National Aeronautics and Space Administration

The Earth Observer. July - August 2016. Volume 28, Issue 4.

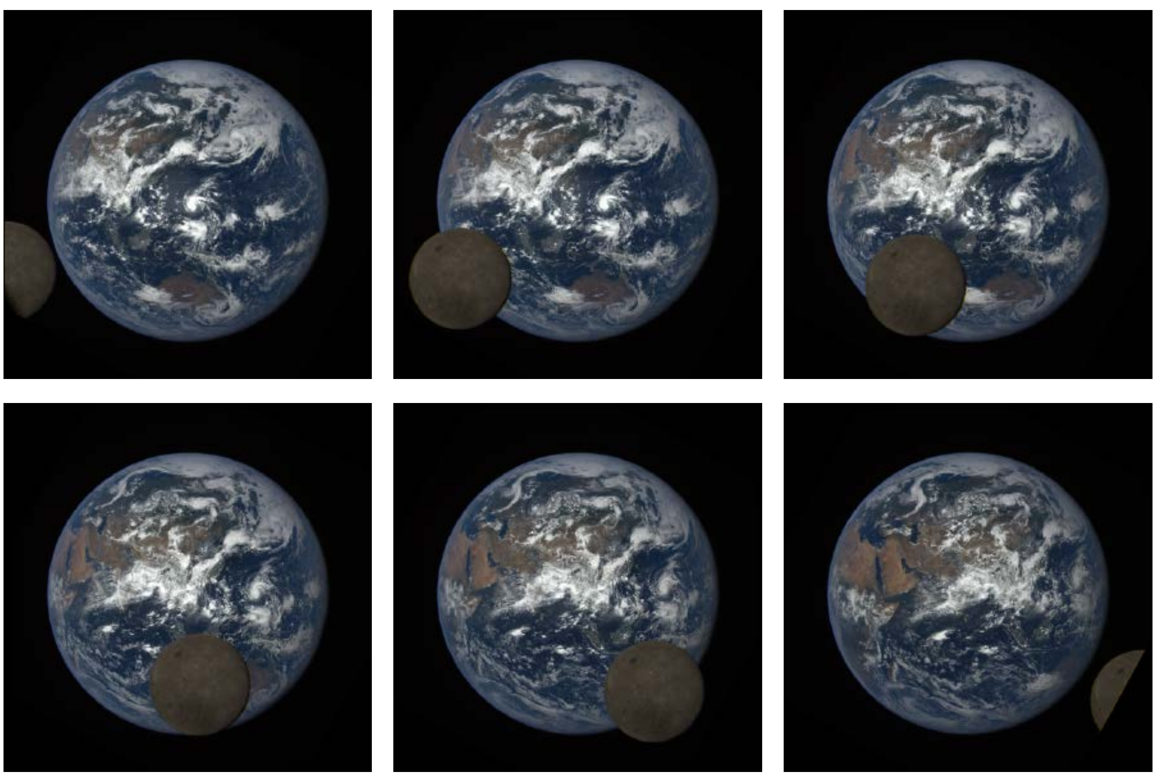
Editor's Corner

Steve Platnick
EOS Senior Project Scientist

In light of recent news headlines, it's vitally important to remember the endeavors that bring us together. Science is fundamentally a collaborative and unifying effort, connecting individuals and nations. Since the agency began almost 60 years ago, NASA—working along with its domestic and international partners—has sought to inspire humanity to work together toward the common goal of exploring and understanding Earth, the solar system, and our place in the universe. People from across the nation and world, representing a wide variety of science disciplines, can now routinely collaborate thanks to modern information technologies. Such broad cooperation has become increasingly important as we work to understand Earth's climate and predict future changes.

A shining example of international cooperation in Earth satellite observations has been the Afternoon ("A-Train") Constellation. The A-Train presently comprises four NASA missions (Aqua, Aura, CloudSat, OCO-2), a joint NASA–CNES mission (CALIPSO), and a JAXA mission (GCOM-W1). (Another CNES mission, PARASOL, was also a member of the A-Train but left the constellation in 2009 and was decommissioned in 2013, exactly nine years after launch.) Aqua and Aura both fly instruments that were contributed by international partners,

continued on page 2



On July 5, 2016, the moon passed between the Deep Space Climate Observatory (DSCOVR) and Earth. Over a period of about four hours, the Earth Polychromatic Imaging Camera (EPIC) snapped a series of images of the far side of the moon, which is never seen by observers on Earth's surface, passing by. Meanwhile, in the backdrop, Earth rotates. The background changes throughout the series, first showing Australia and the Pacific and gradually revealing Asia and Africa. A sampling of the images is shown here; all of the images and the movie for the 2016 Lunar Transit can be viewed at *http://epic.gsfc.nasa.gov/galleries/lunar_transit_2016/*.

the earth observer

www.nasa.gov

In This Issue

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

while CloudSat's radar was developed jointly with the Canadian Space Agency. The constellation was carefully engineered so that all satellites pass over the same ground track (or track offset) within 15 minutes of each other, providing synergistic observations from a wide variety of instruments. Enabling multisensor studies of the same scenes, the A-Train has advanced the horizons of atmospheric research in particular.

In this issue, we focus particular attention on two A-Train missions: CloudSat and CALIPSO. As we reported previously[1], both missions celebrated the tenth anniversary of their co-manifested launch on April 28. Like many of NASA's Earth-observing satellites, CloudSat and CALIPSO have long exceeded their prime mission lifetimes and are in extended operations. While they have each had to overcome technical challenges over the past ten years, both missions continue to collect unique scientific data that improve our understanding of the roles clouds and aerosols play in Earth's climate and weather. Data from CloudSat and CALIPSO—especially when combined with each other and/or with data from other A-Train sensors—have helped us move toward what **Graeme Stephens** [JPL—*CloudSat Principal Investigator*] referred to as the "useful pursuit of shadows[2]." Turn to page 4 to learn more about the story of CloudSat and CALIPSO as they celebrate their first decade of cloud and aerosol observations.

Meanwhile, aboard the International Space Station, another mission has been busily observing clouds and aerosols for the past 18 months. In mid-June 2016, the Cloud–Aerosol Transport System (CATS) celebrated an unprecedented milestone: one hundred billion laser shots on-orbit.

Further out in space, 1.5 million km (930,000 mi) from Earth, the NOAA Deep Space Climate Observatory (DSCOVR) was launched in February 2015 to orbit the L1 Lagrange point, suspended between the gravitational pull of Earth and the sun. From that unique vantage point, two NASA instruments continuously observe the Earth. On July

[1] See the Editorial of the March–April 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 2**, p. 3].

[2] Stevens evokes the words of Luke Howard here. Howard was an amateur meteorologist in Britain (1772–1864) who wrote essays about the nature of clouds. He was one of the first to suggest that clouds were more than passive entities blown around by the wind and that studying clouds was much more than a "useless pursuit of shadows." The Latin cloud classification system he developed in 1802 is still used today. See Howard's full quote on page 4.

20, 2016, the DSCOVR project, together with the DSCOVR Earth Sensors science team and the Atmospheric Science Data Center (ASDC) at NASA's Langley Research Center, released Level 1 data for the Earth Polychromatic Imaging Camera (EPIC). Release of the National Institute of Standards and Technology (NIST) Advanced Radiometer (NISTAR) Level 1 data was expected shortly thereafter. The released datasets have initial versions of instrument calibration and geolocation applied. The EPIC data are not yet stray-light corrected but this is expected later in the year. The released data are available from June 2015 through the current day via the ASDC at *https://eosweb.larc.nasa.gov*. EPIC has obtained two spectacular sequences of lunar transit images since being in operation. The most recent transit images of the Earth and the moon are shown on the front cover.

Looking toward the future, the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE[3]) mission passed its Mission Confirmation Review in March 2016 and its Key Decision Point A in June 2016, making it an official mission in formulation[4]. PACE will deliver the most comprehensive global combined ocean-atmosphere measurements in NASA's history, providing observations for synergistic understanding of ocean biology, biogeochemistry and ecology, as well as aerosols and clouds. PACE products will be used, in part, to resolve and understand many factors related to the marine carbon cycle.

PACE is being implemented by NASA's Goddard Space Flight Center (GSFC), who will design and build the primary instrument, the Ocean Color Instrument (OCI), as well as maintain responsibility for project management, safety and mission assurance, mission operations and ground systems, launch vehicle, spacecraft, instrument payload integration and testing, OCI calibration, validation, and science data processing. The project is designing an OCI concept that builds on the SeaWiFS heritage and ten years of lessons learned by GSFC scientists and engineers in the NASA Instrument Incubator Program. The OCI will incorporate a SeaWiFS-like rotating telescope with a spectroradiometer that is expected to cover a spectral range of 350–890 nm at 5 nm intervals, plus six short-wave infrared bands. Like SeaWiFS and its predecessor CZCS, the OCI will tilt 20° forward to avoid sun glint and sample at 1 km (~0.6 mi) ground sample distance at nadir. The project is currently evaluating options to acquire a multiangle polarimeter as a second instrument within the mission's design-to-cost paradigm. A decision about whether and how to acquire a polarimeter will occur at a formal acquisition strategy meeting at NASA Headquarters later this year. Ultimately, PACE will not only extend the high quality observations of ocean color, marine biogeochemistry, ocean productivity, clouds, and aerosols begun by NASA in the late 1990s, but also advance these fields far into the future to improve our understanding of how Earth systems are responding to a changing climate[5]. ■

[3] Note the meaning of the PACE acronym has been officially changed. PACE used to stand for Pre-Aerosol, Clouds, and ocean Ecosystems.

[4] Having successfully passed its KDP-A, PACE now enters "Phase A" of the six-phase NASA mission project life cycle. It can continue concept studies and begin technology development. The Project life cycle is discussed in detail at *http://nodis3.gsfc.nasa.gov/displayCA.cfm?Internal_ID=N_PR_7120_005D_&page_name=Chapter2#2_3*.

[5] To learn more about PACE, see "NASA Sets the PACE for Advanced Studies of Earth's Changing Climate" in the July-August 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 4**, pp. 4-12].

Undefined Acronyms Used in Editorial and Table of Contents

AIRS	Atmospheric Infrared Sounder
CALIPSO	Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations
CERES	Clouds and the Earth's Radiant Energy System
CNES	Center National d'Études Spatiale [French Space Agency]
CZCS	Coastal Zone Color Scanner
GCOM-W1	Global Climate Observation Mission—Water
JAXA	Japan Aerospace Exploration Agency
JPL	NASA/Jet Propulsion Laboratory
NOAA	National Oceanic and Atmospheric Administration
OCO-2	Orbiting Carbon Observatory
SeaWiFS	Sea-view Wide Field-of-view Sensor

feature article

A Useful Pursuit of Shadows: CloudSat and CALIPSO Celebrate Ten Years of Observing Clouds and Aerosols

Todd Ellis, Western Michigan University, todd.ellis@wmich.edu
Alan Ward, NASA's Goddard Space Flight Center, alan.b.ward@nasa.gov

Introduction

At 3:02 AM PDT on April 26, 2006, a Boeing Delta II rocket carried a payload of two spacecraft into a cloud-filled sky over Vandenburg Air Force Base in California. The cloudy sky was apropos as CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations mission, better known as CALIPSO, were beginning their planned missions to study clouds and *aerosols*—minute atmospheric particles that influence the properties of clouds. CloudSat and CALIPSO would observe important cloud and aerosol characteristics using their unique spaceborne radar and lidar instruments, respectively. As both missions enter their second decade, it is fitting to acknowledge and celebrate what they have accomplished, together.

The cloudy sky was apropos as CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations mission, better known as CALIPSO, were beginning their planned missions to study clouds and aerosols—minute particles suspended in the atmosphere.

CloudSat and CALIPSO have long exceeded their prime missions (which were intended to show the value of active remote sensing instruments in space) and are in extended operations. Both missions have had to overcome some significant performance challenges over the past ten years, some of which will be described herein. Nevertheless, both missions continue to collect important scientific data that improve our understanding of the roles clouds and aerosols play in regulating Earth's climate and weather. Some of the information has even made its way from the realm of research to the realm of education—see *Bringing Clouds and Aerosols into the Classroom* on page 12.) More information is available at the websites for CloudSat (*http://cloudsat.atmos.colostate.edu*) and CALIPSO (*http://www-calipso.larc.nasa.gov*).

The Challenge of Quantifying Clouds: The Need for CloudSat and CALIPSO

For as long as humans have gazed at the sky, they have been captivated by clouds. Their beauty and mystery have inspired artists and amateur skywatchers over the centuries, and have led to more than a few childhood art projects using cotton balls and glue sticks. The scientific study of clouds traces back to the British amateur meteorologist Luke Howard, who wrote essays about clouds and sketched and named them using a Latin classification system that we still use today—see **Figure 1**. His astute observation that clouds were more than passive entities being blown around by wind was predictive:

> *If Clouds were the mere result of the condensation of Vapour in the masses of atmosphere which they occupy, if their variations were produced by the movements of the atmosphere alone, then indeed might the study of them be deemed [a] useless pursuit of shadows. ...they are commonly as good visible indications of the operation of [atmospheric processes] as the countenance is to the state of a person's mind or body.*
>
> —**Luke Howard**, *On the Modifications of Clouds* (1802).

Indeed, scientists have come to realize that clouds and aerosols play vital roles in regulating Earth's climate system. This means that in order for projections of Earth's climate to be accurate, the computer simulations, or *models*, that scientists use must realistically and accurately portray cloud characteristics. But therein lies the challenge: For a variety of reasons, clouds and aerosols have proven themselves notoriously difficult to be accurately represented in such models. Even today, these phenomena still represent two of the largest sources of climate model uncertainties.

In the late 1980s and early 1990s, when the research questions that led to CloudSat and CALIPSO as measurement tools were first conceived, scientists found significant variability in how their models addressed the types, areal coverage, and optical thickness of clouds and resulting precipitation. This variability biased the amount of warming projected by climate models by as much as 5 °C (9 °F), leading to vastly different, model-specific depictions of how precipitation was distributed around the planet.

Figure 1. Image of *stratocumulus* clouds sketched by Luke Howard and published in his essay "On the Modifications of Clouds" in 1802. **Image credit**: University of California, San Diego online exhibit "Weathering the Weather: The Origins of Atmospheric Science," *http://libraries.ucsd.edu/speccoll/weather/b4164774.html*

Scientists knew that resolving these differences in model predictions required more observations of real clouds. The problem was that, in the early 1990s, such observations were limited. The observations that were available at the time came almost exclusively from *passive remote sensing instruments*—which measure electromagnetic radiation emitted by distant sources. While these instruments could produce impressive images of clouds, they could only reliably detect the clouds and aerosols closest to the sensor, and could not determine their vertical distributions. Improving our understanding of the climate system, therefore, required developing a different kind of observing capability. Enter CloudSat and CALIPSO.

Unlike earlier passive remote sensing instruments, both the CloudSat radar and CALIPSO lidar (to be described later) have provided the first longterm spaceborne *active remote sensing* observations[1]. These active instruments radiate pulses of energy towards Earth's surface. Scientists then use the timing of the returned energy to determine the distance to a target, and the strength of the returning signal to determine the properties of a target. This allows scientists to observe vertical profiles of clouds and aerosols throughout the atmosphere, thereby reducing the uncertainty in our knowledge of these two important atmospheric constituents.

