, the words of John Hagan[14] are most fitting. He stated that: "…the most significant achievement of Project Vanguard was to bring together a group of dedicated and talented scientists and engineers who came to understand the complexities and challenges of the space sciences program. This team was assimilated into the National Aeronautics and Space Administration, where it became the human core of the Goddard Space Flight Center and served as the foundation for the distinguished space sciences programs which were to emerge."

Vanguard and Explorer were truly pioneering missions for future Earth science exploration. They demonstrated that a satellite orbiting Earth provides a unique perspective that can reveal interrelationships of geophysical parameters on a global scale.

Vanguard Evolves: TIROS Becomes Operational for Weather Forecasting

In April 1959 the U.S. Department of Defense's Advanced Research Projects Agency (ARPA) assigned a new satellite program—called TIROS—to NASA. While the program was still at ARPA, the Radio Corporation of America (now RCA) was contracted to build and test the satellite. The purpose of the TIROS mission was to test experimental television techniques designed to develop a global meteorological satellite information system. Subsequently, a group was assembled at GSFC to form a project to continue the TIROS mission, the core members of which were those who had worked on the Vanguard project. The TIROS Project was led by William Stroud, who had worked on Vanguard II, as described earlier.

Figure 5. Engineers prepare to perform a vibration test on the first TIROS satellite at GSFC in 1959. **Image credit:** NASA

Much of the Vanguard flight and ground technologies were upgraded and subsequently applied to the TIROS mission. Additional responsibilities assigned to the TIROS project were to coordinate elements of the Department of Defense and USWB scientists who would be responsible for analyzing the satellite data. This was the beginning of a long-term relationship between NASA and what is now called the National Weather Service that is now part of the National Oceanic and Atmospheric Administration (NOAA).

The first TIROS payload consisted of wide-angle, low-resolution, and narrow-angle, high-resolution video cameras—whereas Vanguard only used two photocells viewing in opposite directions. Also onboard were a horizon scanner and a Sun angle sensor to determine the spacecraft's attitude—also a major advance over Vanguard. **Figure 5** is a picture of the satellite on a test stand.

TIROS 1 was launched on April 1, 1960, from Cape Canaveral, FL, and put into a 48°-inclination orbit. The spin-stabilized satellite axis was fixed to a point to space. The cameras viewed Earth in daytime and pointed into space at night. The video system relayed about 23,000 views of Earth with varying cloud cover conditions. How clouds were correlated to concurrent meteorological

[13] Watch Explorer 6 on its mission to "Explore the cosmos" at *https://www.youtube.com/watch?v=x-ECknLJsWI.*

[14] Hagen, John P., "The Viking and the Vanguard," in Emme, Eugene M. (ed.), *The History of Rocket Technology (1964)*, 122-141. John P. Hagen was the Director of Project Vanguard at the Naval Research Laboratory.

features was the subject of research by the USWB. **Figure 6** shows a sequence of pictures over the Arabian Peninsula and the Mediterranean Sea.[15] TIROS 1 operated only 78 days, but firmly demonstrated that satellites could be used for global weather surveys that would lead to more accurate weather forecasts.

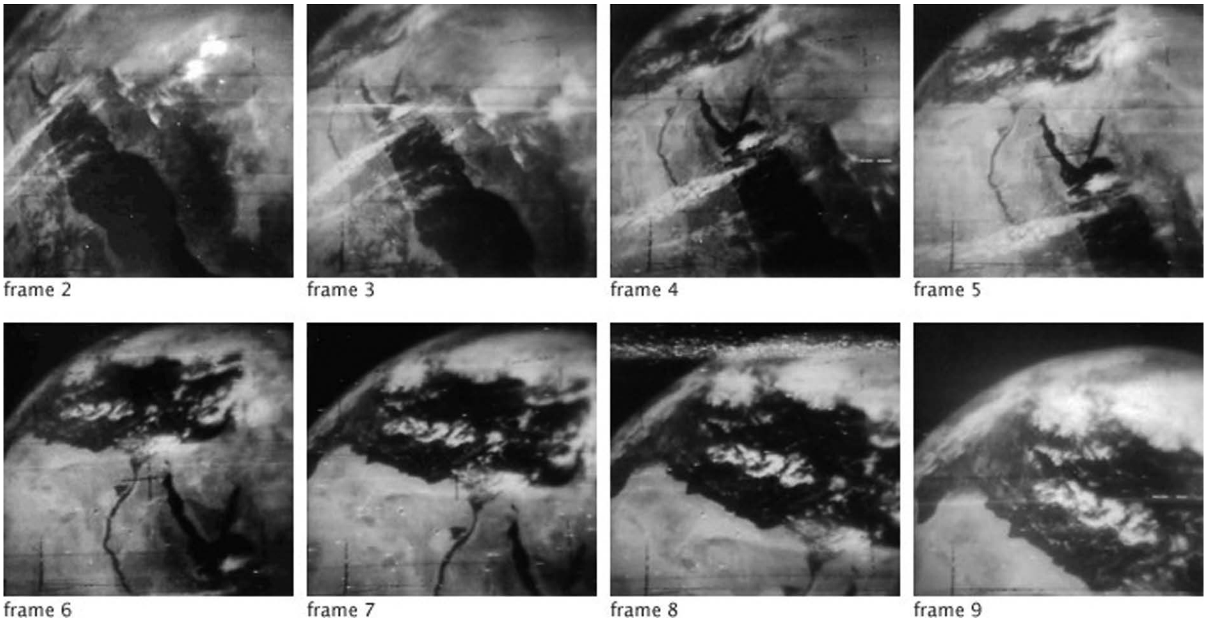


Figure 6: Sequence of TIROS images at intervals of 30 seconds. The upper row shows the Arabian Peninsula. The lower row shows the Mediterranean Sea. The images were captured on April 1 and June 18, 1960, respectively. **Image credit:** NASA

NASA launched nine more TIROS satellites; the series ended with TIROS 10 on July 1965. Each successive launch incorporated improvements to the video and spacecraft support systems, which then provided better coverage and spatial resolution. Additional meteorological data products, such as temperature, humidity, and cloud height, came about as infrared channels were added to the cloud-mapping instrument. These additions were a major step forward for improving weather predictions. Satellite data could now supplement ground-based data by providing a more global picture of atmospheric conditions. With the success of the TIROS series, research mission activities ended, and an era of operational missions for use by the USWB began.

Nimbus: First Step in Earth System Science

The story of Vanguard is not complete without mentioning the Nimbus series of satellites. Nimbus was developed to further advance spacecraft and instrument technology and to continue NASA research on Earth science and weather forecasting. Its story has been told many times elsewhere, and will not be repeated here.[16] The Nimbus program was highly successful with seven spacecraft launched into near-polar, Sun-synchronous orbits beginning with Nimbus-1 launched in August 1964, and ending with Nimbus-7, launched in October 1978.

The Nimbus satellite series revolutionized weather forecasting leading to more accurate and timely long-term forecasts.

The Nimbus satellite series revolutionized weather forecasting leading to more accurate and timely long-term forecasts. The series provided the first reliable measurements of Earth as a system with near-global and near-simultaneous measurements of the characteristics of sea and ice, oceanic plant life, weather phenomena, land use, vegetation, and the ozone layer. Nimbus paved the way for NASA's present day high-performance Earth-observing satellites such as Aqua, Terra, Aura, Landsat, Global Precipitation Measurement, Soil Moisture Active Passive, and many more.

[15] Consider these images with respect to the various "Blue Marble" images from contemporary satellites. For example, visit *https://jointmission.gsfc.nasa.gov/npp_marble_collection.html.*
[16] A history and summary of Nimbus key science achievements, titled "Nimbus Celebrates Fifty Years," can be found in the March-April 2015 issue of *The Earth Observer* [**Volume 27, Issue 2**, pp. 18-31—*https://eospso.gsfc.nasa.gov/sites/default/files/eo_pdfs/Mar_Apr_2015_color_508.pdf#page=18*].

Moving Forward, Looking Back: The Vanguard Legacy

As noted, remarkable progress has been made in satellite technologies that enable significant improvements in science and applications since the early, exploratory days of Vanguard and Explorer. Some examples of this progress follow.

Standing out is the highly improved reliability of launching a satellite and having it operate long enough to collect useful science. Using 1958, the year NASA was established and began taking responsibility for civilian launches, as the beginning point, there were 21 launches of Explorer and Vanguard, combined. Of these launches, 11 failed to deliver science and demonstrate new technology. A mission success rate of less than 50% would be unacceptable compared to present launch success rates of roughly 95%.[17] Whereas the Explorer and Vanguard payloads actively operated for roughly a month, a decade or so is typical for modern space missions. In fact, today's satellite missions routinely exceed their designed lifetime by many years. For example, Landsat 5 was designed for a minimum 3-year mission, but lasted nearly 29 years (from 1984 to 2013).

Furthermore, as rocket reliability increased so did lift capacity. For instance, early satellite weights ranged from about 2 kg (4.4 lb) to about 25 kg (55 lb), while the Joint Polar Satellite System (JPSS)[18] payload, a moderate-sized spacecraft by today's standards, weighs about 2500 kg (5500 lb). This carrying capacity allows multiple instruments to measure the same Earth scenes simultaneously. For instance, JPSS-1 carries five science instruments—including sounders and mapping imagers that all have heritages that can be traced directly to Nimbus.

As noted, remarkable progress has been made in satellite technologies that enable significant improvements in science and applications since the early, exploratory days of Vanguard and Explorer.

Two other major advances that enabled comprehensive Earth science observations were the capabilities to both control the satellite attitude and to deploy the satellite into a Sun-synchronous polar orbit. The former achievement allowed for continuous viewing of the Earth—unlike the views taken from a camera on a spinning satellite such as Vanguard and the early TIROS missions. The stable attitude was first tested on Nimbus 1 and employed in every Earth-observing satellite since then. And for the latter achievement, a Sun-synchronous polar-orbit means that the satellite flies overhead at nearly the same time of day for each orbit while the Earth rotates underneath. This type of orbit provides near-global coverage every 24 hours. Achieving daily global coverage was a major step forward toward monitoring global change from space. This capability enabled the development of a more comprehensive satellite observing system such as the Earth Observing System (EOS) and set the stage for the Morning and Afternoon "A-Train" Constellations that followed.[19]

Finally, there have been huge advances in the performance of modern science instruments from those in orbit 60 years ago. As one example, the Vanguard II cloud-mapping instrument had a single channel sensitive in the 0.5-to-0.8-μm wavelength range, while modern Earth-observing instruments use sophisticated radiometers and spectrometers—some with hyperspectral capabilities—to measure from the short ultraviolet wavelengths to those in the long microwave region. Further advances in remote sensing include the deployment of active instruments such as lidars and radars. Even global positioning satellite (GPS) signals originating in space are used for Earth observations.

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[17] This number is approximate since it relies on start and end dates and what launches are included: For a listing of launches, see *http://planet4589.org/space/log/launchlog.txt*. The NASA Delta II launch reliability was 98% (depending on success criteria).

[18] JPSS is the U.S.'s new generation polar-orbiting operational environmental satellite system. It is a collaborative program between NOAA and NASA. JPSS-1 was named NOAA-20 after successfully reaching orbit in 2018.

[19] These two Constellations have been discussed in previous articles in *The Earth Observer*. For an excellent summary of the A-Train's history and achievements, read "The Third A-Train Symposium and Perspectives on a Decade of Constellation Based Observations" in the July–August 2016 issue of *The Earth Observer* [**Volume 29**, **Issue 4**, pp. 4-18—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/July%20August%202017%20color%20508.pdf#page=4*].

The NASA–NOAA partnership that began so auspiciously with TIROS continues to the present day. The NASA-funded Suomi National Polar-orbiting Partnership (Suomi NPP)[20] launched in October 2011, uses the most modern satellite technology and advanced instruments with legacies that go back to Vanguard. Data from the satellite, originally destined for research, have now taken on additional purposes by becoming available for NOAA's operational applications. NOAA-20 has capabilities similar to those of Suomi NPP, extends the legacy of the Vanguard and Explorer missions to the present day.

The NASA–NOAA partnership that began so auspiciously with TIROS, continues to the present day.

Conclusion

The U.S. entry into space was fraught with many obstacles that included technical challenges, political hurdles, as well as funding uncertainties. There was tremendous pressure on the scientists and engineers because of competition between the Army and Navy to launch a satellite. The situation became even more intense when the Soviet Union launched a satellite first.

The public thought Vanguard was a failure because it was not first to go into space. But "...the record is clear. Project Vanguard justified the faith of its supporters not only because of its participation in the IGY, but also for developing a vehicle with growth potential..."[21]

To realize that potential, both the Army and Navy rallied their resources and—despite repeated failures—methodically developed the technology, tests, and procedures to successfully build a rocket and put a satellite into orbit—capabilities that form the basis for our present-day run of sophisticated satellites and instruments, to the clear benefit of our global society.

