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Editor's Corner

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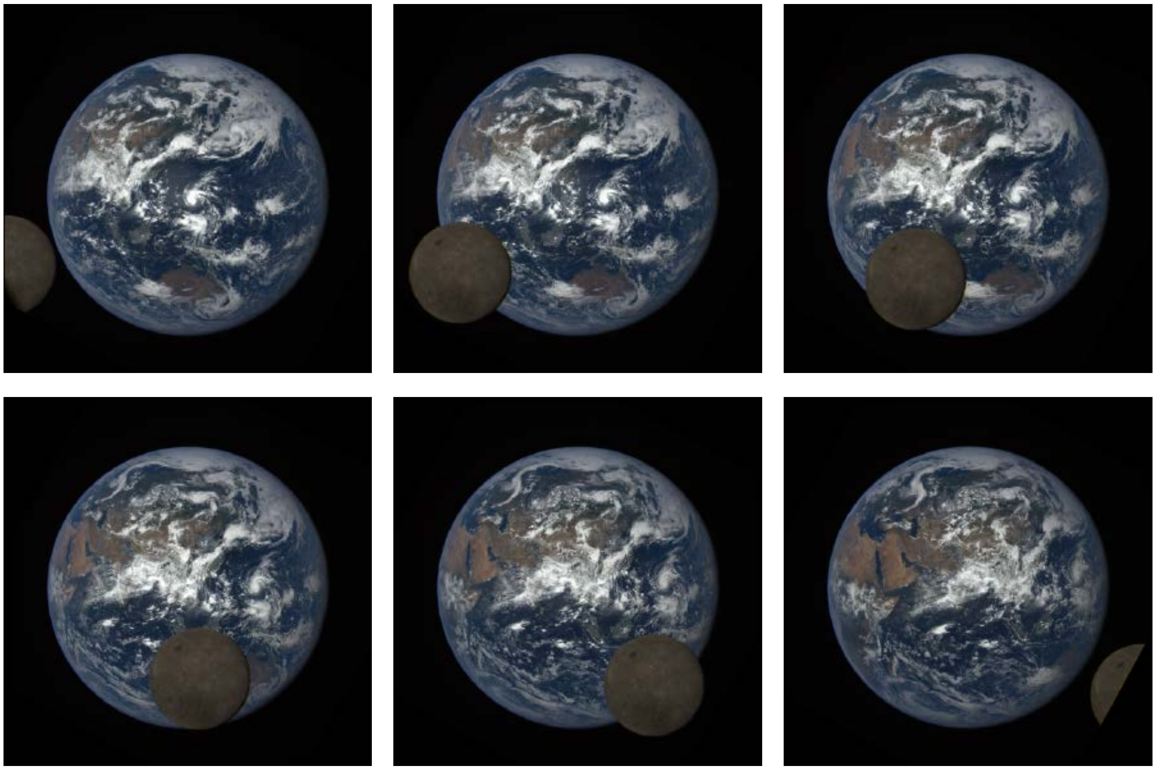
In light of recent news headlines, it's vitally important to remember the endeavors that bring us together. Science is fundamentally a collaborative and unifying effort, connecting individuals and nations. Since the agency began almost 60 years ago, NASA—working along with its domestic and international 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/*.

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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

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[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]. ■

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

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[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].

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

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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.

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 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.

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

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[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

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[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**.