CloudSat and CALIPSO Overview: Origins, Objectives, and Instruments

The original idea for a cloud-observing mission can be traced back to discussions in 1991-1992 during a World Climate Research Programme workshop. Initial concepts from NASA's Langley Research Center (LaRC) and the NASA/Jet Propulsion Laboratory (JPL) included instruments to study clouds from space onboard a single spacecraft that housed radar and lidar systems. Around that same time, NASA's Earth System Science Pathfinder (ESSP) program was initiated, which encouraged the development of relatively low-cost, small platforms. CloudSat and CALIPSO were not funded in the initial 1996 selections for the ESSP program; however, both missions were reconsidered for the second ESSP Announcement of Opportunity in 1997. The decision was made to separate the lidar and radar into two separate ESSP mission proposals. CALIPSO was selected in 1998 and—after a six-month study required by NASA Headquarters—CloudSat in 1999. An innovative new concept called *constellation flying* was also coming of age at the time that would allow the two separate missions to achieve the same results as if they were flown together on the same platform.

Improving our understanding of the climate system, therefore, required developing a different kind of observing capability. Enter CloudSat and CALIPSO.

Originally, two separate groupings were planned. CALIPSO proposed to fly with the Aqua satellite to take full advantage of the multiple sensors available on both platforms. Meanwhile, CloudSat originally proposed to fly with ICESat[2]—because, at

[1] The Lidar In-space Technology Experiment (LITE) flew onboard Space Shuttle *Discovery* [STS 64] in 1994 and demonstrated the potential of measuring clouds and aerosols from space using a lidar instrument. Similarly, a number of satellite-, Shuttle-, and ground-based radar systems were the forerunners of the CloudSat radar. LITE and several Shuttle-based radars are discussed in "The Earth Observing Legacy of NASA's Space Shuttle Program" in the September–October 2011 issue of *The Earth Observer* [**Volume 23**, **Issue 5**, pp. 4-17].

[2] ICESat stands for Ice, Cloud, and land Elevation Satellite, which flew from 2003-2010 to study ice mass, cloud and aerosol properties, and detailed land elevation data. To learn more, see *http://icesat.gsfc.nasa.gov*.

the time, it was the only lidar planned. After learning about the successful selection of CALIPSO, however, CloudSat changed its plan to fly with CALIPSO. Eventually, this grouping of satellites, along with Aura, became known as NASA's Afternoon Constellation, gaining the nickname "A-Train." While the radar and lidar would physically be located on separate satellites, this would be the only functional "separation" between the missions. The two satellites fly close to each other in the same carefully maintained orbit. This synergy allows the science teams to combine the data from these unique active remote sensing instruments into a near-synchronous, combined radar–lidar dataset to further study clouds, aerosols, and climate, as described below. In addition, because the constellation's platforms (which at the time also included the Aqua, Aura, and PARASOL[3] satellites) pass over the same surface locations within 15 minutes of each other, their observations of the Earth system are close enough in time that the meteorology they observe doesn't appreciably change. Thus, the A-Train became an ideal opportunity to conduct multisensor studies of the same phenomena, expanding the horizons of atmospheric research.

The two satellites fly close to each other in the same carefully maintained orbit. This synergy allows the science teams to combine the data from these unique active remote sensing instruments into a near-synchronous, combined radar–lidar dataset to further study clouds, aerosols, and climate.

CloudSat's Objectives

The science objectives for CloudSat are to better understand the vertical structure and the physical and chemical properties of clouds. Specifically, they include:

1. **Profiling the vertical structure of clouds**. Measurements of the vertical structure of clouds are fundamentally important to improving our understanding of how clouds affect both local- and large-scale environments.

2. **Measuring the profiles of cloud liquid water and ice water content**. These two quantities, predicted by cloud-resolving models and global-scale models alike, determine practically all other cloud properties, e.g., precipitation and cloud optical properties.

3. **Retrieving profiles of cloud optical properties.** These measurements, when combined with water and ice content information, provide critical tests of key cloud process *parameterizations*—i.e., bulk estimates of processes too small to be resolved by a given model but necessary to accurately represent the science.

CloudSat's Instrument

The CloudSat instrument is called the Cloud Profiling Radar (CPR). It is a 94-GHz radar with 500-m (~0.3-mi) vertical and 1.4-km (~0.9-mi) horizontal resolution, developed in partnership with the Canadian Space Agency. It is able to sample over 90% of all ice clouds and over 80% of all liquid water clouds in the footprint of its radar. Its 98.2° inclination orbit allows the instrument to sample clouds between roughly 82° N and S latitudes. The spacecraft was designed and built by Ball Aerospace. CloudSat suffered a battery anomaly on April 18, 2011, and now operates only on the daylight side of its orbit[4]. However, it is still operating with its primary power amplifier system and continues to collect useful scientific data.

CALIPSO's Objectives

CALIPSO's overall goal was to provide global, vertically-resolved measurements of aerosol and thin cirrus distribution. The specific objectives focus on improving scientists' understanding of the direct and indirect roles aerosols play in Earth's climate

[3] PARASOL stands for Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar. This was a Centre National d'Études Spatiale [French Space Agency] mission that was part of the A-Train until April 2013. See the A-Train website, referenced in Footnote 2, for more details.

[4] The Editorial of the July–August 2011 [**Volume 23**, **Issue 4**, p. 2] issue of *The Earth Observer* was the first to report on the CloudSat battery anomaly; there was a "CloudSat Update" sidebar in the September–October 2011 issue [**Volume 23**, **Issue 5**, p. 3] that provided more details; the May–June 2012 Editorial [**Volume 24**, **Issue 3**, p. 2] reported on the successful return of CloudSat to the A-Train, but now making daylight observations only.

system through direct observation of aerosols or their influences on cloud properties. They include:

1. **Developing a global suite of measurements from which the first observationally-based estimates of aerosol direct radiative forcing can be determined.** As they absorb and reflect visible and infrared radiation in the atmosphere, aerosols affect how the sun's energy moves through Earth's energy system. The exact nature of those effects, referred to as the *aerosol direct effect*, depends on the size and composition of the aerosols. CALIPSO is designed to measure those aerosol properties to quantify the aerosol direct effect over a variety of locations and surface types.

2. **Dramatically improving the empirical basis for assessing aerosol indirect radiative forcing of the Earth's climate system.** Aerosols also affect the energy budget of the planet by changing the size and number of droplets or ice crystals in clouds, which can then lead to clouds becoming less transparent to electromagnetic radiation and affecting the formation of precipitation. This is known as the *aerosol indirect effect*.

3. **Improving the accuracy of satellite estimates of longwave radiative energy fluxes at the Earth's surface and in the atmosphere**. The infrared energy that flows into and out of the surface of the Earth is hugely impacted by clouds and aerosols. With CALIPSO's improved observations, estimates have improved significantly over the past ten years.

4. **Creating a new ability to assess cloud-radiation feedback in the climate system.** Clouds and the radiant energy budget of the climate are intimately connected. Changes in cloud properties lead to changes in the amount of energy passing through the system, and that in turn influences where and when clouds form. The study of these feedback mechanisms requires accurate measurements of clouds and radiant energy, available from the A-Train satellites.

The specific objectives focus on improving scientists' understanding of the direct and indirect roles aerosols play in Earth's climate system through direct observation of aerosols or their influences on cloud properties.

CALIPSO's Instruments

There are three scientific instruments onboard CALIPSO. The most important of these is the Cloud Aerosol LIdar with Orthogonal Polarization (CALIOP). CALIOP uses a diode-pumped Nd:YAG[5] solid-state laser that nominally produces 110-mJ pulses at wavelengths of 1064 and 532 μm, with a 20.2-Hz pulse repetition rate. Upon returning from the target clouds or aerosols, the 532-μm signals are divided into two components that are polarized parallel and perpendicular to the direction of travel; the polarization helps to distinguish the shape and composition of the detected particles. The lidar can sample every 30 m (~98 ft) in the vertical plane and 333 m (~1093 ft) in the horizontal; pulses are averaged to 60-m (~197-ft) by 1-km (~0.6-mi) resolution in the upper troposphere and 180 meters (~591 ft) by 5 km (~3.1 mi) in the stratosphere, producing images such as the one shown in **Figure 2**.

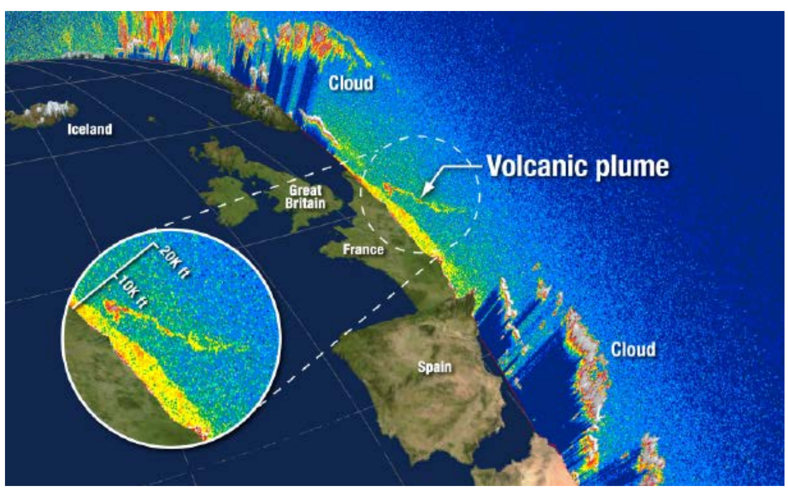


Figure 2. These data were obtained on April 17, 2010, as CALIPSO passed over continental Europe. The Eyjafjallajökull volcano had erupted earlier that spring and the CALIOP lidar detected the plume. The inset focuses on the ash plume. **Image credit**: NASA's Science Visualization Studio

There are two passive instruments onboard CALIPSO: the Imaging Infrared Radiometer (IIR), provided by Centre National d'Études Spatiale (CNES) [French Space Agency], and the Wide Field Camera (WFC), a modified commercial off-the-shelf star-tracker camera

[5] Nd:YAG stands for neodymium-doped yttrium aluminium garnet; more specifically in this usage, Nd:$Y_3Al_5O_{12}$.

developed by Ball Aerospace. Both of these images are aligned with CALIOP to observe the same scenes. The IIR measures infrared energy at wavelengths of 8.65 μm, 10.6 μm, and 12.05 μm over a swath 64 km (~40 mi) wide. These bands were chosen to optimize measurements of cirrus cloud emissions and particle size. The WFC covers visible wavelengths between 620 and 670 nm. It is primarily used to observe visible cloud properties, to provide images of the meteorological context surrounding the lidar measurements, and to provide georeferencing of images, as necessary.

CloudSat and CALIPSO Data Products

From their inception, the capabilities of CloudSat and CALIPSO were intended to complement one another.

From their inception, the capabilities of CloudSat and CALIPSO were intended to complement one another. This is reflected in each mission's list of data products which, while supporting the objectives of the individual mission, also enhances the other, often shoring up a data gap in the counterpart mission. For example, while CloudSat can penetrate thicker clouds to give scientists the best cloud-detection data available from space, it is not as effective at detecting thin cirrus clouds. CALIPSO, on the other hand, has superior thin-cloud detection capabilities, and thus complements CloudSat. Combined, they allow detection of almost all clouds from the thinnest clouds in the stratosphere down to 500 m (~1,640 ft) above the surface in all but the heaviest rain conditions.

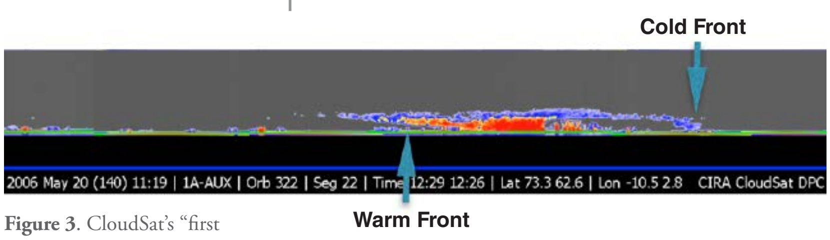


Figure 3. CloudSat's "first light" image on May 20, 2006, revealed a cross-section of the atmosphere across a low-pressure system in the North Atlantic Ocean. The bubble-like structure on the right is a representation of the thin clouds at the leading edge of a cold front, and the wedge shaped intrusion of clear air under thick clouds on the left side of the image represents the structure of a classic warm front. The red colors represent thick clouds that are likely precipitating, although these data, at the time, were uncalibrated. **Image credit**: NASA

The designed complementarity of CloudSat and CALIPSO also benefits the observing capabilities of other missions in the A-Train. For example, one of the CALIPSO products is designed to be used in concert with the two CERES[6] instruments on Aqua. It works both ways as well, since many of the other sensors that are sensitive to the presence of clouds use CloudSat and CALIPSO's superior cloud-detection ability to filter out any data contaminated by clouds. The data products described here have allowed the CloudSat and CALIPSO science teams to push the boundaries of what we know about aerosols and clouds and their impacts on the Earth-atmosphere system.

CloudSat's Data Products

CloudSat data products[7] are archived at the CloudSat Data Processing Center at the Cooperative Institute for Atmospheric Research (CIRA) at Colorado State University, Fort Collins, CO. The primary data product for this mission is the Level-1B calibrated, range-resolved radar reflectivities. From these data, Level-2 data that contain derived cloud properties are then calculated, often in combination with other observations from CALIPSO and the A-Train constellation. Images, such as the one shown in **Figure 3**, are freely available to the public within a few hours of an overpass from the CloudSat Data Processing Center (*http://www.cloudsat.cira.colostate.edu/quicklooks*).

A few of the other frequently used data products currently available at the Data Processing Center to members of the science team are:

- cloud classification profiles that combine CloudSat radar and CALIPSO lidar data to classify observed clouds by type (e.g., cirrus, stratus, cumulus);

- the flux heating rate product, which calculates upwelling and downwelling *shortwave* (or *solar*) radiation—with wavelengths less than 4 μm—and *longwave* (or *terrestrial*) radiation—with wavelengths greater than 4 μm—energy fluxes due to the presence of clouds; and

[6] CERES stands for Clouds and the Earth's Radiant Energy System; the instrument flies on the Terra, Aqua, and the Suomi National Polar-orbiting Partnership (NPP) satellites.
[7] A complete list of CloudSat's data products can be found at *http://cloudsat.atmos.colostate.edu/data*.

- rain and snow profiles that use radar attenuation caused by precipitation to estimate the rain and snow rates in precipitating clouds.

CALIPSO's Data Products

CALIPSO data products are available through the LaRC Atmospheric Science Data Center (*http://eosweb.larc.nasa.gov*). In addition to the attenuated backscatter profiles such as those seen in Figure 3, scientists can access additional data such as:

- cloud and aerosol *extinction profiles*, which present vertical observations of how the laser light was diminished by either absorption of or scattering by particles;
- cloud-top and cloud-base heights, which are extremely accurate since the lidar can detect even the smallest cloud particles at the edges of clouds;
- cloud ice/water phase information, which is determined from the use of polarized light detectors;
- cloud emissivity and particle sizes, determined by combining data from all three instruments onboard CALIPSO;
- infrared radiances, from the IIR;
- reflected visible light, from the WFC; and
- radiant energy fluxes from the surface and in the atmosphere, determined by combining CALIPSO data with data from the two CERES instruments on the Aqua satellite.

As they enter their second decades, these two satellites have more than met their initial science goals, and groundbreaking results are being shared even today.