Acknowledgment

This article relied heavily on *NASA Report SP-4202* and the book by the same author, titled "Project Vanguard" by Constance McLaughlin Green and Milton Lomask. This author also consulted *NASA Report SP 4301*, "Venture Into Space—Early Years of Goddard Space Flight Center" and *NASA Technical Report R-131*, "TIROS I Meteorological Satellite System Final Report" (1961) edited by William B. Stroud, Lewis J. Allison, and Ernest A. Neil (GSFC) who were colleagues of this author. Multiple NASA, NRL, and NOAA websites were also used as resources. Finally, this author would like to acknowledge **Mitch Hobish** [Sciential Consulting, LLC], co-editor for *The Earth Observer*, for his comprehensive reviews of this article and the suggestions he made. ■

[20] The satellite is named after Verner E. Suomi, recognized as a developer of imaging technologies that made modern weather satellites possible. He was also originator of the radiation budget series of satellite measurements beginning on Explorer 7 launched in October 1959.
[21] Quoted from *NASA Report SP-4202*; see *Acknowledgment.*

Summary of 2018 Ocean Surface Topography Science Team Meeting

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Introduction

The 2018 Ocean Surface Topography (OST) Science Team Meeting (STM) was held September 27-28, in Ponta Delgada, Sao Miguel Island Azores Archipelago, Portugal. This year's meeting was also part of a larger event titled the "25-Years of Progress in Radar Altimetry" Symposium, which took place September 24-29, 2018, at the same location. The European Space Agency (ESA) and Centre National d'Études Spatiale (CNES) [French Space Agency] organized this symposium, which was dedicated to reviewing the scientific and technical accomplishments of the past two-and-a-half decades of satellite altimetry.

The primary objectives of the OST STM were to address specific technical issues on the Ocean Topography Experiment (TOPEX)/Poseidon-Jason series of missions, including algorithm and model improvement, calibration/validation (cal/val) activities, merging TOPEX–Jason data with those from other altimetric satellites, and preparation for future OST missions.

In terms of agenda for the OST STM, the meeting began with an opening plenary session, followed by a series of splinter sessions, and then a closing plenary session. The splinter sessions included:

- Application Development for Operations;
- Instrument Processing: Measurement and Retracking;
- Instrument Processing: Propagation, Wind Speed, and Sea State Bias;
- Outreach, Education, and Altimetric Data Services;
- Precise Orbit Determination;
- Quantifying Errors and Uncertainties in Altimetry Data;
- Regional and Global Calibration/Validation for Assembling a Climate Data Record;
- The Geoid, Mean Sea Surfaces, and Mean Dynamic Topography;
- Tides, Internal Tides, and High-Frequency Processes; and
- Advances in Coastal Altimetry: Measurement Techniques, Science Applications, and Synergy with *In Situ* Observations and Models.

This report begins with an overview of the status of current and planned OST missions, followed by a brief summary of the STM. The official report from the OST STM, along with all of the presentations from the plenary, splinter, and poster sessions are available at *http://meetings.aviso.altimetry.fr*.

Status Report on Ocean Surface Topography Missions

This section reports on the status of several current and planned OST-related satellite missions.

Jason-3

Jason-3, which was launched on January 17, 2016, continues the 27-year reference series of measurements of sea level, ocean winds, and waves. It took over as the reference mission on June 21, 2016, replacing Jason-2 in that role, and is fully operational with all redundant systems available. In early 2019 Jason-3 will complete its three-year prime mission and begin its extended phase.

Jason-2

Jason-2 (launched in June 2008) remains in operation and continues to provide data of excellent quality—but with reduced availability since March 2017, due to issues with the satellite's attitude control system—after about five months in an *interleaved orbit* with Jason-3.[1] Despite the issues with its attitude control system, the overall availability of Jason-2 data has been unexpectedly high (89% availability since the 2017 OST STM). In July 2017 Jason-2 was moved to a long repeat orbit (LRO), which is colloquially referred to as the *geodetic orbit*, approximately 27 km (~17 mi) below the reference orbit as recommended by the Ocean Surface Topography Science Team (OSTST) in 2016. Finally, Jason-2 was moved again to an interleaved LRO in July 2018 after the first LRO cycle was achieved. In light of this assessment, the OSTST adopted two recommendations:

- Recognizing the ongoing importance of Jason-2 and SARAL/AltiKa[2] for operational oceanography and improvement of the marine geoid, the OSTST recommends that operation of these missions be continued beyond 2019.

[1] The interleaved orbit of Jason-2 was identical to the one that Jason-1 assumed after the launch of Jason-2, and was designed to provide improved spatial and temporal coverage of sea surface height observations.

[2] SARAL stands for Satellite with Argos (a French data-collection system) and AltiKa (itself a K_a-band altimeter). It is a cooperative altimetry mission between the Indian Space Research Organisation (ISRO) and CNES.

- To support higher resolution of the mean sea surface and geoid for upcoming missions like SWOT as well as operational oceanography applications, the OSTST recommends that Jason-2 should complete an additional interleaved ground track, 2-km (~1-mi) offset from its current orbit.

Sentinel-3B

Sentinel-3B[3] was launched on April 25, 2018, joining Sentinel-3A, which had been in orbit since its launch in February 2016. A *tandem phase* between Sentinel-3A and -3B (which both have high-inclination altimeters onboard) was performed until October 16, 2018, with a 30-second temporal separation of between spacecraft. After a drifting phase, Sentinel-3B has reached its nominal orbit, 140° out of phase with Sentinel-3A[4], and the routine operation phase will begin early 2019. First analyses of the tandem data show excellent agreement between Sentinel-3A and Sentinel-3B.

Copernicus Sentinel-6/Jason Continuity of Service and Beyond

Turning to the future, the Copernicus Sentinel-6/Jason Continuity of Service (S6/JCS) mission, the successor to Jason-3, is now in full development with the partner agencies [ESA, NASA, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and the U.S. National Oceanic and Atmospheric Administration (NOAA), with CNES providing expert support in and advisory capacity]. Operational continuity of Jason-3 is assured by the Sentinel-6A and Sentinel-6B satellites that will occupy the reference orbit and role with a planned launch of Sentinel-6A in November 2020. Both Sentinel-6A and -6B will carry a new high-resolution-mode (HRM) synthetic aperture radar (SAR) altimeter capable of simultaneously generating low-resolution-mode (LRM; conventional pulse-limited altimeter operation) and HRM products. The mission also includes the trifrequency Advanced Microwave Radiometer (AMR-C). The Mission Advisory Group (MAG) will also continue to report to and report back from the OSTST to ensure that OSTST and MAG activities are aligned and shared.

[3] The Sentinel Missions are part of ESA's Copernicus Programme. They are detailed at *http://m.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4.* Sentinel-3 and -6 are mentioned in this article.

[4] The Sentinel-3A and -3B satellites have the same period, altitude, and inclination, but when they cross the Equator they are separated by 140° of latitude.

There were presentations on several other missions that are either proposed or in various stages of development, each with applications relevant to OST. These include (the):

- Chinese–French Oceanography Satellite (CFOSA), which is a wind and wave scatterometer mission scheduled for launch in October 2018;[5]
- NASA's Surface Water Ocean Topography (SWOT) mission, a high-resolution swath altimeter for the ocean, lakes, and rivers, planned for launch in 2021;
- ESA's Sea Surface Kinematics Monitoring Mission (SKIM) concept, which, if selected for development as an Earth Explorer mission, would utilize a novel wide-swath scanning multibeam radar altimeter to measure ocean-surface currents;[6] and
- Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL), which would carry a multifrequency radar altimeter and microwave radiometer to measure and monitor sea-ice thickness and overlying snow depth.[7]

Each presentation included information on the mission's status and development plans. Concerning these future missions, the OSTST adopted one recommendation and expressed its appreciation as follows:

- Because of rapid climatic changes at the poles and the importance of missions like CryoSat-28 for observing these changes, the OSTST recommends a long-term commitment to full Arctic coverage altimetry (e.g., as will be achieved if CRISTAL is chosen for development) in support of its objectives.
- The OSTST recognizes the importance of future missions that will provide unique opportunities to investigate direct measurement of surface currents and support the work of OSTST (e.g., SKIM).

[5] **UPDATE**: CFOSAT successfully launched on October 29, 2018, at 12:30 AM UTC aboard a Chinese Long March 2C rocket from Jiuquan Satellite Center in China.

[6] SKIM was one of two mission concepts that ESA chose for further development in November 2017 [the other being the Far-Infrared Outgoing Radiation Understanding and Monitoring (FORUM) mission]. One of these will be chosen in July 2019. The "Earth Explorer 9" will launch in the 2025 timeframe.

[7] CRISTAL is one of six high-priority candidate missions that are being studied to address European Union policy and gaps in Copernicus user needs, as well as to extend the current capabilities of the Copernicus space components.

Opening Plenary Session Highlights

Pascal Bonnefond [CNES—*Jason Project Scientist*] began with welcoming remarks on behalf of all the project scientists, who (in addition to himself) include **Josh Willis** [NASA/Jet Propulsion Laboratory (JPL)], **Eric Leuliette** [NOAA], **Remko Scharroo** [EUMETSAT], and **Craig Donlon** [ESA].

Because the OST STM took place in conjunction with the "25-Years..." symposium, all keynote presentations and science splinter-group meetings were held as part of the symposium and can be found at the URL referenced in the Introduction.

The following program managers presented the status of altimetry and oceanographic programs at their respective institutions: **Eric Lindstrom** [NASA]; **Sophie Coutin-Faye**, on behalf of **Juliette Lambin** [both from CNES]; **François Parisot** [EUMETSAT]; **Eric Leuliette** [NOAA]; and **Jérôme Benveniste** [ESA].

Splinter Session Highlights

The foci of the 10 splinter sessions are listed in the Introduction. Space precludes describing all the sessions in detail, but complete coverage of the results can be found at the AVISO website mentioned in the Introduction. This report will focus on two of the splinter sessions that presented subjectively scientifically compelling results.

Regional and Global Calibration/Validation for Assembling a Climate Data Record

Although this splinter session was rather technical in nature, its activities remain some of the most important for the OSTST as a group. Each year this splinter makes a careful assessment of the satellite altimeter data and its accuracy. The satellite altimeters provide the most accurate and complete measure of global sea level rise—the clearest indicator of human-caused warming of the climate. **Figure 1**, presented by **Eric Leuliette** [NOAA], shows how satellite altimeters compare with long-term tide gauges around the world, which provide a completely independent measure of sea level change at their locations. Averaged globally over dozens of tide gauges and other altimeter measurements, it is clear that they agree to better than 1 cm (~0.4 in), with no significant drift between, across all four reference missions dating back to TOPEX/Poseidon in 1993. Such excellent agreement provides independent verification that the roughly 3 mm (~0.1 in) per year rise in global sea levels measured by the satellite missions during the last quarter century is real and accurate.

The Geoid, Mean Sea Surfaces, and Mean Dynamic Topography

Although satellite altimeters now track global sea level rise as part of their primary mission objectives, ocean altimetry began in the early 1990s with a science objective of monitoring ocean currents and how they change over time and space. Large-scale ocean currents that persist for more than one day and travel over distances of many kilometers manifest a tilt in the level of the ocean. This means that measurements of sea level can be used to infer ocean currents. This splinter group was dedicated to separating out the sea level signal related to ocean currents from the complicated gravity field, which reshapes the ocean surface to reflect changes in the thickness of the crust and the shape and depth of the sea floor, and which doesn't really change much over time. Recent work can now separate these two signals with very high accuracy and resolution. The part due to time-averaged ocean currents is known as the *mean dynamic topography.*

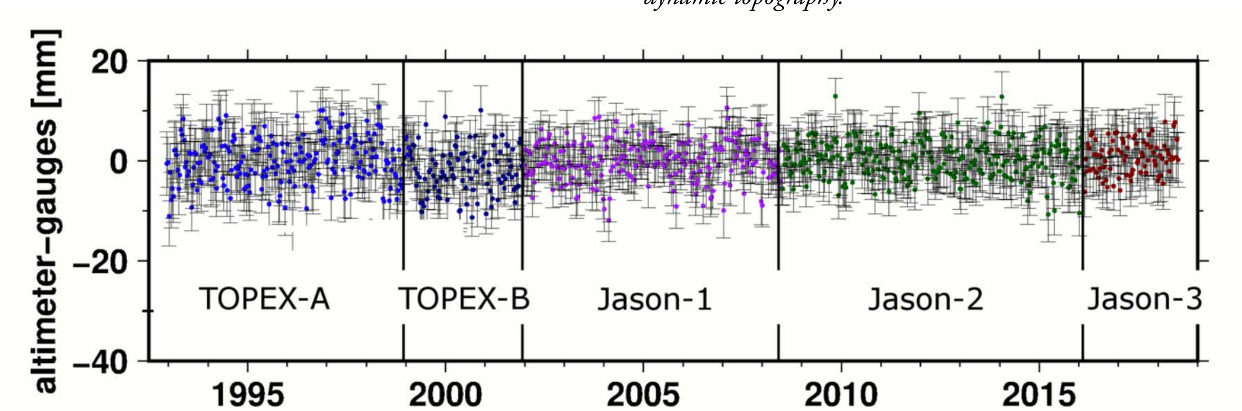


Figure 1. This time series shows the difference between sea level measured by satellite altimeters and local tide gauges. The differences are averaged over dozens of tide gauges for each 10-day repeat cycle of the satellite altimeter. The different missions are shown across the time series. Note that TOPEX was switched to its redundant altimeter in February of 1999—which is why there is a TOPEX-A and TOPEX-B section of the graph. The drift between the tide gauges and the altimeters is constrained to be less than 0.2 mm (~0.01 in) per year across the entire record. The fact that the data are so close to zero over the entire 25-year period is a testament to the accuracy of the altimeter missions at measuring sea level change. **Image credit**: Eric Leuliette

Figures 2 and **3**—presented by **Marie-Helene Rio** [ESA] and **Per Knudsen** [Technical University of Denmark, Danmarks Tekniske Universitet (DTU) Space; Denmark's national space institute], respectively—show two examples of mean dynamic topography estimates over the East Sea (north of Japan) and the Gulf Stream (off the U.S. East Coast). Each case contrasts a newer estimate of the "mean dynamic" part of OST with a previous version. In both cases, the newer version of the estimate [see right image in both Figures] does a better job resolving the smaller scale ocean features than its predecessor, which, in each case, uses less data as input [see left image in both Figures]. This means that maps of absolute ocean currents based on satellite altimetry can now be made with much higher resolution and fidelity than before.

