Aqua 10 Years After Launch

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Introduction

A little over ten years ago, in the early morning hours of May 4, 2002, crowds of spectators stood anxiously watching as the Delta II rocket carrying NASA's Aqua spacecraft lifted off from its launch pad at Vandenberg Air Force Base in California at 2:55 AM—see photograph. The rocket quickly went through a low-lying cloud cover, after which the main portion of the rocket fell to the waters below and the rocket's second stage proceeded to carry Aqua south across the Pacific, onward over Antarctica, and north to Africa, where the spacecraft separated from the rocket 59.5 minutes after launch. Then, 12.5 minutes later, the solar array unfurled over Europe, and Aqua was on its way in the first of what by now have become over 50,000 successful orbits of the Earth.

Following a sequence of six ascent burns, all planned long before, Aqua reached its operational orbit on June 17, 2002. That near-polar, sun-synchronous orbit has Aqua at an altitude of 705 km (~438 mi), orbiting the Earth once every 98.8 minutes and crossing the equator going north at 1:30 PM and south at 1:30 AM, local time. Before reaching that operational orbit, four of Aqua's six Earth-observing instruments had been turned on and tested out, and by June 25, 2002, the remaining two instruments had also been turned on and tested out. Ten years later, these Aqua instruments have provided the world with a wealth of information about the Earth system and the interactions within it. Four of the Earth-observing instruments and the spacecraft continue to work well, four years beyond the planned six-year prime mission. This article provides a brief summary of the Aqua mission and what it has accomplished so far.

The Delta II rocket carrying the Aqua spacecraft lifts off from its launch pad at Vandenberg Air Force Base in California at 2:55 AM, May 4, 2002. **Image credit**: **Bill Ingalls**, courtesy of NASA.

The Aqua Earth-Observing Instruments

Aqua's six Earth-observing instruments are the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Sounding Unit (AMSU), the Humidity Sounder for Brazil (HSB), the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Clouds and the Earth's Radiant Energy System (CERES). The Brazilian Institute for Space Research provided HSB; the Japan Aerospace Exploration Agency (JAXA) provided AMSR-E; and NASA provided the remaining instruments and the spacecraft.

The three sounders on Aqua—AIRS, AMSU, and HSB—work together as a unified sounding system, and as a result there is one science team covering the three instruments. With AIRS the centerpiece of the threesome, the science team is generally referred to as the AIRS Science Team, although sometimes as the AIRS/AMSU/HSB Science Team. AIRS was a major technological advance developed for the Aqua mission. It has 2382 channels, 2378 of them measuring in infrared (IR) wavelengths and the remaining four measuring in visible wavelengths. In contrast, the 15-channel AMSU and four-channel HSB both measure in microwave wavelengths. While AIRS is unique to Aqua, AMSU and HSB are near-copies of instruments that have flown on various satellites of the National Oceanic and Atmospheric Administration (NOAA).

HSB collected valuable information about atmospheric humidity and cloud liquid water for the first nine months of the Aqua mission but ceased operations in February 2003. AIRS and AMSU continue to transmit high-quality data, and the AIRS Science Team, centered at the NASA/Jet Propulsion Laboratory (JPL), is using these data to determine vertical profiles of atmospheric temperature, moisture, and key trace gases in the atmosphere, as well as cloud and surface parameters.

"During the last ten years no other satellite instrument has been more essential to improve global weather forecasts than AIRS."
*—**Joao Teixeira** [JPL—AIRS Science Team Leader]*

The CERES instrument (of which Aqua has two identical copies) has only three channels, but these three channels are geared specifically at the highly important issue of the Earth's overall radiation budget. The three channels measure reflected shortwave radiation at the top of the atmosphere, total outgoing radiation at the top of the atmosphere, and the outgoing radiation in the 8-12 μm atmospheric window. The CERES Science Team, centered at NASA's Langley Research Center (LaRC), can easily obtain outgoing longwave radiation by subtracting the reflected shortwave radiation from the total outgoing radiation and is using the CERES data in conjunction with MODIS and other data for extensive studies on clouds and the Earth's radiation budget.

MODIS is a multipurpose, 36-band radiometer measuring numerous atmosphere, land, and ocean variables at visible and infrared wavelengths. Among the many variables measured are cloud cover, aerosols, water vapor, ocean color, sea surface temperature, surface reflectance, vegetation indices, net primary productivity, leaf-area index, snow cover, and sea ice. MODIS has the finest spatial resolution of any of the Aqua instruments, providing data at resolutions between 250 m (~820 ft) and 1 km (~3280 ft). The MODIS Science Team is centered at NASA's Goddard Space Flight Center and at the University of Colorado.