Science Highlights from Ten Years Profiling Clouds and Aerosols

Armed with these two unique, cutting-edge satellites and their respective data products, scientists on the CloudSat and CALIPSO science teams have been digging into the scientific questions posed at the start of each mission. As they enter their second decades, these two satellites have more than met their initial science goals, and groundbreaking results are being shared even today. At this milestone for both missions, we highlight several of the scientific discoveries made possible since their 2006 launch. This is by no means an exhaustive list; rather, it gives only a sense of what CloudSat and CALIPSO have brought forth to date.

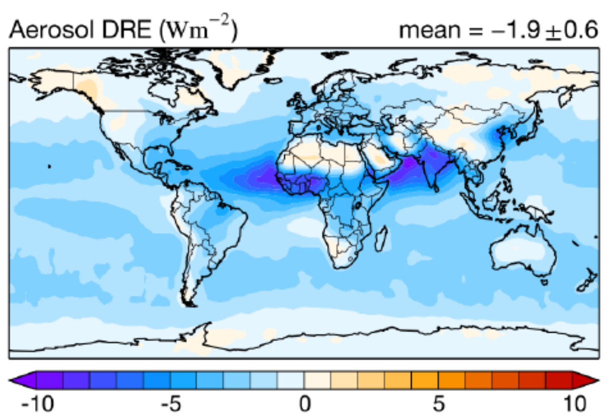


Figure 4. Map of the annual mean, all-sky (including clouds) direct radiative effect (DRE) of aerosols at the top of the atmosphere (TOA), as observed by CloudSat and CALIPSO over a 10-year period. Negative numbers indicate that aerosols are reducing the amount of solar radiation penetrating the atmosphere, which should indicate a cooling effect on the climate. **Image credit**: Alexander Matus

The impacts of aerosols in Earth's climate system

One of the main charges of the CALIPSO mission was to assess the impact of aerosols on Earth's radiation budget through the aerosol direct and indirect effects, as described earlier.

CALIPSO data have been used to estimate the global aerosol direct radiative effect, in both clear and cloudy skies, as well as above and below clouds for the first time. These results are more representative than previous measurements attempted with passive satellite observations (e.g., the Moderate Resolution Imaging Spectroradiometer, MODIS, onboard NASA's Terra and Aqua platforms) largely because of assumptions that had to be used to estimate aerosol effects near clouds. While there is still no agreement on the size of the effect of aerosols near clouds, scientists are for the first time able to base their estimates on observations rather than assumptions. **Figure 4** illustrates where this effect is strongest, typically downwind of areas of biomass burning, sources of dust and sand, and anthropogenic air pollution.

In turn, the aerosol indirect effect is believed to be caused by two distinct mechanisms: A cloud polluted with additional aerosols will have many more droplets of water, each of which is relatively small compared with the droplets found in a non-polluted cloud. Such clouds with smaller droplets appear to be thicker to visible-light wavelengths, giving rise to what scientists call the *first aerosol indirect effect*, reducing the amount of sunlight that reaches the surface. Clouds that are more polluted also are believed to be less likely to produce rain or snow. Thus, the *second aerosol indirect effect* results in clouds that last longer, thereby reducing the amount of sunlight reaching the surface over time.

Additional investigations have shown that, in warm clouds near the surface, there may be a third mechanism in place, one that shows aerosols actually allowing these clouds to increase in water content by trapping the clouds near the surface of the ocean for longer periods. Better understanding of the mechanisms through which clouds affect aerosols should improve scientist's ability to model these interactions and, in turn, incorporate the information into future climate scenarios.

Better understanding of the mechanisms through which clouds affect aerosols should improve scientist's ability to model these interactions and, in turn, incorporate the information into future climate scenarios.

Our discussion of the impact of aerosols thus far has focused on their impacts on Earth's atmosphere. This is, after all, the most intuitive place to search for the impacts of these tiny airborne particles. However, scientists have recently quantified another way aerosols impact climate: through the fertilization of soils where they land after having been carried by the prevailing winds. A recent study showed that the productivity of the Amazon rainforest, which is nutrient-limited by the availability of phosphorus, gains an estimated 28 Tg of phosphorus per year from aerosols (i.e., dust) transported from sources that originate in the African Sahel region. While 28 Tg represents a small portion of the overall phosphorus budget of the Amazon, it is of the same magnitude as the loss of phosphorus due to water flowing out of the basin. Thus, it appears that African dust transport is an important balancing mechanism for maintaining phosphorus levels in the Amazon over decades and centuries.

The impacts of different cloud types around the world

As described earlier, the combined observing capabilities of CloudSat and CALIPSO allow detection of most cloud types, ranging from the thinnest cirrus clouds to the thickest tropical cumulonimbus clouds. This has allowed scientists to delve deeply into questions about the distribution of certain cloud species on the planet, and how these distributions impact our thinking about climate. For example, high, thin cirrus clouds tend to have a warming influence on our climate, as they allow incoming sunlight to filter through them unfettered while preventing Earth's outgoing infrared emissions to space. Meanwhile, low, thick, water clouds can cool our climate by reflecting sunlight away before it is absorbed into Earth's surface. Thus, from early on scientists recognized the importance of identifying and cataloguing these clouds and sought to do so using data from these missions.

A few years after launch, there was an intercomparison of cloud detection products using data from CloudSat, CALIPSO, and the Atmospheric Infrared Sounder (AIRS) flying on the Aqua satellite. The results show the value of identifying areas where the passive AIRS instrument could be improved in detecting high, thin clouds that CALIPSO could readily see, and the lower, thicker, precipitating clouds observed by CloudSat.

Around the same time, scientists used data from CloudSat and CALIPSO to produce the first global map of cirrus clouds; they demonstrated that previous passive satellite measurements of cirrus frequency were too low in the tropics and too high in the polar regions. Subsequent studies confirmed these results and showed that thin cirrus clouds were in fact responsible for a significant amount of the warming observed in the tropical atmosphere. They used CloudSat and CALIPSO data to suggest a better way to represent such clouds in climate models in order to more accurately represent the impact of those clouds.

Meanwhile, another investigation revealed that passive satellite measurements of intense thunderstorms with *overshooting tops*—cloud tops that protrude above the rest of the thunderstorm into the lower parts of the stratosphere—significantly underestimated their heights compared to active measurements (i.e., from CloudSat and

CALIPSO). Thunderstorm height is often a strong indicator of how much energy such storms inject into their environment, which suggests that these underestimates of cloud tops also could impact climate model predictions. All of these studies combined have helped to improve weather and climate modeling by providing better data for how clouds behave in the real atmosphere.

A recent study used CloudSat and CALIPSO data on *mixed-phase clouds*—clouds containing both liquid water and ice—and that also contained *supercooled water*—liquid water at temperatures below the freezing point—to constrain the energy balance of climate models. The results showed that, when climate models represented these clouds more accurately, the climate models realized an additional 1.3 °C (2.3 °F) of warming.

The common thread running through all of these important studies over the past decade is that, prior to the advent of CloudSat and CALIPSO data, only less-accurate passive satellite observations were available for comparison to climate and weather models. Now that more-precise and unique measurements are available from these missions, it is possible to more accurately represent cloud characteristics in climate models. Incorporating all this new information into the models should lead to continued improvements in the depiction of clouds, and their impacts on Earth's climate system.

The common thread running through all of these important studies over the past decade is that, prior to the advent of CloudSat and CALIPSO data, only less-accurate passive satellite observations were available for comparison to climate and weather models.

Clouds in the polar regions may be more important than we thought

Another important aspect of CloudSat and CALIPSO (as well as the other missions in the A-Train) is that they are capable of measuring clouds over Arctic and Antarctic climate zones. As a result, data from these missions have provided a treasure trove of insights into the unique roles that polar clouds play in influencing the climate of these regions. For example, clouds over the Arctic region have been shown to have a major impact on summer sea ice extent in the Arctic Ocean. CloudSat and CALIPSO observations revealed a 16% decrease in cloudiness from 2006 to 2007 that contributed enough extra solar energy to melt an additional 0.3 m (~1 ft) of ice, or to warm ocean water by 2.4 °C (4.3 °F) over the three summer months. A follow-on study used similar data to show that in the Arctic fall low clouds increase in response to the warmer ocean waters, marking the first direct observational evidence of clouds changing in response to anthropogenic greenhouse gases and climate change. These studies both help to explain many of the key features of how the relationships between the atmosphere and sea-ice coverage respond to climate changes.

Clouds have also been recently identified as playing a greater-than-expected role in the melting of Greenland's ice sheets. For example, one recent study showed that, while the sun is primarily responsible for melting ice during the day, clouds are preventing meltwater from refreezing at night, due to extra infrared energy emitted by clouds toward Earth's surface. At the last CloudSat–CALIPSO science team meeting[8], evidence was presented that mixed-phase clouds are responsible for most of that energy—enough to melt 90 billion tons of ice per year. For reference, a 2012 study led by **Andrew Shephard** [University of Leeds] estimated that between 1992 and 2011, the Greenland ice sheet lost 142 ± 49 billion tons of ice. Indeed, it is difficult to explain the rate of Greenland's ice loss without taking into account these clouds and their surface-heating effects.

Finally, the impact of clouds on Earth's climate extends well above Earth's surface. *Polar stratospheric clouds* (PSCs) are a combination of water, sulfuric acid, and nitric acid that form in the very cold polar stratosphere. Scientists have long known that PSCs play a significant role in ozone-hole chemistry due to their ability to catalyze reactions with chlorine-bearing compounds that can destroy ozone. In another recent study, CALIPSO data were used to monitor the evolution of different kinds of PSCs and their relative ability to catalyze such ozone-destroying reactions. These observations have the potential to address hypotheses about the kinds of clouds involved in ozone chemistry—phenomena that had been heretofore very challenging to observe directly.

[8] See the May-June 2016 edition of *The Earth Observer* for more information on the results shared at this meeting, including more information on these particular results [**Volume 28**, **Issue 3**, pp. 30-34].

Bringing Clouds and Aerosols into the Classroom

Since before the 2006 launches of CloudSat and CALIPSO, the education and public outreach (EPO) teams for the two missions have worked closely together to bring the science of clouds and aerosols into K-12 classrooms around the world. As the missions celebrate 10 years in orbit, the EPO teams look back at their achievements and also share some of the highlights of new projects currently underway.

Even before launch—since 2005—both CloudSat and CALIPSO mission EPO efforts have been married to the Global Learning and Observations to Benefit the Environment (GLOBE) program (*http://www.globe.gov*). The GLOBE program is best known for providing measurement protocols to observe the environment so that K-12 students around the world can engage in authentic scientific investigations. In the case of these two missions, mission scientists and education specialists helped to train teachers in specialized protocols for students to enable them to participate in collecting data related to mission science objectives.

CALIPSO-related training featured an *aerosol optical thickness* measurement that used an inexpensive, handheld sun photometer to measure the atmospheric aerosol direct effect, while CloudSat-related training featured an enhanced version of GLOBE's clouds protocol that could be completed when the satellite was about to pass overhead. Student observations have helped to provide CloudSat ground truth data from several countries, including Australia, India, Thailand, Estonia, and the U.S., for the cloud classification data product. Because of these efforts, student participation with data collection protocols was shown to enhance learning scientific practices and has engaged students in designing their own research projects. Every year at the GLOBE annual meeting, students from around the world present results from their own research using CloudSat- and CALIPSO-related data.

Both missions have taken slightly different directions since these early "pre-launch" efforts to maintain engagement. CALIPSO, and later CloudSat, made their data available at the MyNASAData educational data portal (*http://mynasadata.larc.nasa.gov*). This site allows students to access all manner of data from NASA Earth-observing missions, and to conduct data analyses to support learning goals and independent research. The CALIPSO team has also provided scientific support to the authorship of a new Elementary GLOBE storybook, written for students aged 5-10, called *What's Up in the Atmosphere: Exploring Colors in the Sky*. This book and accompanying learning activities, along with a protocol for simplified observations of sky color as it related to aerosols in the atmosphere, can be downloaded at no charge from *http://www.globe.gov/web/elementary-globe/overview/aerosols/story-book*.

Meanwhile, CloudSat educators developed a series of professional development workshops designed to train teachers in how to blend NASA data and GLOBE observations into their regular teaching practice. This continues to be important with the advent of the Next Generation Science Standards, which emphasize engaging U.S. learners of all grade levels in authentic scientific practice.

The photos below were captured during GLOBE teacher training sessions over the past 10 years. For more information on these and other CloudSat and CALIPSO education and communication efforts, please contact **Todd Ellis** [Western Michigan University—*CloudSat Education and Communication Lead*] at *todd.ellis@wmich.edu* or **Jessica Taylor** [LARC—*CALIPSO Education and Communication Lead*] at *jessica.e.taylor@nasa.gov*.

Selected photos from CloudSat and CALIPSO teacher training events around the world over the past decade. Training sessions were designed to provide tools to allow teachers to engage their students in scientific investigations relevant to the missions, using freely available NASA data to better understand clouds and aerosols in Earth's atmosphere. **Image credit(s):** Matt Rogers [*top*] and Jessica Taylor [*middle and bottom*]

Making it rain (or snow) around the world

One of the most remarkable achievements by the CloudSat science team is the development of precipitation profile products. Over the years, rainfall modeling has been challenging—and snowfall modeling has been even more difficult. CloudSat observations have changed that. CloudSat rainfall data have been available since 2007; more recently, the first-ever global estimate of snowfall has become available. Both products are now standard data outputs from CloudSat and CALIPSO observations and have opened the doors to new insights on how and where precipitation falls, globally.

One of the most remarkable achievements by the CloudSat science team is the development of their precipitation profile products.

For example, from the CloudSat rainfall data, scientists have learned that, averaged globally, clouds produce rain nearly 20% of the time, with a significant amount of that rainfall falling as lighter precipitation from shallow cumulus clouds over the tropical oceans. By comparison, heritage passive measurements of rainfall often grossly underestimate the amount of rain falling around the globe—in some cases by almost 60%—because they miss the precipitation from these shallower cumulus clouds.