Closing Plenary Session Highlights

The closing plenary session took place on Friday afternoon. There was a report on each splinter session which included responses to comments on key discussion items posed by the project scientists at the beginning of the meeting. **Paolo Cipollini** [National Oceanography Centre, U.K.] provided a summary of the Eleventh Coastal Altimetry Workshop, which took

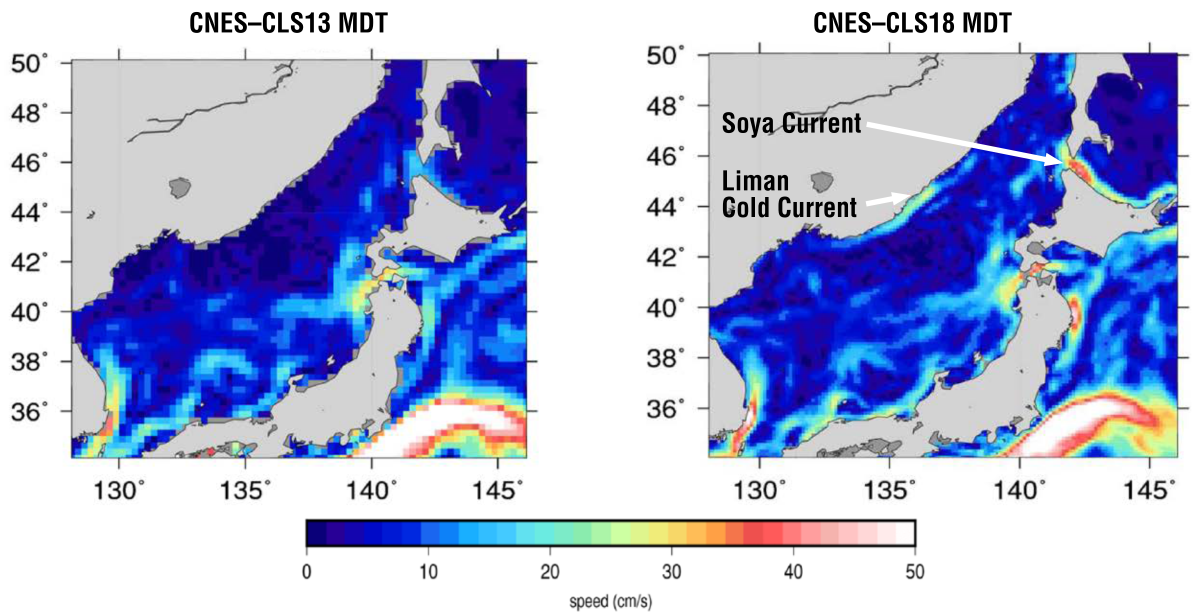


Figure 2. Maps showing currents in the East Sea—north of Japan—from a previous estimate of mean dynamic topography from CNES [*left*], compared to the most recent version [*right*]. The bright features on the maps show currents. Notice that many of the smaller currents near the coast are only visible in the most recent update [*right*], which uses more data and has better resolution than its predecessor. For example, the smaller Liman and Soya currents could not be resolved in the older version [*left*] but now show up in the newer version [*right*]. **Image credit:** Marie-Helene Rio

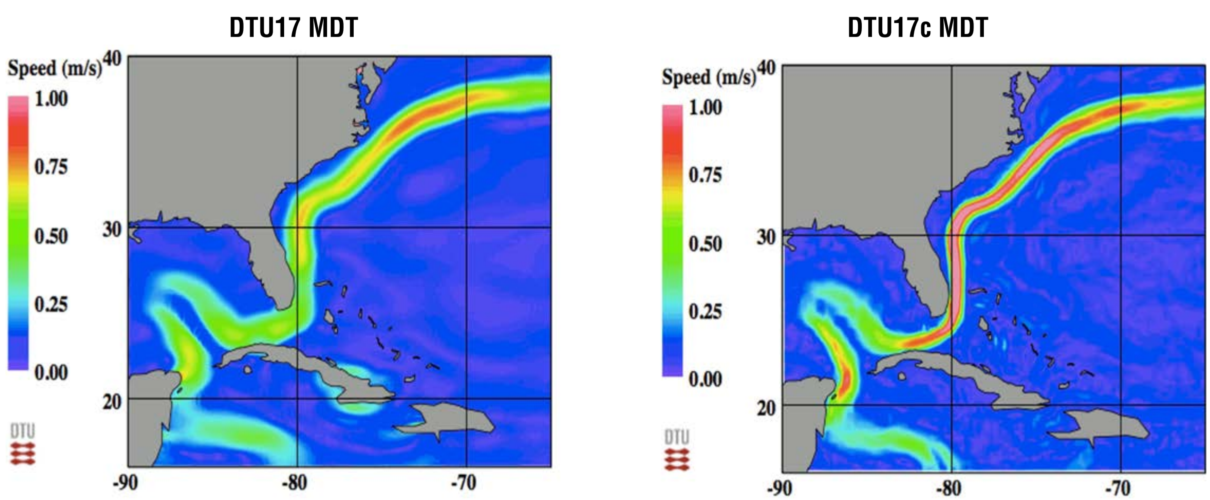


Figure 3. Maps showing the Gulf Stream off the U.S. East Coast based on an estimate of mean dynamic topography from DTU Space. The newest estimate, called "DTU17c MDT" [*right*] combines satellite data and surface drifter data. Notice how it more accurately depicts the speed and narrow extent of the Gulf Stream, than the version shown in the left panel, which shows the same recent estimate—but based solely on satellite data. **Image credit:** Per Knudsen

place February 12-15, 2018, at the European Space Research Institute (ESRIN) in Frascati, Italy. The workshop was "a lively forum for a community-led review of the science and applications of coastal altimetry, from data processing through emerging applications to new technologies."[8] Cipollini also noted that the community continues to exploit the existing constellation of altimeters in preparation for the high-resolution data that will be provide by SWOT in a few years.

Conclusion

During the closing session, the OSTST adopted the recommendations to continue operation of CryoSat-2 beyond 2020, and that the Sentinel-3 missions should continue to perform tandem-phase operation between successive missions to ensure good intercalibration, as was done between Sentinel-3A and -3B. Other specific recommendations can be found in the complete OST STM report referenced in the Introduction.

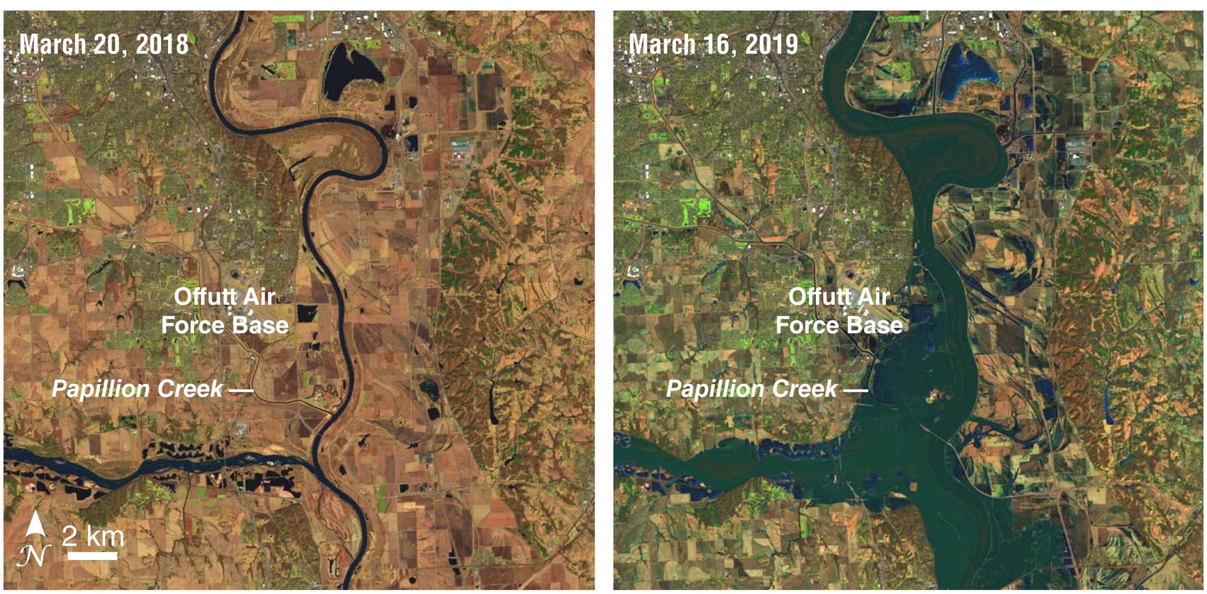
As has become customary for such gatherings, this OST STM ended with a number of acknowledgments and kudos, several of which refer to recommendations made by the OSTST. The team acknowledged the various space agencies for maintaining the launch schedule of Jason-CS/Sentinel-6 to overlap with Jason-3, the successful tandem phase between Sentinel-3A and -3B, maintenance of the aging Jason-2 spacecraft to extend its scientific and operational output, and ongoing work on reprocessing TOPEX data. Additional acknowledgments can be found in the full OST STM report link.

Overall, the meeting fulfilled all of its objectives. It provided a forum for an update on the status of Jason-2 and Jason-3 and other relevant missions and programs, and for detailed analyses of the observations by the splinter groups. The team concluded that data from the Jason-2 and -3 altimeters continue to meet the accuracy and availability requirements of the science community, and that the constellation of altimeters is currently in excellent shape, with 7 satellite altimeters in operation.

The 2019 OST STM will be held October 21-25, 2019, in Chicago, IL.

Acknowledgment: This report is based on the official meeting report, which is referenced in the Introduction of this article, and which was prepared in cooperation with all of the OSTST chairs: **Pascal Bonnefond** [Observatoire de Paris - SYRTE, CNES]; **Josh Willis** [JPL] (author of this summary); **Eric Leuliette** [NOAA]; **Remko Scharroo** [EUMETSAT]; and **Craig Donlon** [ESA]. ■

[8] To learn more about this workshop, visit *https://www.coastalaltimetry.org/QuickEventWebsitePortal/11th-coastal-altimetry-workshop/esa*, and the link to its final report can be found here: *https://www.coastalaltimetry.org/QuickEventWebsitePortal/11th-coastal-altimetry-workshop/esa/ExtraContent/ContentPage?page=10*.



In the wake of an intense winter storm, historic floods broke out across the central U.S. in March 2019. By mid-March, several streams and rivers had risen to all-time record levels in Nebraska, Iowa, South Dakota, and Wisconsin. Nebraska was particularly hard hit. On March 16, 2019, the Operational Land Imager (OLI) on Landsat 8 captured a false-color image that underscores the extent of the flooding on the Platte, Missouri, and Elkhorn Rivers. For comparison, the second image shows the same area in March 2018. Several communities west of Omaha (between the Elkhorn and Platte Rivers) either flooded or temporarily became islands as floodwaters encroached from both sides. A rare confluence of circumstances produced the flooding. Extreme cold earlier in the winter set the stage by preserving a significant amount of snow; it also created a thick layer of ice on waterways and made the ground less permeable than usual. When an intense storm brought downpours and unusually warm air to the region in March, it rapidly melted much of the snow and ice, producing enormous runoff in a short period. As river ice broke up, large chunks compounded the problem by slamming into dams, raking against levees and other infrastructure, and packing together to jam waterways even more. **Credit:** NASA's Earth Observatory

Summary of 2018 Precipitation Measurement Mission Science Team Meeting

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Introduction

The Precipitation Measurement Missions (PMM) Science Team Meeting (STM) took place October 8-12, 2018, in Phoenix, AZ. The PMM program supports scientific research, algorithm development, and ground-based validation activities for the Tropical Rainfall Measuring Mission (TRMM)[1] and Global Precipitation Measurement (GPM) mission—including the GPM Core Observatory.[2] The 150 attendees came from NASA, Japan Aerospace Exploration Agency (JAXA), the U.S. National Oceanic and Atmospheric Administration (NOAA), universities, and other partner agencies, including 28 attendees from 9 countries outside the U.S.