"CERES Aqua is providing unprecedented detail on how reflected solar and emitted thermal radiation from Earth vary over a range of time-space scales. Furthermore, synergistic use of CERES and other Aqua and A-Train instruments such as AIRS, MODIS, and the instruments on CALIPSO and Cloudsat has led to a significantly revised estimate of the energy budget at the surface and a new understanding of how clouds and aerosols influence the vertical distribution of radiative heating within the atmosphere."
*—**Norman Loeb** [LaRC—CERES Science Team Leader]*

The CERES and MODIS instruments launched on Aqua were preceded by CERES and MODIS instruments launched earlier on other satellites. The first CERES was launched on the Tropical Rainfall Measuring Mission (TRMM) in November 1997 and is no longer operational. The next two CERES and the first MODIS were all launched on the Terra satellite in December 1999 and still continue to operate. Having MODIS and CERES on both Aqua and Terra has been of substantial added value, as it has allowed more complete data coverage, including additional information on the daily cycle of variables measured by those two instruments, as Terra crosses the equator at approximately 10:30 AM and 10:30 PM, complementing the 1:30 AM and 1:30 PM equatorial crossings of Aqua. The MODIS Science Team covers both MODIS instruments (on Aqua and Terra), and the CERES Science Team covers all CERES instruments, which by now include not only those on TRMM, Terra, and Aqua, but also one launched on the Suomi National Polar-orbiting Partnership (NPP) in October 2011 and one planned for eventual launch on the first Joint Polar Satellite System (JPSS).

Like MODIS, AMSR-E is a multipurpose instrument. However, AMSR-E's measurements are done at microwave wavelengths. AMSR-E has 12 channels and measures such atmospheric and surface variables as rainfall rates, surface wind speeds over the oceans, vertically integrated water vapor and cloud water amounts, sea surface temperatures, sea ice coverage, snow water content, and soil surface wetness. AMSR-E data have much coarser spatial resolution than MODIS data, but by measuring at microwave wavelengths they have the wonderful advantage of being able routinely to obtain information about surface variables under cloudy as well as cloud-free conditions and during darkness as well as daylight. The U.S. AMSR-E Science Team is centered at NASA's Marshall Space Flight Center and the University of Alabama in Huntsville (UAH); the Japanese AMSR-E Science Team is centered at JAXA and the Japan Meteorological Research Institute.

AMSR-E collected high-quality data for over nine years—well beyond its design lifetime—but experienced a major anomaly on October 4, 2011. The instrument was turned back on in early February 2012, but without rotation of the antenna, which is needed for high-quality AMSR-E data. In September 2012, initial tests were carried out to restart the rotation, although only for brief periods and at a much lower rotation rate than during the prime mission. These tests are now being analyzed, and the hope is that the instrument will be able to operate, while rotating at least slowly, for a sufficient time to obtain enough data overlapping with a recently launched AMSR2 instrument to provide intercalibration between the AMSR-E and AMSR2. AMSR2 was launched by JAXA on its Global Change Observation Mission - Water (GCOM-W) satellite, named "Shizuku," in May 2012.

"AMSR-E has allowed unprecedented monitoring of historic sea ice changes in the Arctic and Antarctic, as well as of sea surface temperature changes on a worldwide basis. Its ability to observe surface characteristics through most types of cloud cover provides valuable synergy with the other Aqua instruments."
*—**Roy Spencer** [University of Alabama, Huntsville—U.S. AMSR-E Science Team Leader]*

Pre-Launch Changes to the Aqua Name and Instruments

The mission that eventually became "Aqua" began early in the planning for the Earth Observing System (EOS) and was originally named "EOS PM" for its early-afternoon equatorial crossing times. Correspondingly, the satellite that eventually became "Terra" was originally named "EOS AM" for its mid-morning equatorial crossing times. The first name to change was "EOS AM", after the EOS AM team ran a contest for renaming the satellite, with "Terra" being the winning entry. Once EOS AM was renamed, it was time to reconsider the name "EOS PM." At the suggestion of NASA Headquarters, the renaming of EOS PM was done internal to the EOS PM program, with 17 nominations submitted, followed by voting by each of the science teams, project management, and the project science leadership. The winning name—nominated by the long-time AIRS Science Team leader Mous Chahine—was "Aqua," Latin for 'water' and selected for the wealth of information that the satellite would provide about water in all its forms (solid, liquid, and vapor) and about the water cycle. NASA Headquarters approved the new name, and "Aqua" replaced "EOS PM" in October 1999. Interestingly, the strong second-place finisher in the voting was "Suomi," in honor of the University of Wisconsin meteorologist Verner Suomi, after whom the Suomi NPP satellite is now named following the NPP launch in October 2011.