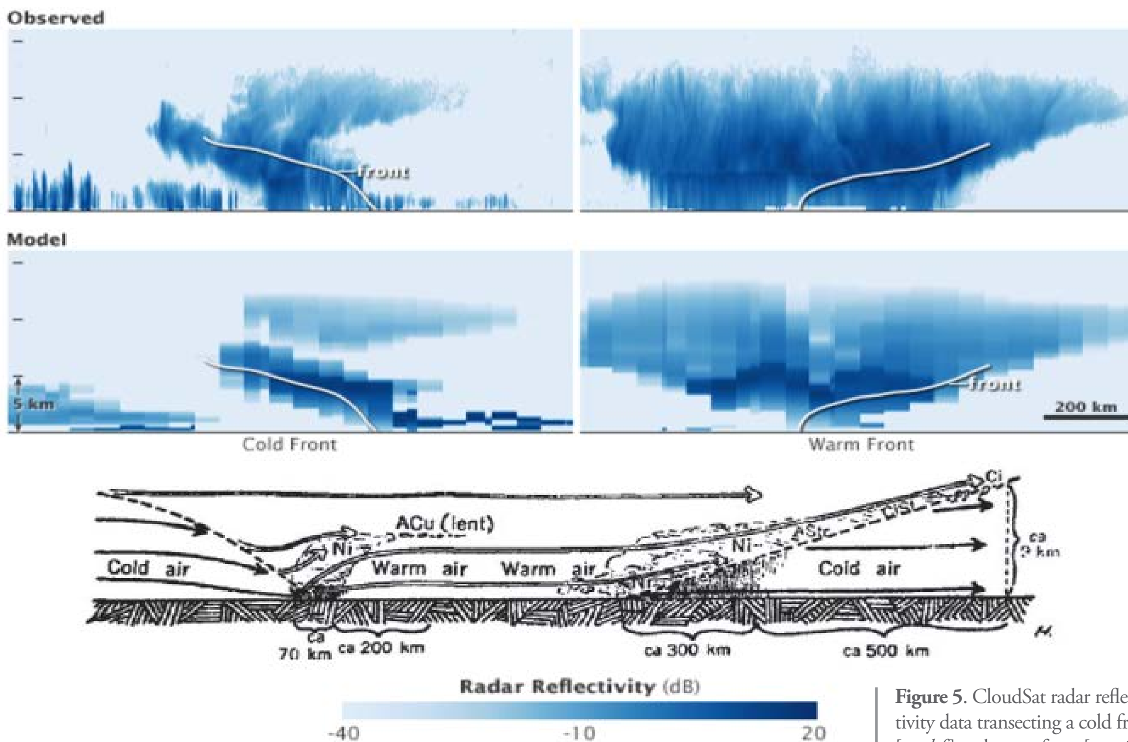


Figure 5. CloudSat radar reflectivity data transecting a cold front [*top left*] and warm front [*top right*] on November 22, 2006. These are compared with European Centre for Medium-range Weather Forecasts (ECMWF) model results for the same systems [*middle left* and *middle right*, respectively]. For comparison, a sketch from a seminal 1922 paper by Jacob Bjerknes and Halvor Solberg, detailing the classical model for clouds and precipitation accompanying frontal systems, is shown [*bottom*]. **Image credits**: NASA Earth Observatory, American Meteorological Society

The A-Train has also allowed us to gather new observations of how warm tropical clouds produce precipitation, which in turn has allowed scientists to improve how precipitation is simulated by weather and climate models. For example, weather models do not always place rainfall in the correct places relative to cold and warm fronts in the mid-latitudes (see **Figure 5**), but CloudSat observations have allowed forecasters to begin to correct this.

In addition, by incorporating CloudSat data, scientists have compiled a comprehensive database of A-Train cloud and precipitation data from tropical cyclone overpasses. This database is intended to facilitate further study of the internal structure and mechanism of how storms strengthen. Samples of some of those data can be found at the CloudSat website (*http://cloudsat.atmos.colostate.edu)*; there is also an illustration in **Figure 6** on the next page.

All of these advances in understanding the internal mechanics of precipitation in clouds have enabled scientists to better model clouds at the regional and global scales, and have greatly reduced the uncertainty in those models' representations of clouds and precipitation in the Earth-atmosphere system.

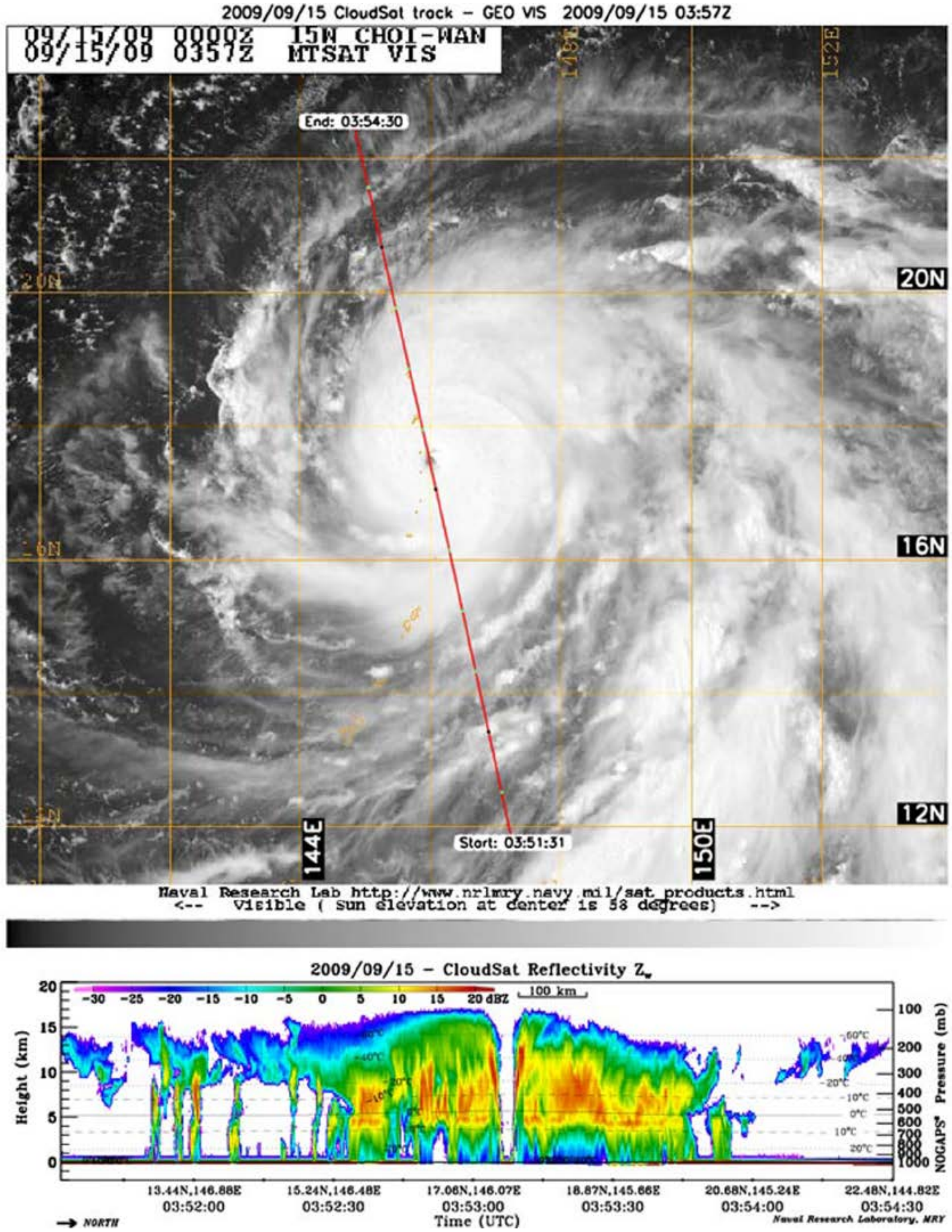


Figure 6. Imagery from an A-Train overpass of Typhoon Choi-Wan on September 15, 2009. In the Moderate Resolution Infrared Spectroradiometer (MODIS) image of the typhoon [*top*] the brighter whites indicate higher clouds, and the red line indicates CloudSat's footprint. Notice that while the image is vivid, MODIS is limited to a two-dimensional view of the storm. The CloudSat radar reflectivity profile [*bottom*] literally adds another dimension to the observations. As the satellite moved from south to north along the indicated path, it observed a cross-section of the typhoon's eye as well as some of the layered cloud structures in the outer spiral bands. **Image credit**: Natalie Tourville

Putting it all together: The global energy balance of the Earth-atmosphere system

Perhaps the most compact way to summarize the importance of the scientific achievements from the first decade of the CloudSat and CALIPSO missions is by revisiting the planetary global energy balance. Clouds play several important roles in modulating how energy moves through Earth's atmosphere: by reflecting sunlight, emitting infrared energy back to the surface as part of Earth's greenhouse effect, and releasing energy into the atmosphere as water vapor condenses to form cloud droplets and precipitation. Other instruments (e.g., CERES) have also been able to measure total energy flows into and out of the atmosphere. But CERES data suffered from the limitations common to all passive measurements, as has been discussed previously. Until the arrival of CloudSat and CALIPSO, the impacts of clouds

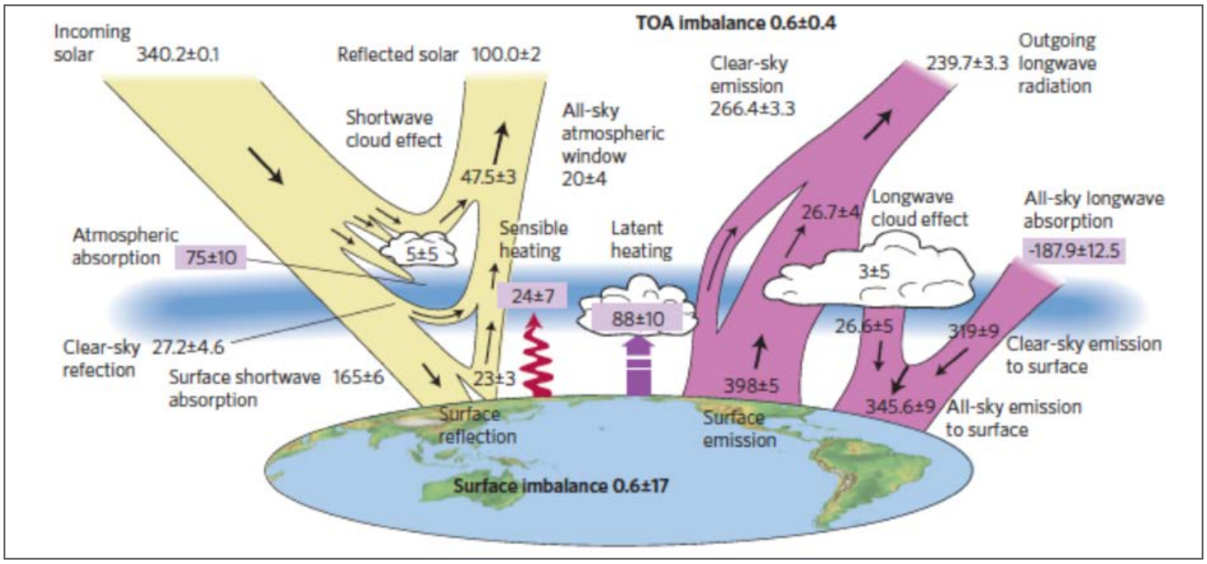


Figure 7. The global annual mean energy budget of Earth for the approximate period 2000-2010—updated to include information from CloudSat and CALIPSO. All fluxes are measured in W/m^2. Solar fluxes are depicted in yellow [*left*], while infrared fluxes are depicted in pink [*right*]. The four flux quantities [*purple-shaded rectangles*] represent the principal components of the atmospheric energy balance. **Image credit**: Graeme Stephens

on radiant energy remained difficult to quantify in part because not all clouds could be identified from space and, in part, because passive measurements could not always accurately characterize the composition of those clouds.

Scientists have developed an updated set of estimates of the global energy budget, which incorporates data from CloudSat and CALIPSO—see **Figure 7**. The estimates of energy flowing to the surface were improved by using satellite data, including CloudSat- and CALIPSO-derived heating rates, to make up for the lack of surface observations over the ocean. As a result, esitmates of the *longwave downwelling radiation*—infrared radiation entering the surface from the atmosphere—increased by over 10 W/m^2, mostly due to improvements in representing the impacts of clouds in calculations of how energy flows through the Earth-atmosphere system. This increase in surface energy is balanced largely by increased evaporation of water vapor into the atmosphere, and consequently by the increased precipitation observed by CloudSat.

This new energy balance calculation required a synthesis of many data products from CloudSat and CALIPSO described in this article. Improvements in understanding aerosol direct and indirect effects shaped the estimates of how much incoming solar radiation clouds reflected and how much aerosols absorbed. Improvements in observations of clouds around the globe have improved our understanding of how clouds are warming or cooling the climate. CloudSat's observations of precipitation showed that scientists had been underestimating global precipitation. Subsequently, CALIPSO and CloudSat observations demonstrated that the additional energy needed to account for that precipitation came from the additional warming clouds were providing to the surface, especially in the polar regions.

*It is fair to say that CloudSat and CALIPSO have indeed helped humanity move toward what **Graeme Stephens** [JPL—CloudSat Principal Investigator]—evoking Luke Howard's words—often jokingly called the "useful pursuit of shadows;" they have improved our understanding of the nature of the ubiquitous clouds and aerosols that float above us in Earth's atmosphere.*

Conclusion

Reflecting on our understanding as of a decade ago of the roles clouds and aerosols play in Earth's climate gives us perspective for just how far CloudSat and CALIPSO have advanced our knowledge in these areas over the past 10 years. In some cases, cloud and aerosol observations made possible by these two missions have fundamentally reshaped our understanding of how the entire climate system works. It is fair to say that CloudSat and CALIPSO have indeed helped humanity move toward what **Graeme Stephens** [JPL—*CloudSat Principal Investigator*]—evoking Luke Howard's words—often jokingly called the "useful pursuit of shadows;" they have improved our understanding of the nature of the ubiquitous clouds and aerosols that float above us in Earth's atmosphere. The science teams are committed to continuing that pursuit as we seek to further expand our knowledge of clouds and aerosols, and the myriad ways they move water and energy around the planet. ■

2016 AIRS Science Team Meeting Summary

Eric J. Fetzer, NASA/Jet Propulsion Laboratory, eric.j.fetzer@jpl.nasa.gov

The NASA Atmospheric Infrared Sounder (AIRS) Science Team Meeting was held March 22-24, 2016 at the California Institute of Technology's Beckman Institute in Pasadena, CA. The AIRS Project at NASA/ Jet Propulsion Laboratory (JPL) hosted the meeting. While the unifying theme of the meeting was atmospheric observations from AIRS, there were presentations about data from other sounders as well.[1] There was also a special session devoted to AIRS Applications. Speakers at the meeting shared results from a broad range of scientific and technical disciplines.

There were 38 presentations spread across 6 themed sessions during the meeting. The sessions included:

- Introductory Remarks/Project Status;
- Atmospheric Composition;
- Weather and Climate;
- AIRS Applications;
- Product Development; and
- Product Validation.

This report focuses on four invited presentations related to two of the six sessions that took place during the meeting, and two additional presentations that were noteworthy. The meeting agenda is available at *http://airs.jpl.nasa.gov/events/36*; most of the presentations from this and related earlier meetings can be downloaded from *http://airs.jpl.nasa.gov/resources/presentations*.

Highlights

Day One

The first day of the meeting began with introductory remarks and updates on the AIRS Project. The AIRS instrument on NASA's Aqua platform has been operational since late August 2002 and has a lifetime expected to last into the early 2020s. AIRS data continue to make significant contributions to global forecasting skill and support a large community of researchers in weather, climate, and atmospheric composition disciplines. Two sessions made up the remainder of the first day: Atmospheric Composition, which included one invited presentation (which had to be delayed until the third day), and Weather and Climate.

Participants at the AIRS Science Team Meeting held March 22-24, 2016, at the California Institute of Technology in Pasadena, CA

In the Atmospheric Composition session, **Dejian Fu** [JPL] described an algorithm to retrieve ozone from collocated radiance observations from AIRS and the Ozone Monitoring Instrument (OMI) onboard NASA's Aura platform. Because Aqua and Aura fly in the A-Train constellation[2], the radiances from the two instruments are obtained within a minute of each another. One of the analyses shown in the presentation demonstrated the synergy of the two sets of observations. Retrievals using the combined radiances have higher information content than the combination of retrievals based on separate radiances. During the Weather and Climate session, **Xun Jiang** [University of Houston] showed how carbon dioxide (CO_2) observed in the middle troposphere by AIRS over the southwestern U.S. is correlated with regional drought. She attributed the higher CO_2 amounts to increased production by wildfires and reduced uptake by drought-stressed vegetation.

Day Two

The AIRS Applications session comprised the entire second day of the meeting, which included three invited presentations (described in some detail below), as well as other presentations on other related topics.