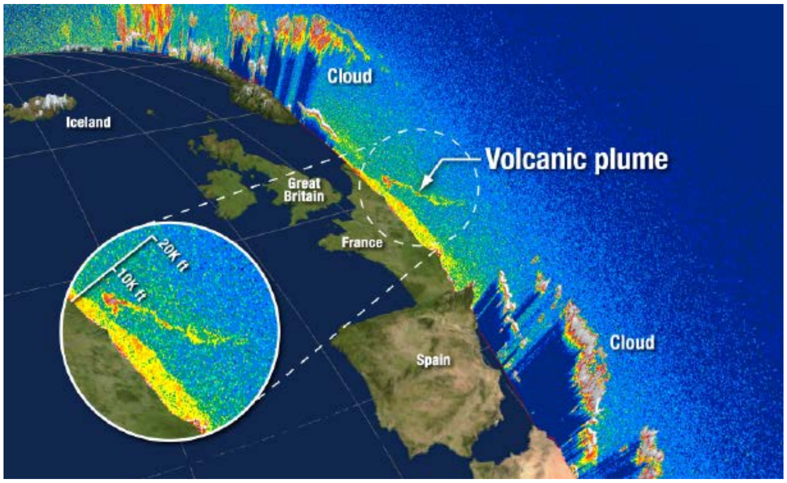

Figure 2. These data were obtained on April 17, 2010, as CALIPSO passed over continental Europe. The Eyjafjallajökull volcano had erupted earlier that spring and the CALIOP lidar detected the plume. The inset focuses on the ash plume. **Image credit**: NASA's Science Visualization Studio

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

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[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. 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.

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

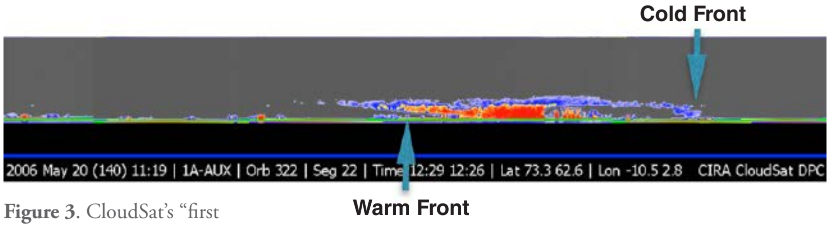

Figure 3. CloudSat's "first light" image on May 20, 2006, revealed a cross-section of the atmosphere across a low-pressure system in the North Atlantic Ocean. The bubble-like structure on the right is a representation of the thin clouds at the leading edge of a cold front, and the wedge shaped intrusion 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

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[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.

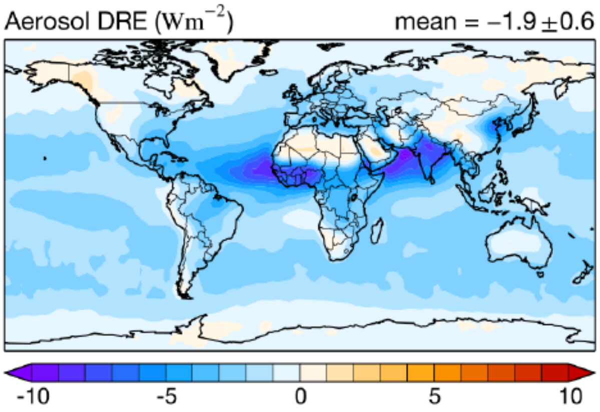

Figure 4. Map of the annual mean, all-sky (including clouds) direct radiative effect (DRE) of aerosols at the top of the atmosphere (TOA), as observed by CloudSat and CALIPSO over a 10-year period. Negative numbers indicate that aerosols are reducing the amount of solar radiation penetrating the atmosphere,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

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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.

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[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.