The name wasn't the only feature to change in the development stage of the Aqua program[1]. Notable among the other changes, the spacecraft had to be downsized in the 1990s to fit into a Delta II launch vehicle, and two early international partners pulled out from providing instruments due to financial considerations. Two new partners, however, stepped in to provide instruments: Japan in the case of the passive-microwave imager that was to become AMSR-E, and Brazil in the case of the microwave sounder that was to become HSB. Both Japan and Brazil have proven to be valued partners in the Aqua program.

Aqua Mission Success Criteria

Prior to launch, the Project Scientist and Aqua Science Teams were given the task of working with NASA Headquarters to develop a set of criteria that would constitute success for the Aqua mission. The result was the following list of ten Aqua Mission Success Criteria:

1. Produce the first high-spectral-resolution global infrared spectra of the Earth.
2. Obtain a highly accurate temperature profile of the troposphere.

[1] **Ghassem Asrar's** article in the May–June 2011 issue of *The Earth Observer* [**Volume 23**, **Issue 3**, pp. 4-7] summarizes the original plans for EOS and how those plans evolved over time into the observing system we have today.

3. Extend the improved TRMM rainfall characterization to the extra tropics.
4. Produce the first global sea surface temperature daily maps under nearly all sky conditions for a minimum of one year.
5. Produce large-scale global soil moisture maps for regions with low vegetation.
6. Produce calibrated global observations of the Earth's continents and ocean surfaces.
7. Capture and document two seasonal cycles of terrestrial and marine ecosystems and atmospheric and cloud properties.
8. Produce two seasonal/annual Earth radiation budget records.
9. Produce improved measurements of the diurnal cycle of radiation by combining Aqua and Terra measurements.
10. Produce combined cloud property and radiation balance data to allow improved studies of the role of clouds in the climate system.

In late 2008, at the Aqua End-of-Prime-Mission Review, following the completion of the six-year prime mission for the spacecraft, the Aqua Project Scientist was pleased to report to NASA Headquarters that each of the ten Success Criteria had indeed been accomplished. The AIRS Science Team had produced the first high-spectral-resolution global infrared spectra of the Earth back in 2002 and had obtained and validated highly accurate temperature profiles of the troposphere by the end of 2004. The AMSR-E Science Team had extended the TRMM rainfall characterization to the extra tropics by the end of 2002 (see **Figure 1**), had produced the first global sea surface temperature daily maps under nearly all sky conditions for a full year by the end of 2003, and had generated global soil moisture maps for regions with low vegetation