Pietro Ceccato [International Research Institute/ Columbia University] described the challenges and benefits of using remote sensing data to monitor atmospheric conditions that affect food security, human health, and disaster management. He described examples of how vector-borne diseases and locust swarms in Africa are affected by variations in local temperature, humidity, and rainfall. Ceccato noted that there are many locations around the world where such observations are available only from satellite instruments. Many of these areas are also regions of lower socioeconomic

[1] Spring meetings tend to focus more on AIRS while fall meetings have a broader international focus and are thus referred to as "Sounder" meetings. To read about the most recent Sounder Science Team Meeting, please see the January-February issue of *The Earth Observer* [**Volume 28, Issue 1**, pp. 27-28].

[2] For more information on the A-Train and the missions that comprise it, please refer to *http://atrain.nasa.gov*.

development, where resilience to natural stressors tends to be more limited. Of particular value is that information about the atmosphere obtained by satellites can be rapidly disseminated to local communities via near-ubiquitous cellular telephone networks.

Chris Barnet [Science and Technology Corporation] described his experience in incorporating retrievals from AIRS and other sounders into forecast systems run by the National Oceanic and Atmospheric Administration (NOAA) and related contracting organizations. Barnet described many challenges, including very diverse user needs and a complex forecast system containing a large number of datasets for assessment. These challenges are being met through close collaboration and careful communication between forecasters and data providers. Barnet also gave several examples of how the forecast community uses sounder information, including atmospheric river monitoring over the Pacific, measurements of cold air aloft near Alaska, and observations of severe summertime weather over the Midwestern U.S.

Amir AghaKouchak [University of California, Irvine] examined drought indicators using AIRS and other information sources. He showed that AIRS near-surface relative humidity can provide improved drought forecast skill over the U.S. as compared to precipitation-based indicators, particularly when warm, dry atmospheric conditions cause plant stress. AghaKouchak described efforts to incorporate AIRS observations into an operational drought monitoring and prediction system.

In addition to the invited presentations, the Applications session also included presentations on a wide range of topics featuring AIRS data, including forecast improvements, using ozone amounts to detect stratospheric air intrusions, visualizing and distributing near-real-time products, incorporating sounder data into geographical information systems, and monitoring volcanic plumes.

Day Three

David Crisp [JPL] opened the third day's sessions with the fourth invited presentation addressing Atmospheric Composition—which had been delayed from day one. He showed analyses of Orbiting Carbon Observatory-2 (OCO-2) satellite observations of atmospheric CO_2. Crisp described his team's work to validate OCO-2 against *in situ* observations. He also shared preliminary global maps of CO_2 from OCO-2, and compared those with maps of AIRS mid-tropospheric CO_2. Crisp also described the first efforts to use OCO-2 observations to close the atmospheric carbon budget (which is the primary scientific goal of OCO-2). He also showed global maps of solar-induced *chlorophyll fluorescence*—a measure of plant activity—also from OCO-2.

The remainder of the third day was devoted to the Product Development and Product Validation sessions. During

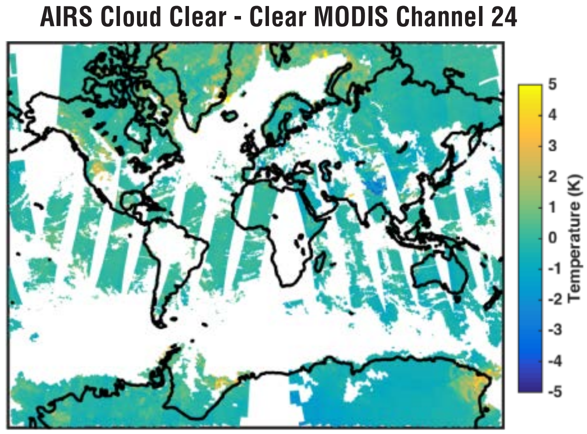


Figure. Difference between AIRS cloud-cleared radiance averaged to Moderate Resolution Imaging Spectroradiometer (MODIS) spectral resolution and Aqua MODIS channel 24 radiance. The agreement is within 1 K over most of the globe, with larger values at high latitudes likely due to contamination by a snow or ice surfaces. **Image credit**: Chris Wilson

the Product Development session, **H. H. Aumann** [JPL] discussed the challenges of developing an AIRS forward model that includes the effects of clouds, noting that this would permit the simultaneous retrieval of clouds and other atmospheric variables. During the Product Validation session, **Chris Wilson** [JPL] described the validation of AIRS cloud-cleared radiance, which is a retrieved estimate of infrared emission from cloud-free parts of AIRS scenes. He collocated radiance observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Aqua with similar observations from AIRS, and then spectrally smoothed the AIRS radiances; this approach allows direct comparison of radiances between the two instruments. The results showed good agreement in all MODIS channels, with better agreement for AIRS scenes flagged as having higher-quality retrievals. One such comparison at a MODIS spectral channel that is sensitive to atmospheric temperature is shown in the **Figure** above.

Summary

The AIRS instrumental record now extends nearly 14 years and contains approximately 3 million spectra observed daily for a total of nearly 15 billion spectra to date. Three related hyperspectral infrared sounders, several lower-spectral-resolution infrared and microwave sounders, and related instruments, e.g., OCO-2, are currently operated by NASA and by other space agencies around the world. (See the Fall 2015 Sounder Science Team meeting summary referenced earlier for a list of these related sounder instruments.) These marvelous machines provide a detailed record of weather and climate phenomena extending over decades. The next Sounder Science Team Meeting, where the more-extended sounder community will share results, is planned for September 2016 in Greenbelt, MD. More details are available at *http://airs.jpl.nasa.gov*. ■

Summary of the Twenty-Fifth CERES-II Science Team Meeting

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

Introduction

The spring 2016 Clouds and the Earth's Radiant Energy System (CERES-II[1]) Science Team meeting was held April 26-28, 2016, at NASA's Langley Research Center (LaRC) in Hampton, VA. **Norman Loeb** [LaRC—*CERES Principal Investigator*] hosted and conducted the meeting. The major objectives of the meeting were to review the performance of CERES instruments[2] and discuss data product validation. The two invited presenters discussed the use of CERES data in understanding climate change, while the contributed science presentations summarized progress among team members related to a variety of scientific topics.

Meeting presentations can be downloaded from the CERES website (*http://ceres.larc.nasa.gov*) by clicking the "CERES Science Team Meetings" button in the "Documentation" menu tab in the top-level navigation bar.

Programmatic and Technical Presentations

The agenda for the first day of the meeting consisted of a series of programmatic and technical presentations.

Norman Loeb gave the opening "State of CERES" address. He mentioned that the next CERES Flight Model (FM), named FM-6, has been integrated into the Joint Polar Satellite System (JPSS-1) satellite[3] scheduled for an early 2017 launch. The Radiation Budget Instrument (RBI) that will replace CERES on JPSS-2 had a successful Preliminary Design Review (PDR) May 10-12, 2016, at the Harris Corporation facility in Fort Wayne, IN. With regard to flight operations, NASA Headquarters is preparing a waiver for the Terra Constellation exit plan that would lower the spacecraft by 4 km (~2.5 mi). This small change in altitude is sufficient to allow Terra to continue to collect data within one minute of its current equatorial crossing time for an additional three years without adversely impacting science results. Loeb went on to illustrate CERES-based science results by showing the December 2015 Top of Atmosphere (TOA) anomalies from the fifteen-year Energy Balanced and Filled TOA (EBAF-TOA) version 2.8 product—derived from CERES on Terra and Aqua—as shown in **Figure 1**. This gives an idea of the impact the 2015-16 El Niño has had on radiation reaching the TOA.

Susan Thomas [Science Systems and Applications, Inc. (SSAI)] presented a comparison of CERES FM-5 (Suomi NPP) and FM-3 (Aqua) data when nadir-looking footprints viewed the same point. The FM-5 shortwave (SW) measurements are 2% higher than those from FM-3; she added that the difference has been decreasing with time. The FM-5 longwave (LW) measurement difference was 0.5 % lower when compared to FM-3. **Wenying Su** [LaRC] reached the same conclusion using Single Scanner Footprint (SSF[4]) data. She did note that there were especially high differences

[1] CERES-II stands for the second CERES Science Team. After the launch of Aqua in 2002, NASA recompeted the membership. The new team held its first meeting in March 2004 and the team has used this nomenclature to refer to its meetings since then.

[2] There are currently five CERES instruments active on three satellites: two on Terra [Flight Model (FM)-1 and -2]; two on Aqua [FM-3 and -4]; and one on the Suomi-National Polar-orbiting Partnership (NPP) [FM-5].

[3] The Joint Polar Satellite System (JPSS) is our nation's next-generation polar-orbiting operational environmental satellite system. JPSS is a collaboration between the National Oceanic and Atmospheric Administration and NASA.

[4] The SSF combines instantaneous CERES data with scene information from a higher-resolution imager such as Visible/Infrared Scanner (VIRS) on the Tropical Rainfall Measuring Mission (TRMM) or Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua.

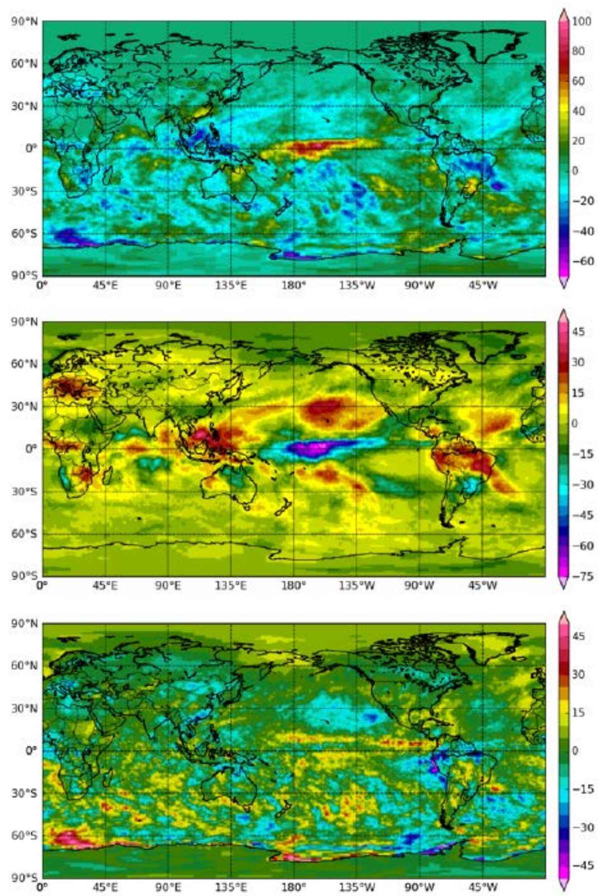


Figure 1. These plots show EBAF-TOA Edition 2.8 product radiative flux anomalies from the 15-year mean during the strong 2015 El Niño in December for reflected solar [*top*], outgoing longwave [*middle*], and net [*bottom*] radiation. The flux anomaly bands in the equatorial Pacific indicate El Niño conditions. **Image credit:** Norman Loeb

in SW radiance over the ocean—reaching as high as 10%—but all other scene types showed comparable differences. Corrections for the spectral differences in the Suomi NPP data that have occurred since launch have not yet been applied. The hope is that agreement between FM-5 and -3 will improve in the future.

Patrick Minnis [LaRC] highlighted that the daytime cloud fraction produced using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard Aqua and the Visible Infrared Imaging Radiometer Suite (VIIRS) on Suomi NPP throughout 2013 are very similar. When averaged over the globe the bias in nighttime cloud fraction values is slightly more than 1%; the greatest differences are observed over the Arctic and over tropical regions. Both day and night cloud phases are consistent between the two imagers, however the microphysical properties show larger differences. **David Kratz** [LaRC] presented validation results of the Aqua and Suomi NPP SW and LW parameterized surface fluxes as compared with surface observations, which had similar biases and root-mean-square errors.

Dave Doelling [LaRC] began a discussion of CERES Edition 4 gridded data products. He described the calibration and advanced quality control of the geostationary imagery used for Edition 4 cloud property products (e.g., cloud fraction, optical depth, and effective pressure). These cloud properties are now incorporated hourly to provide an improved representation of daytime cloud changes in the One-degree Gridded Synoptic (SYN1deg) product suite. Based on six years of recently produced SYN1deg data, **Seiji Kato** [LaRC] reported that using hourly Edition 4 geostationary cloud information allowed the flux calculations from a radiative transfer model to more closely follow TOA observations than was achieved in Edition 3. As an additional refinement, the Edition 4 surface flux biases when compared to surface observations have decreased compared to Edition 3—see **Figure 2**.

Norman Loeb returned to discuss upcoming improvements to the EBAF-TOA Edition 4.0 product. The new version will have the same meteorological data assimilation product for the entire period, the same hourly clouds—derived from geostationary imagers—that were used in SYN1deg processing, and refinements to the high-resolution clear-sky TOA fluxes. In addition, the EBAF-TOA Edition 4.0 product will incorporate ten years of Argo[5] data as opposed to only five in Edition 2.8 to determine Earth Energy Imbalance (EEI). Basic cloud properties (e.g., fraction, optical depth, and effective pressure) will be added to the product to allow scientists to perform additional analyses with consistent information.

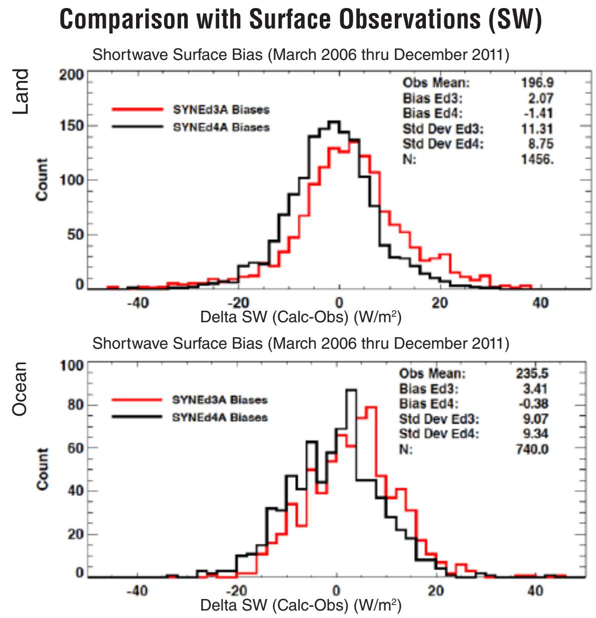


Figure 2. A comparison of calculated SW surface flux from Edition 3 (red) and Edition 4 (black) SYN1deg-Month calculated and surface observation sites for land [*top*] and ocean [*bottom*]. **Image credit**: David Rutan

Fred Rose [SSAI] presented changes to the EBAF Surface product including the use of Atmospheric Infrared Sounder (AIRS) data to adjust the Upper Tropospheric Relative Humidity and decrease in cloud fraction to be more consistent with the previous product (Edition 2.8).

Paul Stackhouse [LaRC] highlighted how net radiation flux changes, caused by the current El Niño, were calculated using the CERES Fast Longwave and Shortwave Radiative Fluxes (FLASHFlux) product to compare conditions in 2013 to those in 2015. The net TOA flux showed little change over the western Pacific, but there is a strong positive net difference over the eastern Pacific and off the western coast of the U.S. The variation in SW net surface flux is the dominant cause of the differences in total surface net flux observed over the Pacific Ocean.

Jonathan Gleason [LaRC] reported that all Edition 4 software has been delivered to the Atmospheric Science Data Center (ASDC) at LaRC, and that only forward production will be done by the end of the year. The Edition 1 data products for Suomi NPP have been produced through December 2015.

John Kusterer [LaRC] highlighted the recently developed capability to search CERES data from the Earthdata Website (*http://earthdata.nasa.gov*) and also reported that Digital Object Identifiers (DOIs) have now been assigned to all CERES data products.