There were 50 oral presentations across 13 sessions, as well as 99 posters presented in two sessions. The presentation and poster topics ranged from algorithm development and status to use of GPM data for new scientific research and societal applications. Presentations also covered mission status and activities. Eleven working group meetings were held throughout the week as well as the Joint PMM Science Team leadership board meeting.[3] This report summarizes the highlights of the PMM Science Team meeting. The agenda for the meeting and the full list of presentations can be found at *https://pmm.nasa.gov/sites/default/files/meeting_files/PMM%20Science%20Team%20Meeting%202018/PMM%20Oct%202018%20Oral%20Agenda.pdf.* For more information about GPM data products, science team activities, and future updates, visit *https://pmm.nasa.gov*.

Programmatic Updates and TRMM and GPM Status Reports

The first day of the meeting began with a programmatic session, detailing TRMM and GPM project status.

[1] While TRMM ended in 2015, data reprocessing is still ongoing.
[2] TRMM and GPM are partnerships between NASA and the Japan Aerospace Exploration Agency (JAXA), with 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.gsfc.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," at *https://doi.org/10.1002/qj.3313*.
[3] NASA's and JAXA's PMM science teams hold an annual invitation-only leadership board meeting designed to coordinate scheduling and approve joint TRMM and GPM mission activities and data products.

Gail Skofronick–Jackson [NASA Headquarters (HQ)—*GPM Program Scientist*] opened the meeting and welcomed participants. She discussed the state of NASA's current and upcoming Earth Science missions. In particular, she showed new results from RainCube—a technology demonstration mission to enable K_a-band precipitation radar technologies in a low-cost, small form-factor platform (i.e., a CubeSat), which was deployed from the International Space Station (ISS) on June 25, 2018, and the Temporal Experiment for Storms and Tropical Systems - Demonstration (TEMPEST-D)[4]—another CubeSat-type technology demonstration mission—which was launched from an Orbital Sciences Cygnus cargo ship in May 2018. Data from these new platforms are being used to demonstrate potential synergistic research using such new-generation small-satellite sensors. She also provided an overview of the 2017 Decadal Survey for Earth Science and Applications from Space,[5] emphasizing that Aerosol-Clouds, Convection, and Precipitation (A-CCP) is one of eight priority observables the Survey identified. Skofronick-Jackson provided status updates on the GPM Core Observatory. Specifically, she noted that the Dual-frequency Precipitation Radar's (DPR)[6] K_a radar has converted to full K_u-swath width and that spacecraft altitude adjustment fuel is currently predicted to last until about May 2035.

Scott Braun [NASA's Goddard Space Flight Center (GSFC)—*GPM Project Scientist*] provided an overview of the current GPM algorithm status, including the release of GPM Version 5 (V05) and V06 products in 2018 and the planned release of the Integrated Multi-Satellite Retrievals for GPM (IMERG)[7] V06 in 2019. As part of the GPM V06 release, TRMM V8 (final production) will be included to provide a consistent record of precipitation from 1998 through the present. He also provided some comparisons of the GPM Goddard Profiling Algorithm (GPROF) for the GPM Microwave Imager (GMI), showing strong consistency across the span between the TRMM and GPM eras. The DPR and combined algorithms show fair consistency, but magnitudes over land appear to

[4] To learn more about TEMPEST-D, visit *https://www.jpl.nasa.gov/cubesat/missions/tempest-d.php*.
[5] To read the 2017 Decadal Survey for Earth Science and Applications from Space, visit *http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm*.
[6] The DPR is one of two instruments onboard the GPM Core Observatory; the other is the GPM Microwave Imager (GMI).
[7] IMERG combines data obtained from all available microwave and microwave-calibrated infrared (IR) platforms of the GPM satellite constellation to make rainfall estimates. To learn more, visit *https://pmm.nasa.gov/data-access/downloads/gpm*.

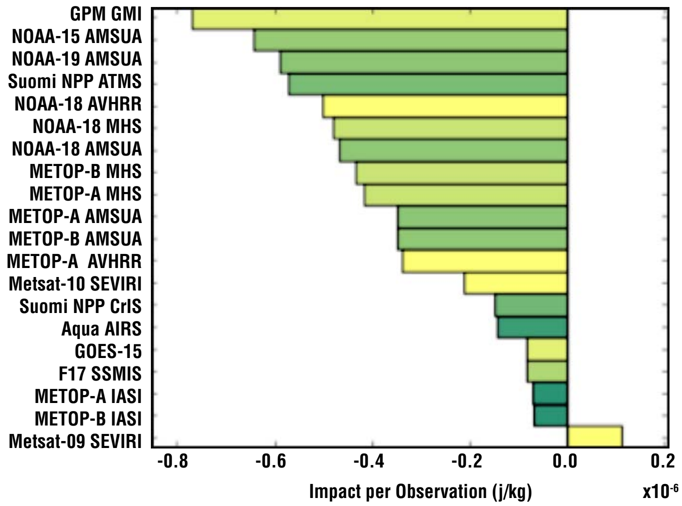

Figure 1. The GMI radiometer was compared to a variety of other NASA, NOAA, and European Space Agency radiometers. The y-axis of this bar graph lists acronyms for each instrument that are either defined in the text or can be easily found online. The unit on the x-axis is a measure of how the forecast improved when data from each instrument was incorporated. A negative value indicates improvement. GMI had the greatest impact per observation on improving forecasts. **Image credit**: Min-Jeong Kim [GMAO]

be low compared to ground observations. An exciting advancement over the past year was the assimilation of GPM GMI all-sky radiances within the Global Modeling and Assimilation Office (GMAO) Global Earth Observing System-5 (GEOS-5) model, with results suggesting that GMI currently has the most positive impact of any of the microwave sensors considered—see **Figure 1**. Finally, Braun announced that Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) was selected in the last Earth Venture Suborbital 3 (EVS-3) solicitation,[8] which will study U.S. East Coast snowstorms and include airborne and ground-based field campaigns. He stated that **Lynn McMurdie** [University of Washington] will be the principal investigator for IMPACTS.

Erich Stocker [GSFC—*GPM Deputy Project Scientist for Data*] discussed the status of GPM data products. GPM Core Observatory and constellation data products are provided through the Precipitation Processing System (PPS) STORM[9] tool and are freely available after registration. He provided a status report on the GMI products, which radiometer-based products are currently at V05 while radar-based products are at V06. The next version of products will be available in roughly two years (2021). He also talked about the changing security considerations, e.g., the decommissioning of anonymous *ftp* and the enlisting of *https* for file transfers, that will require a major rework for PPS's schemes for distributing data. Stocker outlined the different data formats that PPS provides and the opportunities for users to request parameter or spatial subsetting through interactive ordering. He pointed out that with the commercialization of HDF5 it might become necessary to change the archive format for GPM data products to netCDF4.[10,11] He closed by describing some new data products (such as Precipitation Features products and K_u-based subsets) that are of interest to the science community.

Dalia Kirschbaum [GSFC—*GPM Deputy Project Scientist for Applications*] provided an overview of current activities related to GPM applications science and outreach. She introduced an effort that has taken place over the past year to expand the portfolio of applications users, with the goal of better understanding the sectors from which users are pulling data. Over 4000 unique users have been identified across six thematic areas—see **Figure 2** (next page). Another big initiative in 2018 was a co-hosted workshop with The Wilson Center on *Vector and Waterborne Diseases* in May, 2018.[12] Over 100 scientists, practitioners, outreach specialists, and the operational community participated in this day-long event. Kirschbaum also highlighted outreach activities including new data access and visualization tools and new videos,[13] including a new 360˚ visualization of 2018's Hurricane Maria.[14]

[8] To learn more about IMPACTS, visit *https://www.nasa.gov/press-release/new-airborne-campaigns-to-explore-snow-storms-river-deltas-climate*.

[9] STORM is a publicly available Web-based data access interface for the GPM Mission's Precipitation Processing System (PPS). Visit *https://storm.pps.eosdis.nasa.gov* for more details.

[10] HDF5 stands for Hierarchical Data Format-5, which is a general-purpose library and file format for storing scientific data. NetCDF-4 stands for Network Command Data Form-4, which another scientific programming interface for array-oriented data access and a freely distributed set of data libraries for C, Fortran, C++, JAVA, and other programming languages.

[11] While HDF will maintain a public version, which may or may not get new service, the HDF Group's focus will be on improving and selling an HDF5 version. This means that other tools like Interactive Data Language (IDL) and MatLab might eventually stop supporting HDF.

[12] See "Summary of the 2018 Vector-Borne and Water-Related Disease Workshop" in the November–December 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 6**, pp. 23-30—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Nov_Dec_2018_color508_0.pdf#page=23*]. Information on the Vector and Water-Borne Disease Workshop is also available at *https://pmm.nasa.gov/disease-initiative*.

[13] All visualizations and videos are available at *https://svs.gsfc.nasa.gov/Gallery/GPM.html*.

[14] To view the visualization, visit *https://pmm.nasa.gov/articles/dive-360-view-hurricane-maria*.

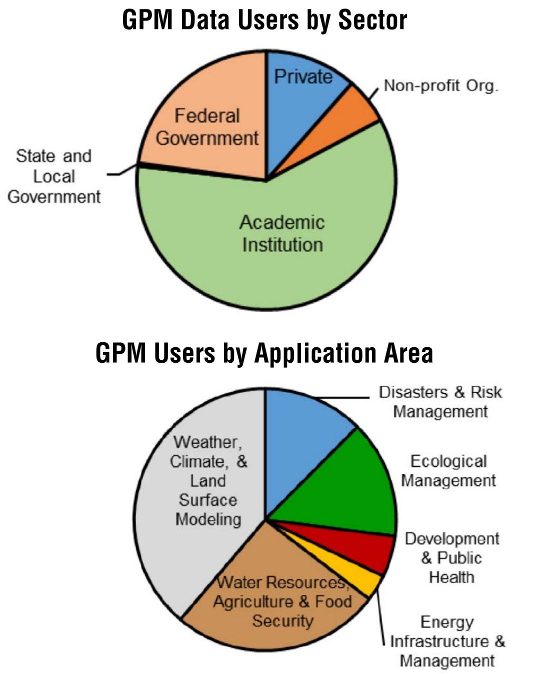

Figure 2. Distribution of GPM Data Users by sector [*top*] and by application areas [*bottom*] based on a database of 4012 users obtained from the PPS team. **Image credit:** Andrea Portier [GSFC/Science Systems and Applications, Inc.]

Next, Japanese PMM STM members provided updates. **Takuji Kubota** [JAXA] gave an overview of JAXA's PMM program status, stating that the Japan Meteorological Agency (JMA) started assimilating DPR data into their numerical weather prediction (NWP) model in March 2016. JAXA is also experimenting with assimilation of JAXA's Global Satellite Mapping of Precipitation (GSMaP) product[15] into the high-resolution Nonhydrostatic ICosahedral Atmospheric Model (NICAM).[16] He announced that JAXA is working with the Indian Space Research Organisation (ISRO) to validate DPR and GSMaP data over India, with a focus on increasing hydrological and NWP applications. **Yukari Takayabu** [University of Tokyo—*GPM Project Scientist*] gave an update on the performance of GSMaP products, providing some science highlights about how rain gauge adjustments and better accounting for the depth of frozen precipitation is helping to greatly reduce the bias of the current version. **Toshio Iguchi** [National Institute of Information and Communications Technology] and **Kenji Furukawa** [JAXA—*DPR Program Manager*] outlined activities related to the DPR algorithms, testing, and calibration being done on the DPR K_a-frequency radar.

Algorithm Status

Following the programmatic updates in the opening session, the Algorithm Status session provided information and updates on various aspects of the GPM algorithms, including discussions of intercalibration of the GPM microwave radiometer constellation and plans for DPR, GPROF, and IMERG.

Wes Berg [Colorado State University (CSU)] presented information on the XCAL Team's[17] work over the past year to extend the GPM Level-1C data record with the addition of data from a number of instruments on partner satellites that represent a long-term, intercalibrated data record that extends over 31 years. The data record includes measurements from 14 conical-scanning window-channel radiometers and 10 cross-track scanning water vapor sounding radiometers. The quality and extent of this combined Level-1C data record (available via "Data Access" on the PMM website referenced in the Introduction) makes it of significant value not only for precipitation applications, but also for climate data records for a number of other applications including ocean surface property retrievals for air-sea interaction research and snow cover, and snow water equivalent retrievals for cryospheric research.

Bob Meneghini [GSFC] gave an update to the group on how the radar team has been developing an improved estimate of path-integrated attenuation (PIA) using the new K_a-band full-scan data that are being applied to both single- and dual-frequency DPR data, which will help reconstruct the range profile of rainfall. The results show that the *hybrid estimate* [i.e., the weighted sum of the *surface reference technique (SRT)* and other methods that help derive PIA] provides more-accurate representations of the PIA than the SRT. Meneghini noted that when SRT (a method which attenuation is estimated as the difference between the surface cross section outside the rain and the apparent surface cross section measured in rain) performs poorly, the other methods will be weighted more highly so that the hybrid estimate of path attenuation generally will be more accurate than the SRT.