a

b

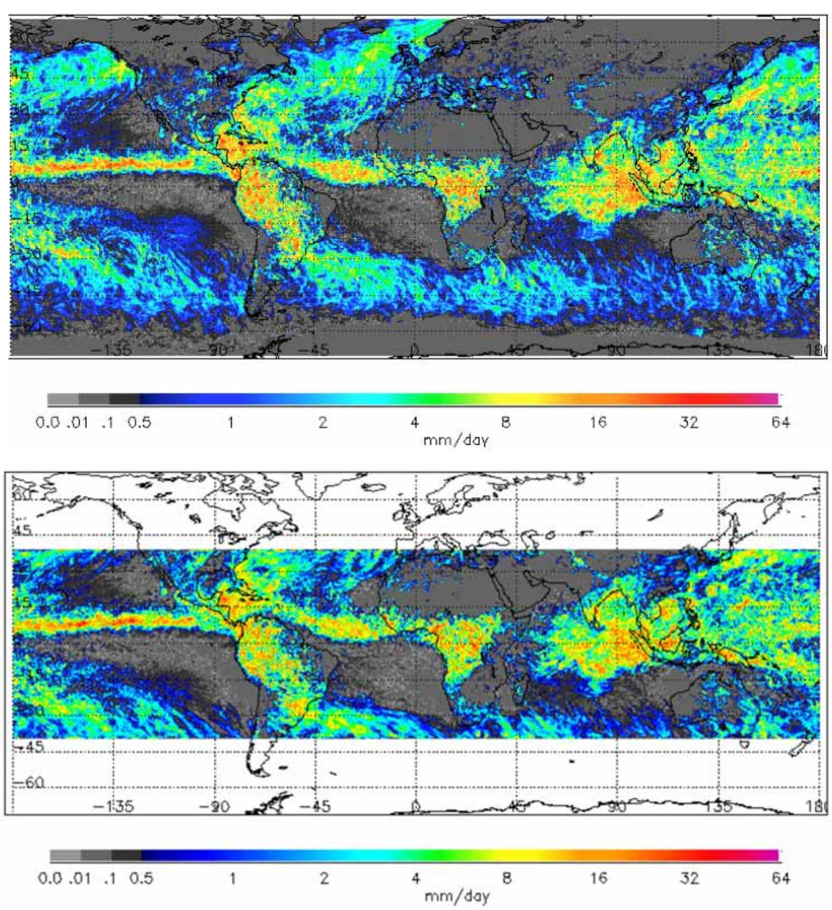

Figure 1. October 2005 rainfall rates as derived from (a) the Aqua AMSR-E and (b) the TRMM Microwave Imager (TMI). The TRMM satellite focuses on tropical measurements and hence has an orbit that is restricted to low- and mid-latitudes. Aqua's near-polar orbit allows AMSR-E to collect data at high latitudes as well. Note in particular the close match of the AMSR-E and TRMM data in the latitudes of the TRMM measurements. **Image credit**: **Chris Kummerow**, **Ralph Ferraro**, and **Elena Lobl** of the AMSR-E Science Team.

by the end of 2002. The MODIS Science Team produced calibrated global observations of the Earth's continents and ocean surfaces by mid-2004 and had documented two seasonal cycles of terrestrial and marine ecosystems and atmospheric and cloud properties by the end of 2004. The CERES Science Team produced the required Earth radiation budget records, combined Aqua and Terra data to produce improved measurements of the diurnal cycle of radiation, and combined Aqua CERES top-of-the-atmosphere and surface flux estimates with a range of data from other sources to produce the required cloud property and radiation balance data for improved studies of the role of clouds in the climate system.

Highlights From the First Ten Years of Aqua Data

As Aqua begins its second decade of on-orbit operations, this is an appropriate time to reflect on its contributions to date and to look toward the future. The Aqua data have provided such a wealth of new information about the Earth system that they have been used in over 2000 scientific publications, making a thorough listing of results quite impractical. Even a mere listing of the approximately 100 core Aqua data products would be cumbersome, and so presented here is instead a small, representative sampling of the Aqua results. These range from large-scale features of the global energy budget down to mapped details of such occurrences as individual oil spills and phytoplankton blooms, beginning with the energy budget.

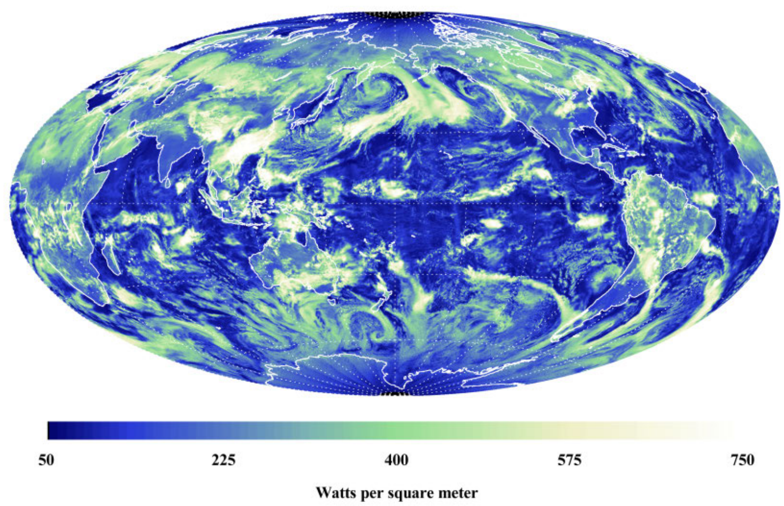

Figure 2. Global map of reflected shortwave radiation, March 18, 2011, as derived from Aqua CERES data. **Image credit**: **Tak Wong** of the CERES Science Team.

Top-of-the-Atmosphere Global Energy Budget

The large-scale global energy budget, involving both the energy entering the Earth system and the energy exiting the system, is fundamental to whether the Earth overall is warming, cooling, or neither warming nor cooling. Aqua does not have instruments measuring the energy entering the Earth system—which is overwhelmingly from the Sun—but it does have the CERES instrument measuring the energy exiting the system, both as the total outgoing radiation and as the shortwave outgoing radiation (which is predominantly reflected solar radiation)—see **Figure 2**.