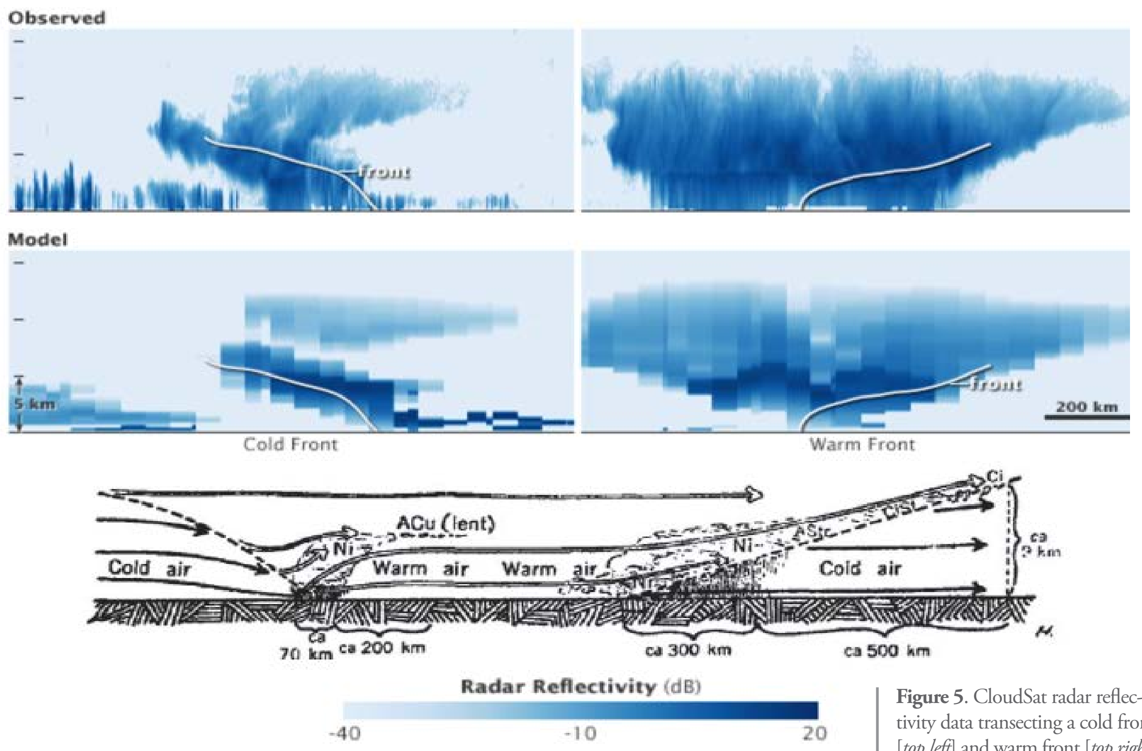

Figure 5. CloudSat radar reflectivity data transecting a cold front [*top left*] and warm front [*top right*] on November 22, 2006. These are compared with European Centre for Medium-range Weather Forecasts (ECMWF) model results for the same systems [*middle left* and *middle right*, respectively]. For 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.