Bill Olson [University of Maryland, Baltimore County/GSFC] outlined how rain rates from the combined radar-radiometer algorithm compare between the TRMM and GPM missions, finding that TRMM mean rain rates are ~3% lower than GPM. He suggested that this negative bias may be largely explained by lower TRMM Precipitation Radar sensitivity relative to the DPR K_u-band on GPM. Olson indicated that future work will test the drop size distribution (DSD) and other parameterizations of the algorithm to determine how products may be adjusted to correct for these biases.

Chris Kummerow [CSU] presented the latest developments of the GPROF algorithm for GPM's passive

[15] GSMaP is the JAXA equivalent of IMERG.

[16] NICAM is used as a Global Cloud Resolving Model. To learn more, visit *http://nicam.jp/hiki/?About+NICAM*.

[17] The XCAL team was established in 2007 as an *ad hoc* working group within the Precipitation Measurement Missions (PMM) science team. The XCAL team has responsibility for the intercalibrated Level-1C Tb files that are used as input for the radiometer retrieval algorithm.

microwave system. He highlighted that results are consistent among sensors and generally are in good agreement with validation statistics. One key advancement this year is how the algorithm separates convective and stratiform rainfall, which is being done using much better artificially intelligence-based "deep learning" tools. Algorithm challenges still exist in resolving high-latitude drizzle and orographic precipitation.

George Huffman [GSFC] gave a status update on the IMERG algorithm, announcing that Version 6 of IMERG will be available in 2019 and will include data from 2000 to the present. Upgrades will include switching to *morphing vector sources*, which are used to express the motion of a data field, provided by the Modern Era-Retrospective Analysis for Research and Applications-2 (MERRA-2)/Goddard Earth Observation System Forward Processing (GEOS FP). Precipitation estimates will be available from pole to pole for all nonsnow/icy surfaces and complete (i.e., snow-covered surfaces included) in the latitude band 60° N-60° S.[18] He noted that the Quality Index, which indicates where precipitation estimates may not be as accurate, will be modified for the half-hourly product at satellite overpass times.

GPM Partner Reports and Related Mission Activities

Day one concluded with a session focusing on programmatic updates from three of GPM's constellation partners: NOAA, the French Centre National de la Recherche Scientifique (CNRS), and the Italian Institute of Atmospheric Sciences and Climate (CNR-ISAC).

Ralph Ferraro [NOAA/National Environmental Satellite, Data, and Information Service (NESDIS)] summarized NOAA's current status of operational precipitation products and contributions made to PMM. He highlighted that NOAA's polar-orbiting and geostationary-orbiting satellites [Suomi National Polar-orbiting Partnership (NPP) and NOAA-20, and Geostationary Operational Environmental Satellites (GOES)-16 and -17, are generally performing well. He summarized how GPM data are being used in NOAA's operational products, including the use of GPROF to support operational use of data from JAXA's Global Change Observation Mission-Water (GCOM-W), which includes NASA's Advanced Microwave Scanning Radiometer 2 (AMSR-2), and the use of GMI snowfall rates within NOAA's operational products. Lastly, Ferraro concluded by stating that the NOAA–PMM memorandum of understanding has been renewed for another five years, and that a NOAA PMM omnibus project is underway.

Rémy Roca [CNRS] provided a status update on the joint CNRS/ISRO Megha-Tropiques satellite, noting that the satellite celebrated its seventh year in orbit during the PMM meeting and is still performing very well. He highlighted that data from the Sounder for Probing Vertical Profiles of Humidity (SAPHIR) instrument onboard Megha-Tropiques is regularly assimilated in many forecast systems around the world and Version 1.5 of the Tropical Amount of Precipitation with an Estimate of ERrors (TAPEER) rainfall algorithm (released in June 2017) provides a multi-satellite, daily precipitation estimate with 1° spatial resolution that is adjusted to the PMM satellite radars. Lastly, Roca informed the group that a five-year mesoscale convective system (MCS) tracking dataset using the Tracking Of Organized Convection Algorithm (TOOCAN)[19] has been recently completed and demonstrates the importance of acquiring data from convective systems lasting longer than 12 hours.

Giulia Panegrossi [CNR-ISAC] presented an overview of Snow retrievaL ALgorithm fOr gMi (SLALOM), which provides snow, supercool droplet occurrence, and snow water path in high latitude regions at each pixel, and uses the CloudSat radar to help calibrate and validate GMI snowfall dataset. She also noted that an independent ground validation (GV) effort would be very useful.

Looking forward, **Scott Braun** presented plans for the A-CCP Designated Observable study. A-CCP was deemed a priority in the 2017 NASA Earth Science Decadal Survey.[20] This multicenter study involves scientists from many institutions (both government and academic), and Panegrossi stressed that strong links are desired to the *program-of-record* (existing and planned observing systems) and outside partnerships.

Science and Applications Activities

The second and third days of the meeting featured seven sessions that focused on science results from TRMM and GPM data. A range of themes emerged from the presentations that included instrument parameterization, advance processing techniques, and GV science highlights.

Several presentations focused on GPM validation and improved approaches to GPM algorithm retrievals of rain and snow. **Robert Adler** [University of Maryland, College Park (UMD)] compared global characteristics of the precipitation products from TRMM, GPM, and the Global Precipitation Climatology Project

[18] For a more detailed explanation of why the coverage is incomplete at higher latitudes, see *https://pmm.nasa.gov/content/what-difference-between-global-90%C2%B0n-s-and-full-60%C2%B0n-s-coverage-imerg.*

[19] TOOCAN is an algorithm for the detection and tracking of tropical mesoscale convective systems using infrared images from geostationary satellite.

[20] To learn more about A-CCP and the other Designated Observables, visit *https://science.nasa.gov/earth-science/decadal-surveys/decadal-survey-questions.*

(GPCP),[21] disaggregating results by sensor and latitude. He showed that over oceans at low (high) latitudes, precipitation estimates from GPM and TRMM were found to be slightly higher (lower) than GPCP and over land GPM and TRMM were low compared to GPCP. **Joe Munchak** [GSFC] focused on the incorporation of "nonrain" parameters such as wind, temperature, and water vapor in the GPM combined algorithm. **Chris Kidd** [GSFC] provided an overview of the newly developed cross-track precipitation retrieval scheme — Precipitation Retrieval and Profiling Scheme (PRPS)— highlighting recent findings to capture emissivity estimates from microwave sounders.

Other presentations evaluated the performance of the GPM instruments for high-intensity precipitation events and large-scale precipitation events. **Chuntao Liu** [Texas A&M University] presented results from two decades of global intense precipitation data from passive microwave (PMW) instruments, finding that the PMW sensors provide better coverage of convection than the TRMM and GPM radars. **Jimmy Booth** [City College of New York] presented a methodology to track extratropical cyclones, which generate the majority of total and extreme precipitation at midlatitudes using the IMERG product, and examined the relationship to cyclone vorticity. **Dan Cecil** [NASA's Marshall Space Flight Center (MSFC)] discussed issues in assigning realistic precipitation rates for intense convection events that have low brightness temperatures such as encountered in GMI data. **Shuyi Chen** [University of Miami] presented a methodology for large-scale precipitation tracking of the Madden–Julian Oscillation (MJO) using 20 years of TRMM and GPM data.

Several other presentations covered GPM's GV and field campaign activities that are supported by the GPM project and GPM partners around the world. **Walt Petersen** [NASA's Marshal Space Flight Center (MSFC)—*GPM Deputy Project Scientist for Ground Validation*] summarized GPM's GV program, including the use of GV data (both rain and snow datasets) to evaluate the performance of DPR, combined, and IMERG products, and introduced new international radar datasets that will support GPM field campaigns. He also summarized the expanded development of field and partner contributions that contributed to the enhancement and production of precipitation products. **Brian Colle** [Stony Brook University] presented material on the differences between collected GV observations and Weather Research and Forecasting (WRF) model simulations using three different bulk cloud microphysics schemes from extreme orographic precipitation events during the Olympic Mountain Experiment (OLYMPEX) field campaign.[22]

[21] To learn more, about GPCP, visit *http://gpcp.umd.edu*.
[22] To learn more about OLYMPEX, visit *https://pmm.nasa.gov/olympex*.

Twenty-eight representatives from the international community participated in the STM, with five giving presentations that highlighted a variety of recent, current, and future potential higher latitude GPM ground validation efforts.

Dmitri Moisseev [University of Helsinki, Finland] provided an overview of multi-year combined multifrequency radar (both scanning and profiling) and *in situ* snow microphysics observations in Finland. The observations have served as one of the premier high-latitude snow validation sites for GPM radar and radiometer snowfall rate retrievals, producing updated snow particle mass retrievals and providing a valuable ice scattering model testbed for radar-forward modeling activities.

GyuWon Lee [Kyungpook National University, Republic of Korea] presented results from the recent snowfall-focused International Collaborative Experiments for Pyeongchang 2018 Olympic and Paralympic Winter Games (ICE-POP) field campaign in South Korea.[23] The field campaign employed multifrequency scanning and profiling radars, *in situ* snow microphysics, and a suite of ancillary sensors at numerous ground-based supersites to study topographic influences of snowfall production and snow microphysical composition.

Jun Park [National Meteorological Satellite Center/ Korea Meteorological Administration (NMSC/KMA), Republic of Korea] reported on GPM GV efforts in South Korea as well, highlighting the evaluation of GPM precipitation products against observations from a very dense network consisting of 600 rain gauges with a density of 1 gauge per 13 km^2 (~5 mi^2). The high-density network allows comprehensive examination of retrieval errors with support of ground-based radar observations.

Remko Uijlenjoet [Wageningen University, Netherlands] suggested that ground-based assets deployed in the Netherlands would be potentially valuable higher-latitude GPM validation datasets. These "opportunistic" datasets include those from personal weather stations and rainfall rate retrievals using attenuation of telecommunication microwave links. Raingauge-adjusted rainfall dataset comparisons to the IMERG product at different time scales were also presented to demonstrate specific GPM-related validation activities.

Daniel Vila [Centro de Previsão de Tempo e Estudos Climáticos/Instituto Nacional de Pesquisas Espaciais (CPTEC/INPE), Center for Weather Forecast and Climatic Studies/National Institute for Space Studies, Brazil] presented physical validation examples using

[23] ICE-POP is a strong collaborative observational effort between South Korea, NASA, and GPM-funded researchers, and serves as a valuable reference dataset for future GPM cold-season precipitation retrieval evaluations. To learn more about ICE-POP, visit *https://pmm.nasa.gov/ice-pop*.

observations from the SOS-Chuva campaign.[24] He also reported on the use of DPR-K_u retrievals to develop a correction model based on histogram matching to improve hydroestimator quantitative precipitation estimates over Brazil, with very good results.

Another topic covered was how GPM data can be used to better characterize microphysical properties and model DSDs, ice particles, and surface emissivities. **Andy Newman** [National Center for Atmospheric Research] summarized applications of new imaging technologies and scattering models used to describe falling snow and ice particles by comparing GCPEx[25] disdrometer data of snow retrievals from D3R K_a-K_u band radar. He noted that D3R K_a-K_u band radar had a lower sensitivity in the retrieval. **Jay Mace** [University of Utah] evaluated snow bulk-property uncertainties derived from forward model errors and W-band radar pointing angles used to observe pristine snow particles. **Norm Wood** [University of Wisconsin-Madison] evaluated the change in snow particle size distribution (PSD) in the radar clutter blind zone between the surface and 1 km above ground level using surface snow imagers and vertically pointing radars.

Science reports also covered topics relating to how GPM retrievals can be used to improve model parameterizations, with topics ranging from ice crystal interactions to the role of convection in global climate models (GCMs). **Xiaowen Li** [Morgan State University/GSFC] discussed ice-phase microphysical processes observed during MCSs over the U.S. and Western Africa using GPM observations. Results showed that the MCS stratiform region can provide fairly consistent signals for model validation. **Anthony Del Genio** [NASA's Goddard Institute for Space Studies (GISS)] described differences between convective and stratiform rainfall and diabatic heating profiles in the GISS global climate model (GCM) and compared them to retrievals from GPM. He showed that the GISS GCM is accurately representing the diabatic heating profiles as compared with the TRMM/GPM latent heating products. An observational database that combines GPM, TRMM, Atmospheric Infrared Sounder (AIRS), and MERRA-2 data, which is useful for examining the heating profiles, rain rates, and life cycles of tropical mesoscale convective systems showed that there were many characteristic trends in the temporal evolution of heating and precipitation that varied as a function of total system life cycle. **Ziad Haddad** [NASA/Jet Propulsion Laboratory (JPL)] and **Raúl Moreno** [University of Castilla-La Mancha, Spain] focused on radiometer observations from the GPM constellation to track the evolution of cloud-top heights and behavior of convective precipitation over oceans. **Guosheng Liu** [Florida State University] discussed the use of CloudSat data to assess the performance of snowfall detection from DPR and constellation radiometers. **Simone Tanelli** [JPL] discussed the effects of multiple scattering and nonuniform beam filling (NUBF) correction methods in DPR observations. **Luca Baldini** [CNR/ISAC] presented a comprehensive assessment of instrument errors due to temperature and wind Doppler effects on the statistics of the dual-frequency DSDs derived from radar profilers, and demonstrated a simple correction model assuming constant wind with height. **Merhala Thurai** [CSU] presented collaborative research on behalf of Alexis Berne's [Swiss Federal Institute of Technology Lausanne (EPFL)] group that described a model to represent the complete form of the rain DSD, especially representation of smaller drops occurring in light rain and drizzle—where many disdrometers have diminished measurement capability.