Sarah McCrea [SSAI] discussed how educational support within NASA is moving from a mission requirement[6] to Cooperative Agreements Notice (CAN) for thematic

[5] Argo is an international project that seeks to measure the "pulse" of the oceans. It employs 3000 floating buoys that collect and distribute temperature and salinity observations. Visit *http://www.argo.net* to learn more.

[6] Historically, 1% of a mission's budget was allocated to education and public outreach efforts.

education content. This directly impacts three educational activities in which CERES participates: the Global Learning and Observations to Benefit the Environment (GLOBE) Program, My NASA Data (*http://mynasadata.larc.nasa.gov*), and Students' Cloud Observations On-Line (S'COOL[7]). These programs are now funded through the CAN. The Earth Right Now program is the agency's communication priority that best aligns with CERES.

Invited Science Presentations

During the morning of the second day, two invited presenters discussed climate model simulations and comparisons thereof with observations.

Kevin Grise [University of Virginia] described the Earth's cloudiest location—the Southern Ocean—and its potential impact on climate change through movement of the polar jet stream. He stated that the stratospheric ozone hole over Antarctica causes a poleward shift of the mid-latitude tropospheric jet every summer. High clouds over the Southern Ocean follow the jet poleward and lower cloud frequency occurred on the equatorial side. Using the Coupled Model Intercomparison Project Phase 5 (CMIP5) models to study the jet shift reveals two distinct responses. In one case, the clouds move with the jet, whereas in the other case, there is no consistent movement of the clouds—a response that is more consistent with observations.

John Fasullo [National Center for Atmospheric Research (NCAR)] showed how the integrated CERES net TOA flux record allowed detection of spurious seasonal drops in the Ocean Heat Content (OHC), using Argo float data. He went on to note that data from the Gravity Recovery and Climate Experiment (GRACE) satellites provide a method to measure terrestrial gravity variations due to local mass changes. The combination of Ocean Mass (OM) and OHC are in turn related to Global Mean Sea Level (GMSL). In 2010 La Niña conditions increased terrestrial precipitation resulting in a GMSL drop. Australia accounted for a larger and longer contribution to land mass increase needed to balance the OM loss—more than would be expected from its size. Further investigation identified that a lack of ocean runoff caused the water to be stored longer in the Australian interior.

The second part of Fasullo's presentation addressed the lower-than-expected increase in GMSL as compared to results from the temperature record. Results from NCAR Large Ensemble models imply that the 1991 eruption of Mount Pinatubo significantly lowered the OHC and GMSL, followed by a sharp increase just as the altimetry record started. A reconstructed flux record using Earth Radiation Budget Experiment (ERBE) and CERES data showed the same trends, providing additional confidence in this explanation.

Contributed Science Presentations

A variety of topics were covered during the many contributed science presentations, which took place on the second and third days of the meeting. These included:

- Status updates to ancillary inputs to CERES processing;
- description of cloud validation efforts—where CERES cloud properties are compared with surface observations or other satellite products;
- assessing the accuracy of other satellite-based measurements of Earth's radiation budget;
- discussion of efforts to improve algorithms for future CERES products; and
- investigation of regional energy-related processes and how climate models and CERES data provide insight into the underlying physics and future impact on climate.

Because several presentations covered inputs that are used to create commonly used CERES products, they are described in more detail below. Refer to the URL in the *Introduction* on page 18 for specific details on these and all other presentations.

Steve Pawson [NASA's Goddard Space Flight Center (GSFC)] provided an update on the Global Modeling and Assimilation Office's Modern Era Retrospective Analysis for Research and Applications 2 (MERRA2), comparing it to the original MERRA. The new product now includes a coupled aerosol analysis, a more realistic middle atmosphere, and better representation of the polar climate. However, the upper-tropospheric moisture remains high, the two-meter temperature does not show the expected increasing trend seen in surface temperature observations, and some components of the radiation balance are not as good as the previous version.

Xiaoxiong Xiong [GSFC] discussed the calibration protocols used for MODIS on Terra and Aqua, and VIIRS on Suomi NPP. Having stable calibration between these two instruments results in consistent CERES cloud properties and prevents introducing unnatural trends into the TOA flux time series.

Robert Levy [GSFC] talked about adapting the MODIS aerosol dark model so it can be used with VIIRS radiance measurements. The effort to determine a consistent calibration between MODIS and VIIRS continues, and it is not unlike the previous successful effort to calibrate the MODIS instruments on Aqua and Terra. As was the case with cloud properties above, differences in aerosol characteristics impact the atmospheric flux profile.

[7] S'COOL is now part of the GLOBE Program and its observation protocol is being incorporated into the GLOBE rubric. For more information on S'COOL, visit *http://scool.larc.nasa.gov*; for more information about GLOBE, visit *http://www.globe.gov*.

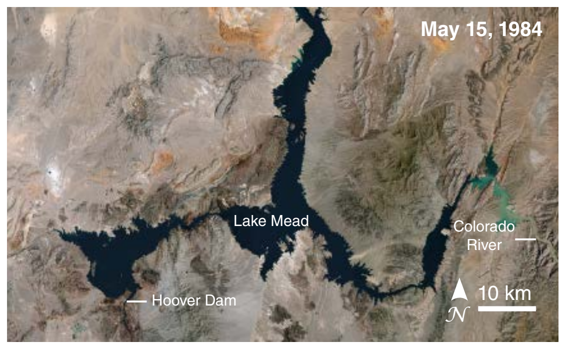
David Fillmore [Tech-X Corporation] showed that the aerosol optical depths from MODIS and VIIRS are consistent in the Model for Atmospheric Transport and Chemistry (MATCH). A comparison between MATCH and the aerosol in MERRA 2 showed significant difference over Asia. This will be one of the considerations in choosing the aerosol product to use in future CERES processing.

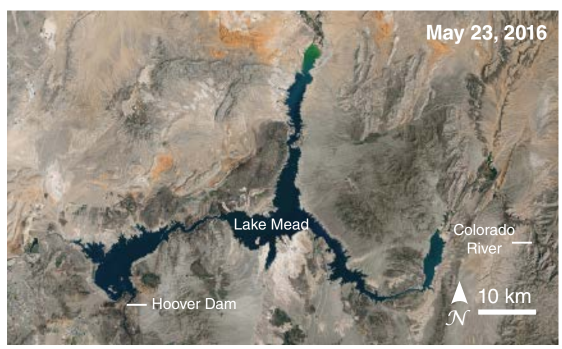
Summary

Overall, the meeting was very productive. The discussions of the validation of the Edition 4 data products that are well underway (comparing them to previous Editions and other observations) and the start of comparisons with Suomi NPP products were particularly beneficial to the team. Many of the presentations covered application of CERES data to understand or validate the changes seen in climate model runs. The climate models still need to improve diurnal and local-scale phenomena, especially convection and cloud placement. The next CERES Science Team Meeting will be held jointly with the Geostationary Earth Radiation Budget (GERB) and Scanner for Radiation Budget (ScaRaB) science team meetings, to be held October 18-21, 2016, at the European Centre for Medium-Range Weather Forecasts, (ECMWF), Shinfield Park, Reading, U.K. ■

Visualizing the Highs and Lows of Lake Mead

NASA Earth Observatory images by Joshua Stevens, using Landsat data from the U.S. Geological Survey. Text written by Mike Carlowicz.





The last time Lake Mead was this low—in 1937—water managers were still filling the reservoir and putting finishing touches on the Hoover Dam. According to data from the U.S. Bureau of Reclamation, the water level has now reached a record low for the second year in a row.

On May 25, 2016, the surface level of Lake Mead at the Hoover Dam stood at 1,074 ft (327 m) above sea level. The previous low of 1,075 ft (327 m) was set in late June 2015. The lowest water levels each year are usually reached in late June or July, after water managers have released the yearly allotment of water for farmers and cities farther down the Colorado River watershed. That means water levels are likely to continue to fall in 2016 to roughly 1,070 ft (326 m), according to the Bureau of Reclamation.

The pair of Landsat images above show the lake near its highest and lowest points over the past 32 years. The top image was acquired on May 15, 1984, by the Thematic Mapper on the Landsat 5 satellite. The lake last approached full capacity in the summer of 1983. The bottom image shows changes in the shoreline after lake water levels dropped 135 ft (41 m), by the Operational Land Imager (OLI) on Landsat 8.

Lake Mead is now roughly 37% full. At maximum capacity, the reservoir would hold 9.3 trillion gallons (35 trillion liters) of water, reaching an elevation 1,220 ft (372 m) near the dam. Most of the water in this great reservoir comes from snowmelt in the Rocky Mountain range and travels through Lake Powell, the Grand Canyon, and into Lake Mead. Farmers and some cities in Arizona, Nevada, California, and northern Mexico all rely on water from Lake Mead.

According to the Bureau of Reclamation, the lake will be refilled enough by the end of 2016 to avoid cuts in water deliveries in 2017. Lake Mead National Recreation Area continues to operate water sports, sightseeing, and hiking facilities in the area, despite ongoing drought.

The Colorado Basin has endured roughly sixteen years of drought and declining water levels in Lake Mead and Lake Powell. At the same time, populations continue to grow in the sun-drenched region.

For more information visit *http://go.nasa.gov/1U0Frwb*. ■

NASA Studies Details of a Greening Arctic

Kate Ramsayer, NASA's Goddard Space Flight Center, kate.d.ramsayer@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 northern reaches of North America are getting greener, according to a NASA study that provides the most detailed look yet at plant life across Alaska and Canada. In a changing climate, almost a third of the land cover—much of it Arctic tundra—is looking more like landscapes found in warmer ecosystems.

With 87,000 images taken from Landsat[1] satellites, converted into data that reflects the amount of healthy vegetation on the ground, the researchers found that western Alaska, Quebec, and other regions became greener between 1984 and 2012—see **Figure**. The Landsat study further supports previous work that has shown changing vegetation in Arctic and boreal North America.

"It shows the climate impact on vegetation in the high latitudes," said **Jeffrey Masek** [NASA's Goddard Space Flight Center (GSFC)—*Landsat 9 Project Scientist*], who worked on the study. Temperatures are warming faster in the Arctic than elsewhere, which has led to longer seasons for plants to grow and changes to the soils. Scientists have observed grassy tundras changing to shrublands, and shrubs growing bigger and denser—changes that could have impacts on regional water, energy, and carbon cycles.

With Landsat 5 and Landsat 7 data, Masek and his colleague **Junchang Ju** [GSFC—*Remote Sensing Scientist*] found that there was extensive greening in the tundra of western Alaska, the northern coast of Canada, and the tundra of Quebec and Labrador. While northern forests greened in Canada, they tended to decline in Alaska. Overall, the scientists found that 29.4% of the region greened up, especially in shrublands and sparsely vegetated areas, while 2.9% showed vegetation decline.

"The greening trend was unmistakable," the researchers wrote in an April 2016 paper in *Remote Sensing of Environment*[2].

Previous surveys of the vegetation had taken a big-picture view of the region using coarse-resolution satellite sensors. To get a more detailed picture of the 4.1 million mi^2 (10.6 million km^2) area, scientists used the Landsat 5 and Landsat 7 satellites.

[1] Landsat is a joint NASA/U.S. Geological Survey program that provides the longest continuous space-based record of Earth's land vegetation in existence. Landsat 9 is scheduled to launch in 2023.

[2] To read the full paper, visit *http://www.sciencedirect.com/science/article/pii/S0034425716300013*.

Figure. Using 29 years of data from Landsat satellites, researchers at NASA have found extensive greening in the vegetation across Alaska and Canada. Rapidly increasing temperatures in the Arctic have led to longer growing seasons and changing soils for the plants. Scientists have observed grassy tundras changing to scrublands, and shrubs growing bigger and denser. From 1984–2012, 30% of Canada became greener while only 3% became browner. (The darker the shade of green on the map, the more greening has occurred.) Note extensive greening has occurred in the tundra of Western Alaska, the northern coast of Canada, and the tundra of Quebec and Labrador. **Image credit:** GSFC/Cindy Starr

The view from a plane that is carrying instruments to measure the health of vegetation in the Arctic tundra of the Northwest Territories of Canada. A new study used measurements from the Landsat satellite mission to get the most detailed and complete view yet of how plant life is changing across Alaska and Canada. **Photo credit:** NASA/Peter Griffith

Landsat, like other satellite missions, can use the amount of visible and near-infrared light reflected by the green, leafy vegetation of grasses, shrubs, and trees to characterize the vegetation. Then, with computer programs that track each individual pixel of data over time, researchers can see if an area is *greening*—if more vegetation is growing, or if individual plants are getting larger and leafier. If, however, the vegetation becomes sparser, the scientists would classify that area as *browning*.

Researchers have used similar techniques to study Arctic and northern vegetation with other satellite instruments, such as the Advanced Very High Resolution Radiometer (AVHRR) which has flown on various National Oceanic and Atmospheric Administration (NOAA) satellite missions. But Landsat can see smaller differences across a landscape—it takes one measurement for each 30 x 30 m (98 x 98 ft) parcel of land, which is about the size of a baseball diamond. AVHRR collected one measurement for each 4 x 4 km (2.5 x 2.5 mi) area.

NASA researchers hike to remote locations to measure the conditions of vegetation in the Arctic tundra of Canada's Northwest Territory. The ground measurements will be used to validate satellite data to give researchers more insight into how climate change is influencing northern ecosystems. Pictured here is **Don Hodkinson** [GSFC, Carbon Cycle and Ecosystems Office—*Field Operations Manager*]. **Photo credit:** NASA/Peter Griffith

"We can see more detail with Landsat, and we can see the trend more reliably," Ju said. With finer-resolution and better calibrated data from Landsat, the researchers were able to mask out areas that burned, or are covered in water, to focus on vegetation changes. The more detailed look—now available to other researchers as well—will also let scientists see if a correlation exists between habitat characteristics and greening or browning trends.

"The resolution with Landsat is drastically improved; it lets you look at the local effects of things like topography, such as in areas where you might have small woodlands or open areas," Masek said. "You can do detailed studies of how climate impacts vary with geography."

Adding the Landsat study to previous studies using the AVHRR sensor also adds to the certainty of what's going on, Masek said. While the two tools to measure the northern vegetation did produce different results in some places, overall the trend was similar—more plants, or bigger plants, in the Arctic reaches of North America.

With the higher resolution Landsat data, the researchers also found a lot of differences within areas—e.g., one pixel would be brown, and its neighbors green, noted Ju. "It's very localized," he said. "The vegetation is responding to the microclimates. The benefit of using Landsat data is that we can reveal this spatial variation over very short distances."

With the large map complete, researchers will focus on these short distances—looking at the smaller scale to see what might control the greening patterns, whether it's local topography, nearby water sources, or particular types of habitat. They also plan to investigate forested areas, particularly in the greening Quebec.

"One of the big questions is, 'Will forest biomes migrate with warming climate?' There hasn't been much evidence of it to date," Masek said. "But we can zoom in and see if it's changing." ■

NASA Study Solves Two Mysteries About Wobbling Earth

Carol Rasmussen, NASA/Jet Propulsion Laboratory, carol.rasmussen@jpl.nasa.gov

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

Using satellite data, NASA scientists have solved two mysteries about wobbles in the planet's rotation—one new and one more than a century old. The research may help improve our knowledge of past and future climate.