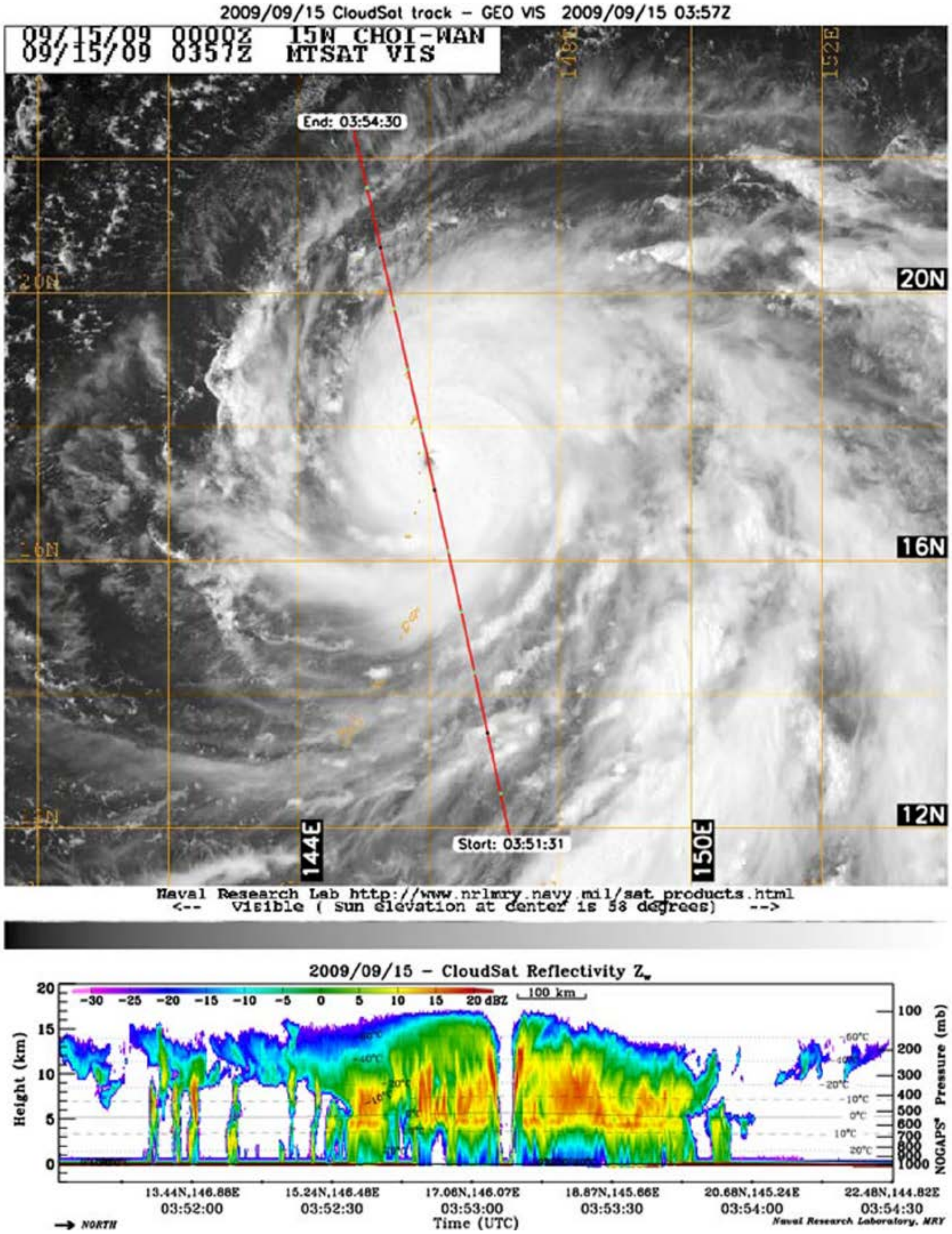

Figure 6. Imagery from an A-Train overpass of Typhoon Choi-Wan on September 15, 2009. In the Moderate Resolution Infrared Spectroradiometer (MODIS) image of the typhoon [*top*] the brighter whites indicate higher clouds, and the red line indicates CloudSat's footprint. Notice that while the image is 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

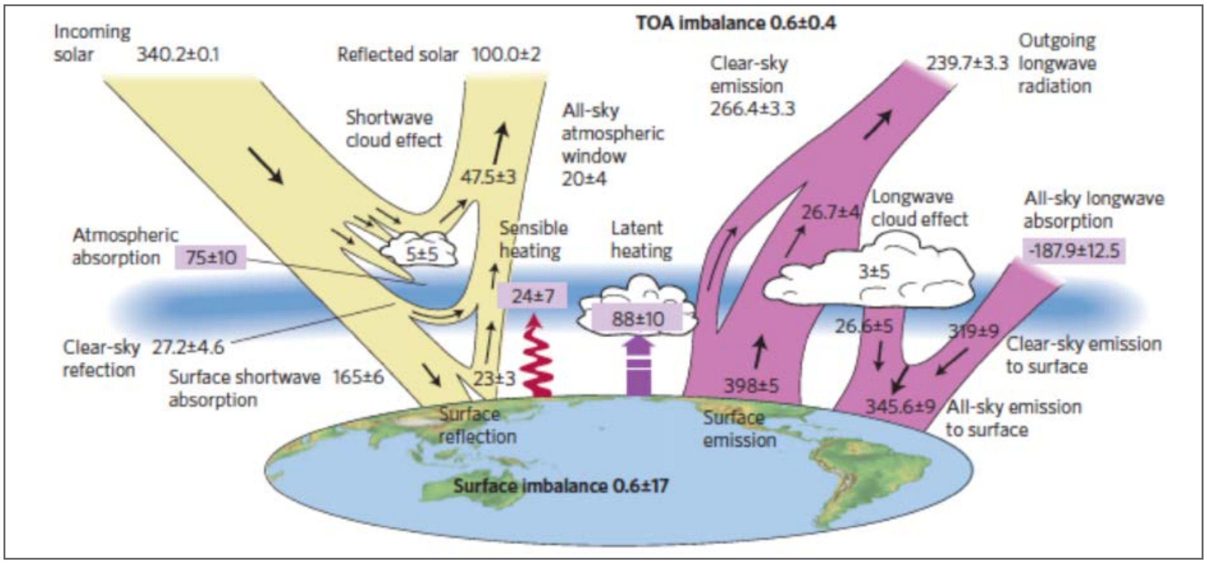

Figure 7. The global annual mean energy budget of Earth for the approximate period 2000-2010—updated to include information from CloudSat and CALIPSO. All fluxes are measured in W/m^2. Solar fluxes are depicted in yellow [*left*], while infrared fluxes are depicted in pink [*right*]. The four flux quantities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

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. ■

*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.*

2016 AIRS Science Team Meeting Summary

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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

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[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*.