Three presentations discussed hydrometeorological studies using TRMM and GPM precipitation products for applications. **Guojun Gu** [University of Maryland, College Park, Earth System Science Interdisciplinary Center (ESSIC)] highlighted that the Global Flood Monitoring System (GFMS) has transitioned from running TRMM Multi-satellite Precipitation Analysis (TMPA) to IMERG in near real time from 50° N – 50° S. He showed results of some flood events, evaluating the applicability and accuracy of using IMERG for GFMS flood calculations. **Robert Field** [Columbia University/GISS] focused on the use of satellite precipitation for fire monitoring, highlighting the recent advances in fire danger ratings using satellite meteorological information. He showed results from recent wildfires around the world including Greece, Siberia, South Africa, and Indonesia. Lastly, **Eugenia Kalnay** [UMD] showed results from the assimilation of precipitation from TRMM and GPM to improve weather and hurricane forecasting. She highlighted that assimilation of IMERG data reduces errors in model-predicted fields, especially in mid- and high-latitude areas. She also noted that within a regional assimilation framework, the structure of simulations of west Pacific basin typhoons were also improved, which can help improve predictions of storm intensities.

Closing

Gail Skofronick-Jackson closed the meeting, announcing Ramesh Kakar's retirement as the GPM Program Scientist, and highlighting his dedicated service to the mission over the past 20 years. She also highlighted important directions for future science investigations, including finalizing the reprocessing of IMERG to the beginning of the TRMM era that will be available in 2019.

Acknowledgment: The authors would like to recognize the contributions that **Scott Braun**, **George Huffman**, **Walt Petersen**, **Erich Stocker**, and **Gail Skofronick-Jackson** made to prepare this article for publication in *The Earth Observer*. ■

[24] "Chuva" means "rain" in Portuguese; SOS-Chuva is the Severe Storm Observation-Chuva campaign, a multiple-sensor-based geographical information system. For more information, see *http://soschuva.cptec.inpe.br/soschuva*.
[25] For more information, see *https://pmm.nasa.gov/GCPEx*.

Overview of 2018 NASA Sounder Community Activity

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Introduction

This report describes two meetings and a workshop that involved the NASA atmospheric sounder community during 2018. The first meeting was the Atmospheric Infrared Sounder (AIRS) Science Team Meeting (STM), which met in April at the Beckman Institute at the California Institute of Technology in Pasadena, CA. The second meeting was the NASA Sounder STM, which was held in conjunction with a Planetary Boundary Layer (PBL) Workshop, both of which met in October 2018 in Greenbelt, MD.

The annual AIRS and Sounder Meetings had different themes. The AIRS STM focused on results from the AIRS instrument only, while the Sounder STM addressed topics relevant to the constellation of past, present, and future sounder instruments.[1] Note that the current operating sounders include six hyperspectral infrared instruments, the most recent being the latest Infrared Atmospheric Sounding Interferometer (IASI) launched with the Metop-C platform in November 2018. The October Sounder STM was merged with the PBL Workshop because of significant overlap between PBL and sounding science.

Selected presentations from the two STMs and the PBL Workshop comprise this report. The presentations chosen reflect important new science results, significant advances, or give an overview of the state of the field. Readers may be interested in other talks on the meeting agendas, which, along with many of the presentations given during these meetings, can be downloaded from the AIRS Project website at *http://airs.jpl.nasa.gov* under the "Events" pull-down tab.

Highlights from the AIRS Science Team Meeting

In keeping with tradition, the AIRS STM was held in springtime, from Wednesday, April 25, through the first half of Friday, April 27. The meeting began with introductory presentations from **Joao Teixeira** [JPL—*AIRS Science Leader*], **Ruth Monarrez** [JPL—*Sounder Science Investigator-led Processing System (Sounder SIPS) Lead*], and **Tsengdar Lee** [NASA Headquarters—*Program Manager for Research and Applications Weather Focus Area*]. These presentations offered programmatic and instrument updates and set the tone for the meeting. After that, the remainder of the meeting agenda consisted of sessions on Weather and Climate, the NASA Decadal Survey, Atmospheric Composition, Retrievals and Validation, Applications, Operations and Calibrations, and Validation.

Four presentations from the AIRS STM are highlighted in this report. The reader is referred to URL in the Introduction for the complete list of presentations.

Brian Kahn [NASA/Jet Propulsion Laboratory (JPL)] gave a presentation titled "Ice Cloud Trends from Fourteen Years of AIRS Observations." He described how AIRS spectra are sensitive to ice particle characteristics, and showed how this sensitivity can be exploited to retrieve ice cloud properties. He showed statistically significant trends of decreasing cloud top temperatures and increasing ice particle radii over 14 years, consistent with ice clouds becoming higher as their particles become larger. These changes were accompanied by no detectable changes to ice cloud frequency of occurrence or ice cloud optical depth, and only very slight increases in the amount of ice.

Peter Kalmus [JPL] gave a presentation titled "Trajectory-Enhanced AIRS Observations of Environmental Factors Leading to Tornadogenesis." He compared temperature and water vapor profiles from AIRS obtained nearest to the location and time of an active tornado outbreak (or *direct observations*) to profiles reconstructed from AIRS observations made prior to the tornadoes at locations upwind—as determined by back-trajectory calculations starting at the locations of active tornadoes—see **Figure**. Essentially, the reconstructed profiles capture the pretornadic

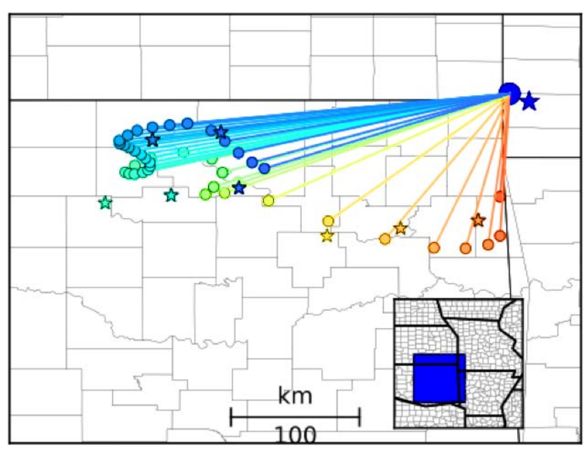

Figure. Map of air parcels converging near Joplin, MO, during the outbreak of May 11, 2011. The tornado location is marked with a single large dot, and the AIRS sounding nearest the tornado is marked with a star. All air parcels converging on the tornado originate over Oklahoma to the southwest. AIRS observations were obtained at the locations of the small filled dots. **Image credit**: Peter Kalmus

[1] To learn more about these Sounder instruments, see the "Overview of 2017 NASA Sounder Science Community Activities" in the March–April 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 2**, pp. 12-16—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Mar_Apr_2018_color%20508_0.pdf#page=12*].

conditions—but often hundreds of kilometers upwind and hours earlier. To demonstrate the technique, Kalmus showed a case study of the destructive (Fujita-5) Joplin, MO tornado of May 11, 2011. In this example, the reconstructed profiles were much more unstable (as measured by convective available potential energy, or CAPE) than the soundings obtained nearest to the tornado in space. (See Figure for a map of the origins of the unstable air in the Joplin case study.) More unstable conditions are more likely to lead to severe weather. Using a wider set of sample storms, from hailstorms through severe tornadoes, he also showed that the difference between directly observed and reconstructed profile stabilities were most pronounced for the most severe storms. This result has important implications for severe weather forecasting in the American Midwest.

John Worden [JPL] gave a presentation titled "Characterization and Initial Validation of AIRS-Based HDO/H_2O Measurements." He described methodologies developed for the Tropospheric Emission Spectrometer (TES)[2] sounding instrument to retrieve deuterated water (HDO), a heavy isotope of water. HDO vapor is slightly heavier than water vapor and has slightly different evaporation and condensation properties, making the combination of H_2O and HDO vapor useful in characterizing the atmospheric water cycle. He showed that AIRS spectra contain sufficient information to retrieve gaseous HDO in the atmosphere, and also showed very good agreement between TES and AIRS HDO observations over six years. Worden noted the promise of a very long HDO record from AIRS.

Ivy Tan [NASA's Goddard Space Flight Center (GSFC)] gave a presentation titled "Investigating the Extratropical Cloud Optical Depth Feedback with MODIS, AIRS, CERES, and AMSR."[3] She described the challenges of realistically representing cloud feedback processes in climate models, and linked what had previously been thought to be spurious negative feedbacks to improper representation of cloud liquid water. She described plans to diagnose cloud feedbacks using data from a variety of sensors in the Afternoon Constellation, or "A-Train," by separating the observations into MODIS-defined weather regimes. Weather regimes can have different cloud feedback responses, and climate models and observations have different prevalent weather regimes; therefore, a regime-based approach offers considerable promise for correcting model feedback mechanisms.

[2] TES flies on NASA's Aura platform and operated until 2018. Aura is part of the international Afternoon, or "A-Train," constellation, along with Aqua, on which AIRS flies. To learn more about the A-Train, visit *https://atrain.gsfc.nasa.gov*.

[3] The following acronyms are used in this title: CERES, which stands for Clouds and the Earth's Radiant Energy System and flies on NASA's Terra and Aqua platforms; MODIS, which stands for Moderate Resolution Imaging Spectroradiometer and flies on Terra and Aqua; and AMSR, which stands for Advanced Microwave Scanning Radiometer and flies on Aqua.

Highlights from the Planetary Boundary Layer Workshop

The 2018 NASA Earth Science Decadal Survey[4] makes boundary layer observations a high priority—and many of those observations will be obtained by remote sounding instruments. Because of this, a PBL Workshop was coordinated and held contiguous with the normal fall NASA Sounder STM. The combined meeting was held during the week of October 1-5, 2018, in Greenbelt, MD. The PBL Workshop agenda filled most of the first day-and-a-half. For organizational purposes, the two meetings are described in separate sections in this article, but content overlapped considerably—and intentionally.

The PBL Workshop agenda included presentations that covered a variety of model processes, and space-based and *in situ* observations systems. The workshop sessions were titled: Current/Near-term Spaceborne PBL Capabilities, Ground and Airborne Measurements of the PBL, and Future/Long-Term PBL Instruments and Mission Concepts.

Three presentations from the PBL Workshop have been chosen to be highlighted in this report. The reader is referred to URL in the Introduction for the complete list of presentations.

Greg Elsaesser [NASA's Goddard Institute for Space Studies (GISS)] described a "Multi-Sensor Analyses of the Evolution of Convection and the Thermodynamic Environment on Sub-Daily Timescales." He compared AIRS observations in the vicinity of tropical convective storm systems with model reanalysis depictions of those same systems. Elsaesser showed that the boundary layer observed by AIRS had more realistic structure over the lifecycle of the systems, with boundary layer warming and moistening prior to storms and subsequent cooling as well as drying after storms. The model reanalysis did not represent those same structures. He argued that an unresponsive boundary layer was one reason climate models underrepresent cumulus congestus clouds and over-represent deep convection.

Chi Ao [JPL] gave a presentation titled "Recent Progress on the Vertical Profiling of the Planetary Boundary Layer from Global Navigation Satellite System (GNSS) Radio Occultations." He described the characteristics of radio occultation (RO) retrievals. These include relatively infrequent sampling—but very high vertical resolution and full coverage of the diurnal cycle. RO observations are important complements to observations from infrared and microwave sounders, which offer both dense spatial coverage (but coarser vertical resolution) and fixed local time coverage. Ao showed

[4] To learn more, read the 2017 Decadal Survey, which is available at *https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

global climatologies of boundary layer depth obtained with RO observations, including the diurnal cycle of boundary layer depth, and used these to assess similar quantities in climate models. He also described planned orbiting RO receivers, which will provide more information about boundary layer structure than currently operating receivers.

Jennifer Comstock [Pacific Northwest National Laboratory] described a very detailed set of ground-based and *in situ* measurements in a presentation titled "Atmospheric Radiation Measurement (ARM) Observations and Science Products for Boundary Layer Studies." ARM measurements are obtained by a suite of instruments at field sites and during campaigns. ARM has a comprehensive strategy to sample a wide range of global conditions, often with more detail than can be obtained by space-based remote sensing instruments. The ARM record overlaps with the record from many modern remote sounding instruments, including hyperspectral infrared sounders, and can help characterize the measurement capabilities of sounders. The ARM data are particularly useful in the boundary layer, where satellite sounders are challenged to resolve fine-scale vertical and horizontal structure.