Although a desktop globe always spins smoothly around the axis running through its north and south poles, a real planet wobbles. Earth's spin axis drifts slowly around the poles; the farthest away it has wobbled since observations began is 37 ft (12 m). These wobbles don't affect our daily life, but they must be taken into account to get accurate results from global positioning systems (GPS), Earth-observing satellites, and observatories on the ground.

In a paper recently published in *Science Advances*, **Surendra Adhikari** and **Erik Ivins** [both from NASA/ Jet Propulsion Laboratory (JPL)] researched how the movement of water around the world contributes to Earth's rotational wobbles. Earlier studies have pinpointed many connections between processes on Earth's surface or interior and our planet's wandering ways. For example, Earth's mantle is still readjusting to the loss of ice on North America after the last ice age, and the reduced mass beneath that continent pulls the spin axis toward Canada at the rate of a few inches each year. But some motions are still puzzling…

A Sharp Turn to the East

Around the year 2000, Earth's spin axis took an abrupt turn toward the east and is now drifting almost twice as fast as before, at a rate of almost 7 in (17 cm) a year—see **Figure 1**. "It's no longer moving toward Hudson Bay, but instead toward the British Isles," said Adhikari. "That's a massive swing." Adhikari and Ivins set out to explain this unexpected change.

Scientists have suggested that the loss of mass from Greenland and Antarctica's rapidly melting ice sheet could be causing the eastward shift of the spin axis. The JPL scientists assessed this idea using observations from the NASA/ Deutsches Zentrum für Luft- und Raumfahrt (DLR) [German Aerospace Center] Gravity Recovery and Climate Experiment (GRACE) satellites, which provide a monthly record of changes in mass around Earth. Those changes are largely caused by movements of water through everyday processes such as accumulating snowpack and groundwater depletion. They calculated how much mass was involved in water cycling between Earth's land areas and its oceans from 2003 to 2015, and the extent to which the mass losses and gains pulled and pushed on the spin axis.

Adhikari and Ivins' calculations showed that the changes in Greenland alone do not generate the gigantic amount of energy needed to pull the spin axis as far as it has shifted. In the Southern Hemisphere, ice mass

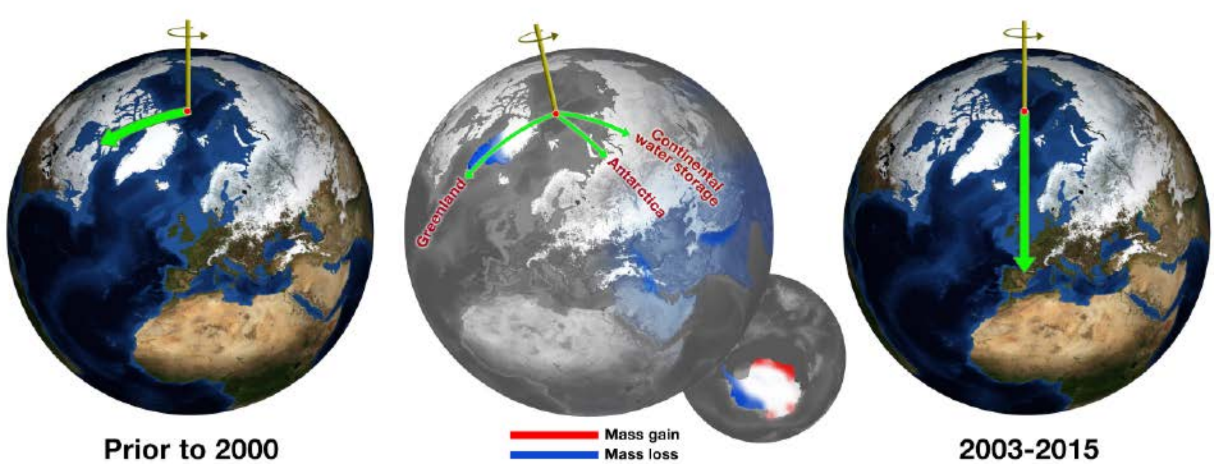


Figure 1. Earth does not always spin on an axis running through its poles. Instead, it wobbles irregularly over time. Before about 2000, Earth's spin axis (depicted by the straight arrow) was drifting toward Canada [*left*]. JPL scientists calculated the effect of changes in water mass in different regions [*center*] in pulling the direction of drift eastward since the beginning of the millennium and speeding the rate [*right*]. **Image credit**: NASA/JPL

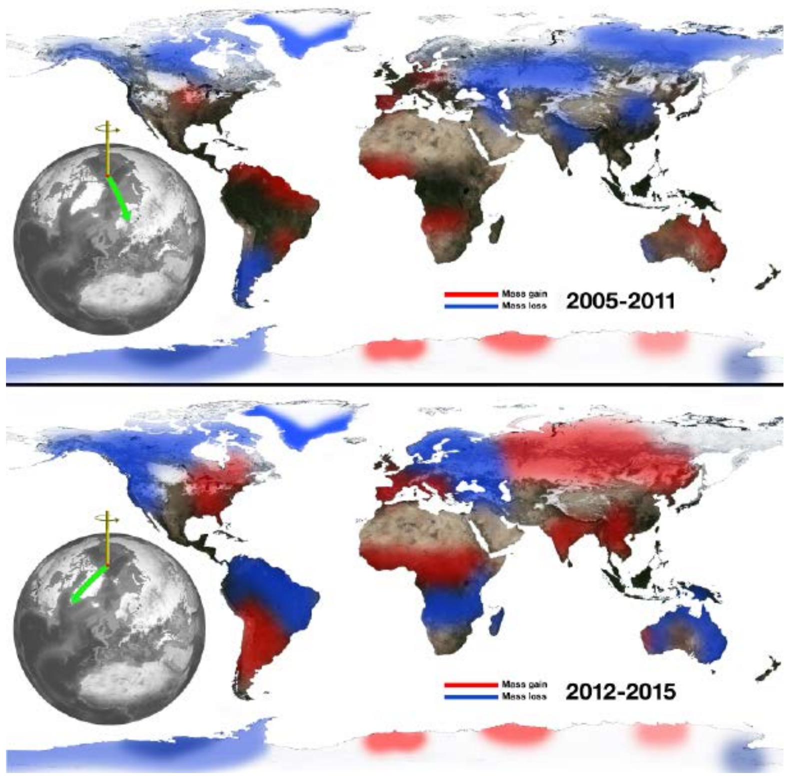


Figure 2. The relationship between continental water mass and the east-west wobble in Earth's spin axis. Losses of water from Eurasia correspond to eastward swings in the general direction of the spin axis [*top*], and Eurasian gains push the spin axis westward [*bottom*]. **Image credit**: NASA/JPL-Caltech

loss from West Antarctica is pulling, and ice mass gain in East Antarctica is pushing, Earth's spin axis in the same direction that Greenland is pulling it from the north, but the combined effect is still not enough to explain the speedup and new direction. Something east of Greenland has to be exerting an additional pull.

The researchers found the answer in Eurasia. "The bulk of the answer is a deficit of water in Eurasia: the Indian subcontinent and the Caspian Sea area," Adhikari said.

The finding was a surprise. This region has lost water mass due to depletion of aquifers and drought, but the loss is nowhere near as great as the change in the ice sheets.

So why did the smaller loss have such a strong effect? The researchers say it's because the spin axis is very sensitive to changes occurring around 45° N and S latitude. "This is well explained in the theory of rotating objects," Adhikari explained. "That's why changes in the Indian subcontinent, for example, are so important."

New Insight on an Old Wobble

In the process of solving this recent mystery, the researchers unexpectedly came up with a promising new solution to a very old problem, as well. One particular wobble in Earth's rotation has perplexed scientists since observations began in 1899. Every 6 to 14 years, the spin axis wobbles about 20 to 60 in (0.5 to 1.5 m) either east or west of its general direction of drift. "Despite tremendous theoretical and modeling efforts, no plausible mechanism has been put forward that could explain this enigmatic oscillation," Adhikari said.

Lining up a graph of the east-west wobble during the period when GRACE data were available against a graph of changes in continental water storage for the same period, the JPL scientists spotted a startling similarity between the two. Changes in polar ice appeared to have no relationship to the wobble—but changes in water on land did. Dry years in Eurasia, for example, corresponded to eastward swings, while wet years corresponded to westward swings.

When the researchers input the GRACE observations on changes in land water mass from April 2002 to March 2015 into classic physics equations that predict pole positions, they found that the results matched the observed east-west wobble very closely. "This is much more than a simple correlation," Ivins said. "We have isolated the cause."

The discovery raises the possibility that the 115-year record of east-west wobbles in Earth's spin axis may, in fact, be a remarkably good record of changes in land water storage. "That could tell us something about past climate—whether the intensity of drought or wetness has amplified over time, and in which locations," said Adhikari.

"Historical records of polar motion are both globally comprehensive in their sensitivity and extraordinarily accurate," said Ivins. "Our study shows that this legacy dataset can be used to leverage vital information about changes in continental water storage and ice sheets over time." ■

NASA Satellite Data Could Help Reduce Flights Sidelined by Volcanic Eruptions

Audrey Haar, NASA's Goddard Space Flight Center, audrey.j.haar@nasa.gov

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

A volcano erupting and spewing ash into the sky can cover nearby areas under a thick coating of ash and can also have consequences for aviation safety. Airline traffic changes due to a recent volcanic eruption can rack up unanticipated expenses to flight cancellations, lengthy diversions, and additional fuel costs from rerouting.

In the aftermath of a volcanic eruption, airlines typically consult with local weather agencies to determine flight safety, and those decisions today are largely based on manual estimates with information obtained from a worldwide network of Volcanic Ash Advisory Centers. These centers are finding timely and more accurate satellite data beneficial.

Researchers at NASA's Goddard Space Flight Center (GSFC) are using already available satellite measurements of sulfur dioxide (SO_2), a main component of magmatic volcanic emissions, along with the more recent ability to map the location and vertical profiles of volcanic aerosols—see **Figure**.

A volcanic cloud contains two kinds of aerosols: sulfuric acid (H_2SO_4), droplets converted from SO_2, and silicate volcanic ash. Satellites can detect volcanic ash by observing the scattering of ultraviolet light from the sun. For aviation, volcanic ash is potentially the most deadly because of the danger it poses to aircraft engines. While measurements of aerosol absorption in ultraviolet do not differentiate between the smoke, dust, and ash aerosols, only volcanic clouds contain significant abundances of SO_2, so satellite measurements of SO_2 are especially valuable for unambiguous identification of volcanic clouds.

Knowing both the physical location and the altitude distribution of aerosols in the volcanic cloud allow more accurate forecasts in the days, weeks, and months after an eruption. "The capability of mapping the full extent of a three-dimensional structure of a moving volcanic cloud has never been done before," said **Nickolay A. Krotkov** [GSFC—*Physical Research Scientist*].

Researchers are currently making these measurements using the Limb Profiler (LP) instrument, part of the Ozone Mapping Profiler Suite (OMPS) instrument, currently flying on the joint NASA/National Oceanic and Atmospheric Administration (NOAA) [with funding from Department of Defense] Suomi National Polar-orbiting Partnership (NPP) satellite, launched in October 2011.

OMPS is a three-part instrument: a nadir mapper that maps ozone, SO_2, and aerosols; a nadir profiler that measures the vertical distribution of ozone in the

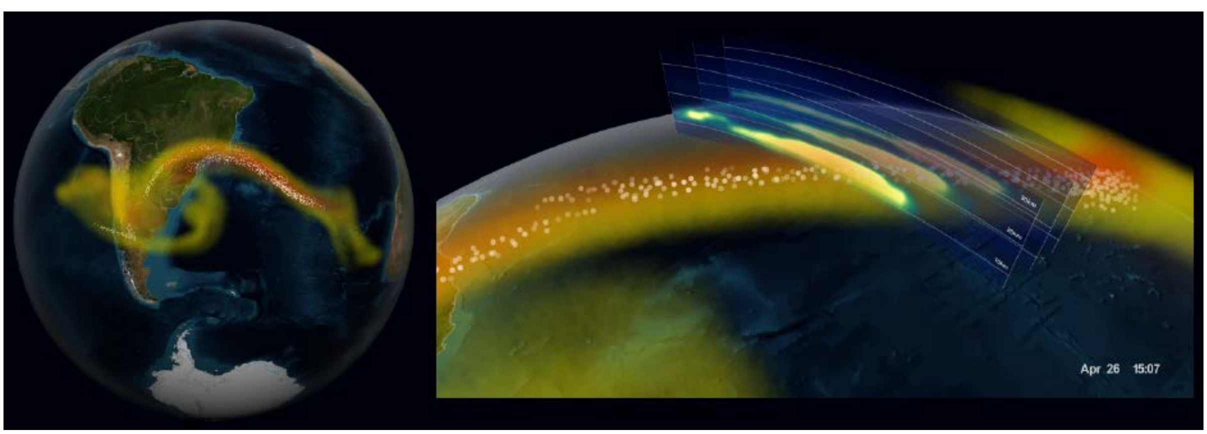


Figure. When the Calbuco volcano erupted in April 2015, it spewed a cloud of sulfur dioxide (SO_2)-laden ash more than 10 mi (16 km) into the atmosphere. NASA scientists tracked the volcanic cloud's movement over time using data from the Ozone Mapping Profiler Suite (OMPS) on the joint NASA–NOAA (with funding from DOD) Suomi National Polar-orbiting Partnership (NPP) satellite. Scientists were able to determine the location and height of the aerosol particles using data from the OMPS-Limb Profiler (LP) instrument [*right*], as well the total column amount of SO_2 present [*left*, red shades indicate the highest SO_2]. These images show results from a supercomputer simulation of ash and SO_2 spreading from the eruption. The model run combines assimilated winds with the physics and chemistry inside the volcanic cloud to simulate the full three-dimensional structure of the volcanic cloud at high temporal resolution. The structure is in turn verified with the profile measurements from OMPS-LP [*right*]. To view the full visualization, visit *http://svs.gsfc.nasa.gov/12221*.

stratosphere; and the LP, which measures aerosols in the upper troposphere, stratosphere, and mesosphere with high vertical resolution.

"With the OMPS instrument, the volcanic cloud is mapped as Suomi NPP flies directly overhead and then as it looks back, it observes three vertical slices of the cloud," said **Eric Hughes** [University of Maryland], who is working with Krotkov at GSFC.

Knowing the timing and duration of an eruption, and the altitude and amount of the volcanic emissions are critical inputs for an accurate volcanic forecast model being developed at the Goddard Modeling and Assimilation Office. The height of the plume is particularly critical for forecasting the direction of the plume. Even several kilometers of height can make a significant difference in predicting plume movement. More accurate volcanic cloud forecasts could reduce airline cancellations and rerouting costs.

While aviation is a short-term immediate application for volcanic cloud modeling, there are also long-term climate applications. "Sulfate aerosols formed after large volcanic eruptions affect the radiation balance and can linger in the stratosphere for a couple of years," said Krotkov.

There have been large volcanic eruptions in the past that have contributed to short-term cooling of Earth from the SO_2 that reaches the stratosphere—e.g., the Mount Pinatubo eruption in the Philippines in June 1991. During volcanic eruptions, SO_2 converts to sulfuric acid aerosols. Now researchers are studying the impacts of deliberately injecting SO_2 into the stratosphere to contract the effects of global warming, known as climate intervention.