Highlights from the NASA Sounder Science Team Meeting

As mentioned above, the NASA Sounder STM followed the PBL Workshop, beginning in the afternoon of October 2 and running until noon on October 5. The Sounder STM sessions were largely continuations of topics from the AIRS STM in April: Weather and Climate, Atmospheric Composition, Applications, Retrievals, Validation, and Calibration.

Three presentations have been chosen for this report. The reader is referred to URL in the Introduction for the complete list of presentations.

Alireza Farahmand [JPL] spoke on the subject of "Using AIRS Observations for Predicting Fire Danger across the Continuous United States." He described an analysis system to predict wildfire conditions, built on capabilities developed for drought forecasting. His fire prediction uses water vapor pressure deficit information from AIRS, but also soil moisture information from NASA's Gravity Recovery and Climate Experiment (GRACE) satellites. Using this method, annual average hindcasted burn area in the northern Rockies had a correlation of 0.82 against observed burn area, for the period 2003–2012. He is using the information in AIRS and GRACE observations, along with plant health information from the MODIS to develop a gridded, monthly mean fire prediction metric.

Callyn Bloch [I.M. Systems Group/National Oceanic and Atmospheric Administration's (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) Center for Satellite Applications and Research (STAR)] gave the talk titled, "Near-Real Time Convective Available Potential Energy Combining Hyperspectral Infrared Satellite Sounding and Surface Meteorological Stations." She began by noting that estimates of surface-based CAPE from AIRS retrievals compare poorly to the same quantities from radiosondes. Bloch showed that much of the discrepancy came from errors in satellite-retrieved temperature and humidity near the surface. She then showed that CAPE estimates are significantly improved when near-surface observations from ground-based instruments are combined with satellite profiles through the remainder of the atmospheric column. This analysis was based on the NOAA Unique Combined Atmospheric Processing System (NUCAPS) algorithm retrieving temperature and water vapor profiles from Suomi National Polar-orbiting Partnership (NPP) sounder radiances and on *in situ* observations from a dense ground-based network over the continental U.S. The combined CAPE estimates are particularly useful over the U.S. Midwest because AIRS and Suomi NPP data are obtained roughly midway between the radiosondes launched at 0Z and 12Z UTC.

Henry Revercomb [University of Wisconsin, Madison] gave a presentation titled "Hyperspectral Infrared Radiances (HIS, AERI, AIRS, IASI, CrIS, HIRAS, GIIRS, WARN, ARI)," which served as a comprehensive overview of measurements by hyperspectral infrared instruments, both in orbit and *in situ*.[5] He presented arguments for an integrated approach to combining observations from all such instruments. Revercomb then noted the importance of well-calibrated radiances from all these instruments, and especially the requirement for small biases (< 0.1 K in brightness temperature) to properly monitor climate and its changes. He argued that creation of a well-calibrated set of observations will require a truly international effort, with wide commitment to high standards of calibration and characterization.

[5] The acronyms in this title describe some of the current and planned ground-based, airborne, and orbiting instruments taking hyperspectral infrared observations. They include: HIS: High-resolution Interferometer Sounder; AERI: Atmospheric Emitted Radiance Interferometer; CrIS: Cross-track Infrared Sounder; HIRAS: Hyperspectral Infrared Atmospheric Sounder; GIIRS: Geostationary Interferometric Infrared Sounder; WARN: Weather Alert Remote Nowcasting; and ARI: Absolute Radiance Radiometer. More information on each is readily available online.

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2015–2016 El Niño Triggered Disease Outbreaks Across Globe

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

The 2015–2016 El Niño event brought weather conditions that triggered regional disease outbreaks throughout the world, according to a new NASA study that is the first to comprehensively assess the public health impacts of the major climate event on a global scale.[1]

El Niño is an irregularly recurring climate pattern characterized by warmer than usual ocean temperatures in the equatorial Pacific, which creates a ripple effect of anticipated weather changes in far-spread regions of Earth. During the 2015–2016 event, changes in precipitation, land surface temperatures, and vegetation created and facilitated conditions for transmission of diseases, resulting in an uptick in reported cases for plague and hantavirus in Colorado and New Mexico, cholera in Tanzania, and dengue fever in Brazil and Southeast Asia, among others.

"The strength of this El Niño was among the top three of the last 50 years, and so the impact on weather and therefore diseases in these regions was especially pronounced," said lead author **Assaf Anyamba** [NASA's Goddard Space Flight Center]. "By analyzing satellite data and modeling to track those climate anomalies, along with public health records, we were able to quantify that relationship."

The study utilized a number of climate datasets, among them land surface temperature and vegetation data from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite, and NASA and National Oceanic and Atmospheric Administration (NOAA) precipitation datasets. The study was published February 13, 2019, in the journal *Nature Scientific Reports*.[2]

Based on monthly outbreak data from 2002 to 2016 in Colorado and New Mexico, reported cases of plague were at their highest in 2015, while the number of hantavirus cases reached their peak in 2016. The cause of the uptick in both potentially fatal diseases was an El Niño-driven increase in rainfall and milder temperatures over the American Southwest, which spurred vegetative growth, providing more food for rodents that carry hantavirus. A resulting rodent population explosion put them in more frequent contact with humans, who contract the potentially fatal disease mostly through fecal or urine contamination. As their rodent hosts proliferated, so did plague-carrying fleas.

Meanwhile, a continent away, in East Africa's Tanzania, the number of reported cases for cholera in 2015 and 2016 were the second and third highest, respectively, over an 18-year period from 2000 to 2017. Cholera is a potentially deadly bacterial infection of the small intestine that spreads through fecal contamination of food and water. Increased rainfall in East Africa during the El Niño allowed for sewage to contaminate local water sources, such as untreated drinking water. "Cholera doesn't flush out of the system quickly," Anyamba said, "so even though it was amplified in 2015–2016, it actually continued into 2017 and 2018. We're talking about a long-tailed, lasting peak."

In Brazil and Southeast Asia, during the El Niño, dengue fever proliferated. In Brazil the number of reported cases for the potentially deadly mosquito-borne disease in 2015 was the highest from 2000 to 2017. In Southeast Asia, namely Indonesia and Thailand, the number of reported cases, while relatively low for an El Niño year, was still higher than in neutral years. In both regions, the El Niño produced higher than normal land surface temperatures and therefore drier habitats, which drew mosquitoes into populated, urban areas containing the open water needed for laying eggs. As the air warmed, mosquitoes also grew hungrier and reached sexual maturity more quickly, resulting in an increase in mosquito bites.

The strong relationship between El Niño events and disease outbreaks underscores the importance of existing seasonal forecasts, said Anyamba, who has been involved with such work for the past 20 years through funding from the U.S. Department of Defense (DOD). Countries where these outbreaks occur, along with the United Nations' World Health Organization and Food and Agriculture Organization, can utilize these early warning forecasts to take preventive measures to minimize the spread of disease. Based on the forecast, the U.S. DOD does pre-deployment planning, and the U.S. Department of Agriculture (USDA) takes measures to ensure the safety of imported goods.

[1] To watch a video produced by NASA's Scientific Visualization Studio on this topic, visit *https://svs.gsfc.nasa.gov/13152*.

[2] To read the paper, visit *https://www.nature.com/articles/s41598-018-38034-z*.

"Knowledge of the linkages between El Niño events and these important human and animal diseases generated by this study is critical to disease control and prevention, which will also mitigate globalization," said co-author **Kenneth Linthicum** [USDA], who is a center director at an entomology laboratory in Gainesville, FL. He noted these data were used in 2016 to avert a Rift Valley fever outbreak in East Africa. "By vaccinating livestock, they likely prevented thousands of human cases and animal deaths."

"This is a remarkable tool to help people prepare for impending disease events and take steps to prevent them," said co-author **William Karesh** [EcoHealth Alliance—*Executive Vice President*].[3] "Vaccinations for humans and livestock, pest control programs, removing excess stagnant water—those are some actions that countries can take to minimize the impacts. But for many countries, in particular the agriculture sectors in Africa and Asia, these climate-weather forecasts are a new tool for them, so it may take time and dedicated resources for these kinds of practices to become more utilized."

According to Anyamba, the major benefit of these seasonal forecasts is time. "A lot of diseases, particularly mosquito-borne epidemics, have a lag time of two to three months following these weather changes," he said. "So seasonal forecasting is actually very good, and the fact that they are updated every month means we can track conditions in different locations and prepare accordingly. It has the power to save lives." ■

[3] EcoHealth Alliance is a New York City-based public health and environmental nonprofit organization.

Overview of 2018 NASA Sounder Community Activity

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Conclusion

Remote sounding observations of the atmosphere have led to significant improvements in weather forecasts, in climate monitoring, and in our understanding of atmospheric processes controlling both weather and climate. These improvements have been enabled by newer, more detailed observations, especially over the past two decades. The improvements are also the results of careful analysis by a dedicated community of data users. The events described in this report were an opportunity to share past and current achievements, and to discuss future challenges. First among those challenges is interpreting an increasingly large and detailed set of observations of a complex and changing atmosphere. Future progress toward this and other challenges will be shared in upcoming sounder meetings.

The AIRS STM was held April 3–5, 2019, once again in Pasadena, CA. A NASA Sounder STM is being planned to take place in the vicinity of Greenbelt, MD, during fall 2019. Details about both meetings can be found at the AIRS website. ■

NASA's Greenland Mission Still Surprises in Year Four

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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.

Only seven months after NASA's Oceans Melting Greenland (OMG) mission wrapped up its last field campaign on the world's largest island, an OMG crew is back in Greenland to collect more data. With two or three field projects a year since 2016, no wonder OMG has made the most comprehensive measurements yet of how ocean water lapping at the undersides of Greenland's melting glaciers affects them. All those data have answered a lot of existing questions—and it's raised plenty of new ones.

"We've seen some really surprising results that suggest the oceans have a huge effect on Greenland's biggest glaciers," said **Josh Willis** [NASA/Jet Propulsion Laboratory (JPL)—*OMG Principal Investigator*]. "This year, we hope to figure out whether the ocean's impact is widespread or if it's just a few big glaciers that care about ocean temperatures."

Ron Muellerschoen [JPL] has flown back and forth across Greenland during its snowiest season for the last three years. He might be excused for feeling a little blasé about spending a few more weeks in an aircraft over Greenland's ice sheet. But no.

"It's huge. It's just amazing," Muellerschoen said. "I'll never reach a time where it's 'just snow' out there. I feel really lucky to be able to do this four years in a row."

Besides the scenery, Muellerschoen is looking forward to this year's inevitable technological challenges. Although he flies NASA's Glacier and Ice Surface Topography Interferometer (GLISTIN-A) radar on a NASA G-III aircraft each year, "It's never the same," he said. "We're always trying to push the limits of what we can look at in the field. There's new hardware, new configurations for installing equipment on the plane, and we have a new recording system."

The GLISTIN-A radar maps the edges of glaciers along the entire coastline of the island and measures their heights precisely. As a glacier loses ice and speeds up, it stretches out and gets thinner, so that its surface is lower than before. The height measurement enables researchers to estimate how much ice has been lost since the preceding year's measurement.

OMG also measures ocean temperatures around the coastline every fall and has completed a multiyear effort to make high-precision maps of the ocean floor off the coast. With these combined datasets, scientists have a complete view of Greenland's 200 or so coastal glaciers and how they are responding to changes in the water below and the air above them.

The G-III aircraft and its crew are based at NASA's Johnson Space Center. This spring campaign is using two bases: Keflavik, Iceland, and the U.S. Air Force's Thule Air Base in Greenland. Flights began the week of March 4, 2019, from Keflavik to map glaciers in southern and eastern Greenland. The crew then transits to Thule to survey western and northern Greenland. The campaign will continue until all measurements have been completed—around March 20, 2019, depending on weather.[1] ■

A large iceberg near Thule Air Base, Greenland. **Photo credit:** NASA

[1] **UPDATE:** Owing to some equipment issues that required the team to return to base and make repairs, the OMG flights are still ongoing as this issue goes to print. Final flights for the 2019 ice survey are expected to take place in mid-April.

Human Activity in China and India Dominates the Greening of Earth, NASA Study Shows

Abby Tabor, NASA's Ames Research Center, abigail.s.tabor@nasa.gov

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

The world is literally a greener place than it was 20 years ago, and data from NASA satellites has revealed a counterintuitive source for much of this new foliage: China and India. A new study shows that the two emerging countries with the world's biggest populations are leading the increase in greening on land. The effect stems mainly from ambitious tree planting programs in China and intensive agriculture in both countries—see **Figure**. This research was published online, February 11, 2019, in the journal *Nature Sustainability*.[1]

The greening phenomenon was first detected using satellite data in the mid-1990s by **Ranga Myneni** [Boston University] and colleagues, but they did not know whether human activity was one of its chief, direct causes. This new insight was made possible by a nearly 20-year-long data record from a NASA instrument orbiting the Earth on two satellites. It's called the Moderate Resolution Imaging Spectroradiometer (MODIS), and its high-resolution data provides very accurate information, helping researchers work out details of what's happening with Earth's vegetation, down to the level of 500 m (~1640 ft) on the ground.

Taken all together, the greening of the planet over the last two decades represents an increase in leaf area on plants and trees equivalent to the area covered by all the Amazon rainforests. There are now more than 2,000,000 mi^2 (~5,180,000 km^2) of extra green leaf area per year, compared to the early 2000s—a 5% increase.

"China and India account for one-third of the greening, but contain only 9% of the planet's land area covered in vegetation—a surprising finding, considering the general notion of land degradation in populous countries from overexploitation," said **Chi Chen** [Boston University], who is the lead author of the study.

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[1] To read the paper, visit *https://www.nature.com/articles/s41893-019-0220-7*.

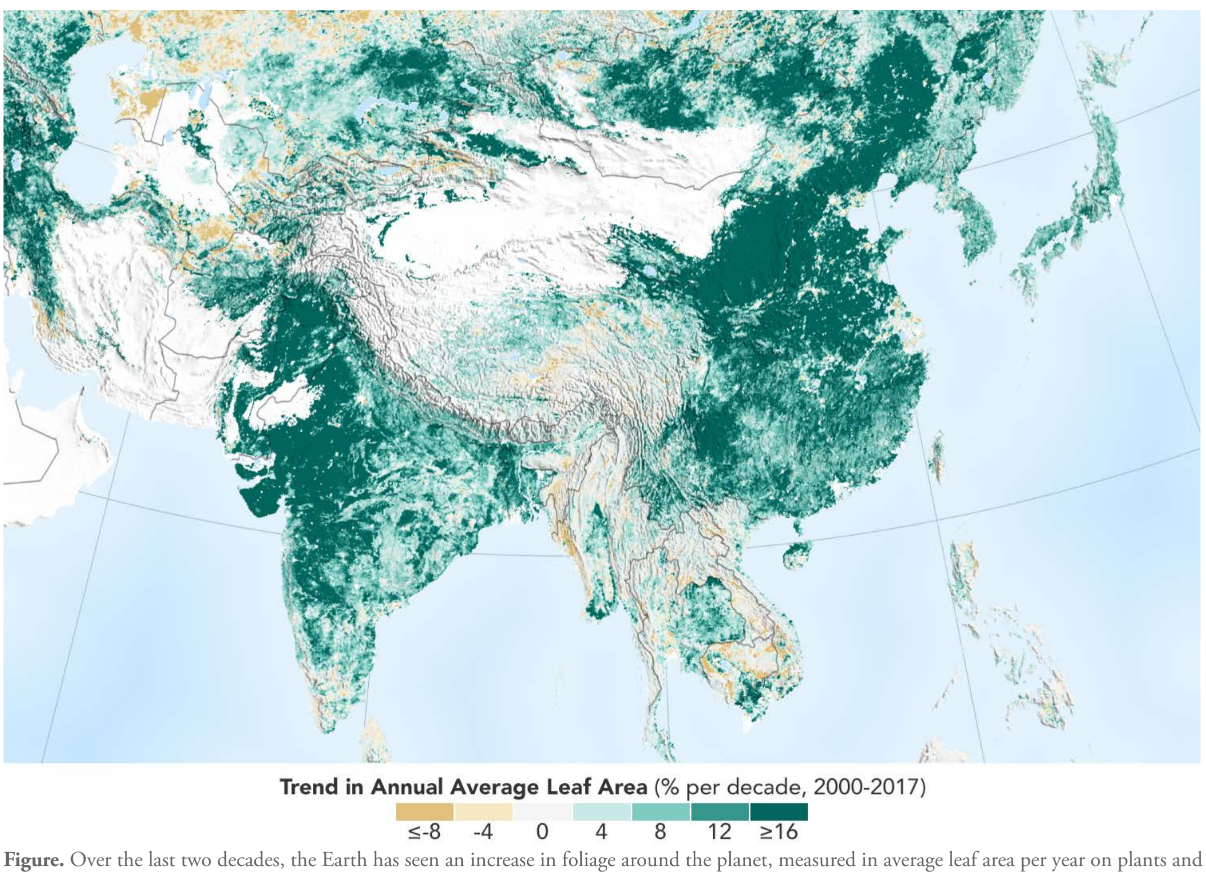

Figure. Over the last two decades, the Earth has seen an increase in foliage around the planet, measured in average leaf area per year on plants and trees. Data from NASA satellites shows that China and India are leading the increase in greening on land. The effect stems mainly from ambitious tree-planting programs in China and intensive agriculture in both countries. **Credit:** NASA's Earth Observatory

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*.

Key Greenland Glacier Growing Again after Shrinking for Years, NASA Study Shows, March 25, *nbcnews.com.* A major Greenland glacier that was one of the fastest-shrinking ice and snow masses on Earth is growing again, according to the results of a new NASA-supported study by the Oceans Melting Greenland (OMG) project. The Jakobshavn glacier around 2012 was retreating about 1.8 mi (~3 km) and thinning nearly 130 ft (~40 m) annually. But it started growing again at about the same rate in the past two years, according to a study published in *Nature Geoscience*.[1] Study authors and outside scientists think this is temporary. A natural cyclical cooling of North Atlantic waters likely caused the glacier to reverse course, said study lead author **Ala Khazendar** [NASA/Jet Propulsion Laboratory (JPL)], a glaciologist on the OMG project. Khazendar and colleagues say this coincides with a flip of the *North Atlantic Oscillation*—a natural and temporary cooling and warming of parts of the ocean that is like a distant cousin to El Niño in the Pacific. The water in Disko Bay, where Jakobshavn hits the ocean, is about 3.6 °F (2 °C) cooler than a few years ago, study authors said. While this is "good news on a temporary basis, it is bad news over the long term," said study co-author **Josh Willis** [JPL—*OMG Principal Investigator*] "because it tells scientists that ocean temperature is a bigger player in glacier retreats and advances than previously thought."

***NASA Study Illuminates Link Between Warming, Disease,** March 18, *buffalonews.com.* According to most computer models, we are in a weak El Niño right now that will persist for months to come. But the last El Niño was a biggie—the biggest in at least 50 years, occurring from late 2015 into 2016. Tropical disease specialists, entomologists, epidemiologists, and public health scientists have long known that a warming climate will impact the epidemiology of tropical diseases, allowing them and their carriers, such as insects, to spread into regions vulnerable to warming and changes in precipitation patterns. The recent massive El Niño has served as a global laboratory as to what can happen over a short time span under conditions of marked and rapid warming. A just-released NASA study is the first of its type to monitor disease patterns related to short-term warming and regional changes in precipitation. As NASA stated, "During the 2015-2016 event, changes in precipitation, land surface temperatures, and vegetation created and facilitated conditions for transmission of diseases, resulting in an uptick in reported cases for plague and hantavirus in Colorado and New Mexico, cholera in Tanzania, and dengue fever in Brazil and Southeast Asia, among others." Lead author **Assaf Anyamba** [NASA's Goddard Space Flight Center] noted the analysis of satellite data, model output, and public health records made it possible to get a handle on numerous disease events on a global basis. The study was able to utilize NASA datasets of land temperature, soil moisture, and vegetation changes in imagery gathered by NASA's Terra satellite, along with NASA and National Oceanic and Atmospheric Administration (NOAA) precipitation datasets.

***NASA Says Earth Is Greener Today than 20 Years Ago Thanks to China, India,** February 28, *forbes.com.* NASA has some good news: the world is a greener place today than it was 20 years ago. What prompted the change? Well, it appears China and India can take the majority of the credit. The results of this study show that these two countries are responsible for the largest greening of the planet in the past two decades. The two most populous countries have implemented ambitious tree-planting programs and scaled up their agricultural policy implementation and associated technology development. India continues to break world records in tree planting, with 800,000 Indians planting 50 million trees in just 24 hours. The recent finding by NASA, published in the journal *Nature Sustainability*,[2] compared satellite data from the mid-1990s to today using high-resolution imagery. Initially, the researchers were unsure what caused the significant uptick in greening around the planet. It was unclear whether a warming planet, increased carbon dioxide, or a wetter climate could have caused more plants to grow. After further investigation of the satellite imagery, the researchers found that greening was disproportionately located in China and India.

[1] To read the study, visit *https://www.nature.com/articles/s41561-019-0329-3*.

[2] To read the paper, visit *https://www.nature.com/articles/s41893-019-0220-7*.

Iceberg Twice the Size of New York City about to Break Off From Antarctica, says NASA, February 26, *usatoday.com.* An iceberg about twice the size of New York City is expected to break off from an ice shelf in Antarctica, NASA says. Researchers are monitoring a giant crack in the center of the Brunt Ice Shelf in Antarctica. The crack had been stable for 35 years but has started accelerating toward another fissure called the Halloween Crack (so named because it first appeared in late October 2016). When the larger crack makes its way completely across, it will create an iceberg of at least 660 mi^2 (1700 km^2) in a process called calving. "We don't have a clear picture of what drives the shelf's periods of advance and retreat through calving," glaciologist **Chris Shuman** [NASA's Goddard Space Flight Center/University of Maryland Baltimore County], said in a statement. "The likely future loss of the ice on the other side of the Halloween Crack suggests that more instability is possible." The iceberg itself isn't as big as other recent masses. In 2017 an iceberg the size of Delaware broke off from the Antarctic ice shelf, one of the largest on record. The potential iceberg, however, could be the largest to break from the Brunt Ice Shelf since observations started in 1915, researchers say. It's not clear when the iceberg will break off, Shuman said, but researchers are closely watching it.

*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**.*

Human Activity in China and India Dominates the Greening of Earth, NASA Study Shows

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An advantage of the MODIS satellite sensor is the intensive coverage it provides, both in space and time: MODIS has captured as many as four shots of every place on Earth, every day, for the last 20 years.

"This long-term data lets us dig deeper," said research scientist **Rama Nemani** [NASA's Ames Research Center], who was a co-author of the new work. "When the greening of the Earth was first observed, we thought it was due to a warmer, wetter climate and fertilization from the added carbon dioxide in the atmosphere, leading to more leaf growth in northern forests, for instance. Now, with the MODIS data that lets us understand the phenomenon at really small scales, we see that humans are also contributing."

China's outsized contribution to the global greening trend comes in large part (42%) from programs to conserve and expand forests. These were developed in an effort to reduce the effects of soil erosion, air pollution, and climate change. Another 32% there—and 82% of the greening seen in India—comes from intensive cultivation of food crops.

Land area used to grow crops is comparable in China and India—more than 770,000 mi^2 (~1,994,000 km^2)—and has not changed much since the early 2000s. Yet these regions have greatly increased both their annual total green leaf area and their food production. This was achieved through *multiple cropping practices*, where a field is replanted to produce another harvest several times a year. Production of grains, vegetables, fruits, and more have increased by about 35-40% since 2000 to feed their large populations.

How the greening trend may change in the future depends on numerous factors, both on a global scale and the local human level. For example, increased food production in India is facilitated by groundwater irrigation. If the groundwater is depleted, this trend may change.

"But, now that we know direct human influence is a key driver of the greening Earth, we need to factor this into our climate models," Nemani said. "This will help scientists make better predictions about the behavior of different Earth systems, which will help countries make better decisions about how and when to take action."

The researchers point out that the gain in greenness seen around the world—and dominated by India and China—does not offset the damage from loss of natural vegetation in tropical regions, such as Brazil and Indonesia. The consequences for sustainability and biodiversity in those ecosystems remain.

Overall, Nemani sees a positive message in the new findings. "Once people realize there's a problem, they tend to fix it," he said. "In the '70s and '80s in India and China, the situation around vegetation loss wasn't good; in the '90s, people realized it; and today things have improved. Humans are incredibly resilient. That's what we see in the satellite data."

Earth Science Meeting and Workshop Calendar

NASA Community

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

August 27–29, 2019
Aura Science Team Meeting, Pasadena, CA
https://mls.jpl.nasa.gov/aura2019

October 21–25, 2019
OST Science Team Meeting, Chicago, IL
https://sealevel.jpl.nasa.gov/science/ostscienceteam/scienceteammeetings

Global Science Community

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

July 28–August 2, 2019
International Geoscience and Remote Sensing Symposium (IGARSS), Yokohama, Japan
https://igarss2019.org

July 28–August 2, 2019
Asia Oceania Geosciences Society (AOGS) Annual Meeting, Singapore
http://www.asiaoceania.org/aogs2019/public.asp?page=home.htm

August 25–29, 2019
American Chemical Society (ACS) National Meeting, San Diego, CA
https://www.acs.org/content/acs/en/meetings/national-meeting.html

September 22–25, 2019
Geological Society of American (GSA), Phoenix, AZ
https://community.geosociety.org/gsa2019/connect/events

December 9–13, 2019
AGU Fall Meeting, San Francisco, CA
https://events.jspargo.com/AGU19/Public/enter.aspx

Undefined Acronyms Used in Editorial and Table of Contents

ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
GEDI	Global Ecosystem Dynamics Investigation
ISS	International Space Station
JPL	NASA/Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
MODIS	Moderate Resolution Imaging Spectroradiometer
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	National Polar-orbiting Partnership [formerly NPOESS]
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
STPSat	Space Test Program Satellite
TIROS	Television Infrared Observation Satellite

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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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