"Nature gives us these volcanic perturbations and then we can see the impact on climate," Krotkov said. "These are the short- and long-term consequences of volcanic eruptions that have both aviation and climate applications." ■

Piers Sellers Receives NASA Distinguished Service Medal and William Nordberg Memorial Award for Earth Science

On June 2, 2016, **NASA Administrator Charles Bolden** presented **Piers Sellers** [NASA's Goddard Space Flight Center (GSFC)—*Deputy Director of the Science and Exploration Directorate*] the NASA Distinguished Service Medal. The Distinguished Service Medal is the agency's highest honor, reserved for those whose "distinguished service, ability, or vision has personally contributed to NASA's advancement of United States' interests." A video of the event is available at *http://science.gsfc.nasa.gov/600/images/SellersDistinguishedServiceAward720p.mp4*.

Piers Sellers receives NASA Distinguished Service Medal from **NASA Administrator Charles Bolden**. **Photo credit:** NASA

Sellers has also been selected as the recipient for the William Nordberg Memorial Award for Earth Science. The award is presented in memory of William Nordberg's many pioneering accomplishments in the use of space technology to understand the Earth system. Each year the award is presented to a civil service employee at GSFC who best exhibits the qualities of broad scientific perspective, enthusiastic programmatic and technical leadership on national and international levels, wide recognition by peers, and substantial research accomplishments in understanding Earth system processes, characteristics that exemplified Nordberg's own career.

Please join us in congratulating Piers on these awards!

NASA Earth Science in the News

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

Why Antarctic Ice Extent Has Increased Over The Past 40 Years Despite Global Warming, NASA Reveals, July 6, *scienceworldreport.com*. A NASA study reveals that even with temperature rise in the Southern Ocean, Antarctic sea-ice extent has been increasing since the 1970s. The NASA experts are now investigating why the sea ice around the Antarctic continent has been increasing despite global warming. This is in contrast to the drastic loss of sea ice that has occurred in the Arctic Ocean. **Son Nghiem** [NASA/Jet Propulsion Laboratory] and his team from NASA and the National Oceanic and Atmospheric Administration (NOAA) used satellite radar, land-form and bathymetry data, and sea-surface temperature to study the physical processes and properties affecting Antarctic sea ice extent. Nghiem explained that their study delivers strong evidence that the behavior of Antarctic sea ice is totally consistent with the geophysical characteristics found in the southern polar region, which are very different from those in the Arctic. The researchers discovered that Antarctic sea ice cover is dominated by first-year, new seasonal sea ice. Nghiem and his team analyzed radar data from 1999 to 2009, obtained by NASA's Quick Scatterometer (QuikScat) satellite, to monitor the paths of Antarctic sea ice movements and map its various types. Their analyses showed that as the sea ice forms and builds up early in the sea ice growth season, it gets shoved offshore and northward by winds. This creates a protective shield of older, thicker ice that circulates around the continent.

The Amazon Is at Extreme Risk of Wildfires, July 5, *cnn.com*. Broad patches of the Amazon rainforest basin are at extremely high risk for wildfires this year, according to a new report from NASA and the University of California, Irvine. Initial conditions going into the area's dry season suggest this could be the toughest year for wildfires since 2002, according to a fire forecast released last week. This is worse than the exceptionally dry years of 2005, 2007, and 2010, according to **Yang Chen** [University of California, Irvine], who worked on the research. Among the areas most at risk are deforested areas, including farms and human settlements. The southern Amazon region has suffered an unusually large deficit of rainfall over the last three years, worsened by a strong El Niño from 2015 to 2016. Chen added that these are only the initial conditions going into the season, and that there may be other factors that lower or raise the risk of wildfires.

Montreal Protocol Pays Off: Antarctic Ozone Layer Shows Signs Of Healing, July 2, *techtimes.com*. The ozone layer, a region of the Earth's stratosphere that absorbs most of the ultraviolet (UV) radiation from the sun, serves as our planet's natural sunscreen protecting humans, plants, and animals from DNA-damaging solar radiation. In the 1980s scientists noticed a dramatic thinning of stratospheric ozone over Antarctica, the so-called "ozone hole." The phenomenon was primarily attributed to gases known as chlorofluorocarbons (CFCs), which were then popularly used in air conditioning units, refrigerators, and chemical sprays. To protect the ozone layer, nations agreed in 1987 to phase out the ozone-depleting substances through an international treaty known as the Montreal Protocol. Those hopes have been realized, as scientists celebrate the success of this agreement by way of a new study that has revealed that the Antarctic ozone layer now shows signs of healing. In a study published in the journal *Science* on June 30, **Susan Solomon** [Massachusetts Institute of Technology] and colleagues found evidence that the areal extent of the Antarctic ozone hole has shrunk by more than 4 million km^2 (1.5 million mi^2) and is no longer as "deep", i.e., ozone concentration is increasing. The findings of the study by Solomon and colleagues support the results of a 2009 analysis performed by NASA scientists. **Paul Newman** [NASA's Goddard Space Flight Center] and colleagues simulated "what might have been" if CFCs and similar chemicals were not banned through the Montreal Protocol. They found that if nothing had been done to stop damage to the ozone layer, 17% of all ozone would be depleted globally by the year 2020.

Google Earth Just Got Way Better, June 28, *cnn.com*. *Google Earth* just got a huge upgrade. The mapping service is now using images from a newer NASA satellite to produce crisper and clearer pictures than its previous offerings. Google says the higher-quality images are possible because of upgraded sensors on Landsat 8, launched in 2013, and new processing techniques. Landsat 8 can take pictures with greater detail and more frequently, Google said in a blog post on June 27, 2016. That means Google has access to twice as many images that are much more recent. Google pieces together the best images to prepare its maps. The extra details mean that users can see more subtleties in landscapes and become more aware of changes over time.

***Thanks to Climate Change, the Arctic is Turning Green**, June 27, *washingtonpost.com*. In early June 2016, NASA scientists provided a visualization of a startling climate-change trend—the Earth is getting greener, especially in its rapidly warming northern regions. This is likely because more carbon dioxide in the atmosphere, along with warmer temperatures have led to longer growing seasons. Research in *Nature Climate Change* not only reinforces the reality of this trend—which is already provoking debate about the overall climate consequences of a warming Arctic—but statistically attributes it to human causes, which largely means greenhouse gas emissions (albeit with a mix of other elements as well).

California Snowpack Won't Recover from Drought for Years, June 21, *cnbc.com*. The hyped and hoped-for strong El Niño barely made a dent in California's snowpack deficit, and that is not good news for the state's water supply. Even if the state receives above-average amounts of rain and snow for the next few years, the snowpack will not be replenished to its pre-drought levels until 2019, according to a new study. That could mean that the state has more years of tight water ahead of it—as rain and snow from the Sierra Nevada mountains makes up about 60% of the developed water supply in the state, and this has not been much affected by the recent El Niño. The team used measurements taken over the last 31 years by Landsat satellites. The satellite images provide a more complete picture of the snowpack than frequently used ground sensors, which are typically stationed at more-accessible middle elevations. The team built a dataset based on the satellite-based information and ran models of thousands of possible future scenarios of near-term climate and precipitation levels. They concluded that it will likely take about four years for the snowpack deficit to be overcome. The results were published in the American Geophysical Union's journal *Geophysical Research Letters*.

Carbon Dioxide Hits Record Highs Over South Pole in Hottest May on Record, June 20, *gizmag.com*. It's not something to be wished for, but Earth is on a bit of a hot streak when it comes to global temperatures. Newly released data on Earth's climate has revealed that 2016 saw the hottest May on record, marking the thirteenth successive time a monthly global temperature record has been broken as the atmospheric concentration of carbon dioxide, the main reason for this warming trend, hits new levels over the South Pole. The data released by NASA and the National Oceanic and Atmospheric Administration shows average global temperatures for May over land and ocean surfaces were 0.87 °C (1.57 °F) higher than the twentieth-century average of 14.8 °C (58.6 °F). This surpassed the previous record set in May 2015 by 0.02 °C (0.04 °F).

NASA Steps Up to Track the Shrinking of Earth's Coral Reefs, June 3, *wired.com*. If transposed to North America's west coast, the Great Barrier Reef, located off the Queensland coast of Australia, would stretch from Baja, California, to British Columbia. "How do you study that big of an area by doing hour-long hikes?" asked marine biologist **Eric Hochberg** [Bermuda Institute of Ocean Sciences]. Yet for a long time, scientists studying coral have essentially had to do just that. Since the 1950s, says Hochberg, the state-of-the-art in "hiking" gear has been a mask and a scuba tank. Scientists studying coral reefs do so an hour at a time, limited by the air in their tanks. Hochberg is principal investigator of a NASA-backed experiment called the COral Reef Airborne Laboratory (CORAL), which will use a state-of-the-art spectrometer onboard a Gulfstream-IV aircraft to map reefs in four locations: Hawaii, Palau, the Mariana Islands, and parts of the Great Barrier Reef. (Even from the air, that thing is too big for one bite.) These maps will provide a baseline comparison for future surveys. Climate change and recent widespread coral bleaching events make such a project particularly urgent.

*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**.* ■

NASA Science Mission Directorate – Science Education and Public Outreach Update

Call for Submissions—NASA Announcement for High-Impact/Broad-Implementation STEM Education Partnerships

The NASA Headquarters Office of Education, in cooperation with the agency's four mission directorates, nine center education offices, and the Jet Propulsion Laboratory education office, announces this competition to improve science, technology, engineering, and mathematics (STEM) education. Responses must be submitted electronically via the NASA data system NSPIRES (*http://nspires.nasaprs.com*).

NASA Education seeks to partner with eligible domestic or international organizations on a no-exchange-of-funds basis to reach wider and more diverse audiences and to achieve mutually beneficial objectives. The announcement places a priority on collaborations involving the following: digital learning, engaging underrepresented groups in STEM activities, NASA-themed STEM challenges, and youth-serving organizations. NASA also is receptive to other creative ideas, e.g., investigations or application of science, technology, engineering, arts, mathematics, and design (STEAMD), or activities culturally relevant to or focused on populations underrepresented in STEM careers, such as women, ethnic minorities, and persons with disabilities.

Submission deadline: December 31, 2017

For more information about this opportunity, visit NSPIRES at *http://go.nasa.gov/1RZwWCi*.

Call for Proposals—Citizen Science for Earth Systems Program

NASA is seeking proposals for a new program as part of the NASA Research Announcement *Research Opportunities in Space and Earth Sciences (ROSES) 2016*. The Citizen Science for Earth Systems Program's primary goal is to develop and implement capabilities to use contributions from the public to advance understanding of Earth as a system. The program will complement NASA's observations of Earth from space, air, land, and water by engaging the public in relevant NASA missions. The program will advance scientific research about Earth by directly supporting citizen science activities, as well as by developing technology to further citizen science research.

Through this solicitation, two types of proposals are sought: citizen science research and low-cost sensor deployment to collect well-calibrated citizen science data.

Submission deadline: July 21, 2016

For more information, visit *http://go.nasa.gov/1SUOO63*.

Searchable Portals for Federally Sponsored Opportunities for STEM Undergraduate and Graduate Students

Are you an undergraduate or graduate student seeking opportunities in STEM? The U.S. Department of Energy's Office of Science—in collaboration with the participating agencies in the National Science and Technology Council's Committee on STEM Education (CoSTEM) and the *Science.gov* Alliance—has launched a search portal for both students and universities to discover federally sponsored STEM education training and funding opportunities.

Student users can search the site for opportunities for which they can apply directly, such as research internships and fellowships. Similarly, universities can search the site for federal funding opportunities to establish innovative training programs for undergraduate or graduate students.

For programs and opportunities for undergraduate students, visit *http://stemundergrads.science.gov*.

For graduate student programs and opportunities, visit *http://stemgradstudents.science.gov*.

National Science Foundation's Historically Black Colleges and Universities—Undergraduate Program

The National Science Foundation is seeking proposals for the Historically Black Colleges and Universities—Undergraduate Program (HBCU-UP). HBCU-UP is committed to enhancing the quality of undergraduate STEM education and research at HBCUs as a means to broaden participation in the nation's STEM workforce. HBCU-UP works to realize this goal by providing awards to develop, implement, and study innovative models and approaches for making dramatic improvements in the preparation and success of HBCU undergraduate students. In so doing, students may then participate successfully in graduate programs and/or careers in STEM disciplines.

HBCU-UP provides support for a variety of opportunities with a variety of proposal deadlines. If interested, visit *http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5481*. ■

EOS Science Calendar

August 30–September 1, 2016
Aura Science Team Meeting, Rotterdam, The Netherlands.
http://aura.gsfc.nasa.gov

September 13–16, 2016
Sounder Science Team Meeting, Greenbelt, MD.
http://airs.jpl.nasa.gov

October 5–7, 2016
GRACE Science Team Meeting, Potsdam, Germany.
http://www.csr.utexas.edu/grace/GSTM

October 18–21, 2016
CERES Science Team Meeting, Reading, U.K.
http://ceres.larc.nasa.gov

October 31–November 4, 2016
Ocean Surface Topography Science Team Meeting, La Rochelle, France.

Global Change Calendar

September 1–10, 2016
IUCN World Conservation Congress, Honolulu, HI.
http://www.iucnworldconservationcongress.org

September 15–16, 2016
Our Ocean Conference, Washington, DC.
http://www.state.gov/e/oes/ocns/opa/ourocean

September 25–28, 2016
Geological Society of America Annual Meeting, Denver, CO.
http://www.geosociety.org/meetings

October 18–21, 2016
Earth Radiation Budget Workshop, Reading, U.K. [Convened by GERB, ScaRaB Megha-Tropiques, and CERES STMs]
http://www.ecmwf.int/en/learning/workshops-and-seminars/earth-radiation-budget-workshop

November 7–18, 2016
22nd Session of the Conference of the Parties (COP 22), Marrakesh, Morocco.
http://climate-l.iisd.org/events/unfccc-cop-22

December 12–16, 2016
American Geophysical Union Fall Meeting, San Francisco, CA.
http://fallmeeting.agu.org/2016

April 18–21, 2017
A-Train Symposium, Pasadena, CA.
https://espo.nasa.gov/a-train_2017/content/A-Train_2017

Code 610
National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, MD 20771

PRSRT STD
Postage and Fees Paid
National Aeronautics and Space Administration
Permit 396

Official Business
Penalty for Private Use: $300

(affix mailing label here)

eos.nasa.gov

The Earth Observer

The Earth Observer is published by the EOS Project Science Office, Code 610, NASA's Goddard Space Flight Center, Greenbelt, Maryland 20771, telephone (301) 614-5561, FAX (301) 614-6530, and is available in color at *eospso.nasa.gov/earth-observer-archive*. Black and white hard copies can be obtained by writing to the above address.

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.

To subscribe to *The Earth Observer*, or to change your mailing address, please call Cindy Trapp at (301) 614-5559, or send a message to *Cynthia.trapp-1@nasa.gov*, or write to the address above. If you would like to stop receiving a hard copy and be notified via email when future issues of *The Earth Observer* are available for download as a PDF, please send an email with the subject **"Go Green"** to *Cynthia.trapp-1@nasa.gov*. Your name and email address will then be added to an electronic distribution list and you will receive a bi-monthly email indicating that the next issue is available for download. If you change your mind, the email notification will provide an option for returning to the printed version.

The Earth Observer Staff

Executive Editor:	Alan B. Ward (alan.b.ward@nasa.gov)
Assistant/Technical Editors:	Heather H. Hanson (heather.h.hanson@nasa.gov) Mitchell K. Hobish (mkh@sciential.com)
Technical Editor:	Ernest Hilsenrath (hilsenrath@umbc.edu)
Design, Production:	Deborah McLean (deborah.f.mclean@nasa.gov)

Scan code to access *The Earth Observer* archive online

Printed on Recycled Paper

NP-2016-1-380-GSFC