Furthermore, the CERES Science Team combines the outgoing radiation measurements from the Aqua and Terra CERES instruments with incoming solar radiation measurements obtained from the Total Irradiance Monitor (TIM) on the Solar Radiation and Climate Experiment (SORCE) to obtain the global energy budget. Doing so, they have calculated a slight imbalance at the top of the atmosphere, finding that in recent years more energy has been entering than leaving the Earth system and quantifying the amount of the imbalance. The results are in line with the overall global warming that has received much discussion and concern among both the general public and scientists.

While the CERES measurements obtain information about the energy budget as a whole, other Aqua instruments obtain information about many of the forcing factors affecting that energy budget. Key among these are greenhouse gases, which hinder terrestrial radiation from leaving the Earth system and hence promote warming, and particulate matter, much of which has the opposite effect of cooling the Earth system by reflecting sunlight away.

Greenhouse and Other Atmospheric Trace Gases

Greenhouse gases have a warming effect on the Earth system because they tend to allow solar radiation to enter the system easily but hinder some of the Earth's radiation from exiting. The most abundant greenhouse gas is water vapor; but the second most abundant, carbon dioxide, has received much of the attention when it comes to greenhouse gas effects on recent global warming. This is because there is a solid record of carbon dioxide increases in the atmosphere and a widespread recognition that these increases are in substantial part due to industrial and other human activities.

Both the AIRS/AMSU and MODIS datasets have been used to derive global records of water vapor, and the AMSR-E dataset has been used to derive water vapor over the oceans. Furthermore, AIRS/AMSU data are additionally used to derive global records of carbon dioxide (see **Figure 3**), and in fact the first global maps of mid-tropospheric carbon dioxide concentrations from satellite data were from the AIRS/AMSU data. The AIRS/AMSU record shows that atmospheric carbon dioxide distributions are strongly influenced by such factors as the mid-latitude jet streams and synoptic weather systems.

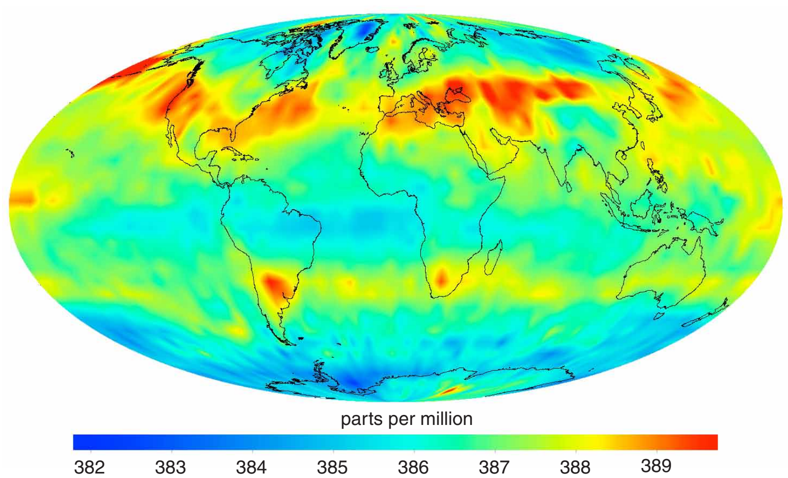

Figure 3. Global carbon dioxide concentrations in the mid-troposphere in July 2009, as derived from AIRS/AMSU data. **Image credit**: **Mous Chahine** and the AIRS Science Team.

However, they also clearly show: (1) a strong seasonal cycle, with atmospheric carbon dioxide increasing during the Northern Hemisphere winter and decreasing during the Northern Hemisphere summer, when vegetation removes carbon dioxide from the atmosphere and uses it for photosynthesis; and (2) an overall upward trend. Through the innovative and persistent efforts of Charles David Keeling and his successors, the seasonal cycle and upward trend of atmospheric carbon dioxide have been carefully monitored since the late 1950s for the location of Mauna Loa, HI; but the AIRS/AMSU data now show these features globally. The long Mauna Loa record and the much shorter but global AIRS/AMSU record nicely complement each other.

In addition to water vapor and carbon dioxide, the AIRS/AMSU data are also used to derive records of several other atmospheric trace gases, including methane, sulfur dioxide, carbon monoxide, and ozone. Methane is a greenhouse gas that could become increasingly important—as its presence in the atmosphere is anticipated to increase with continued decay of high-latitude permafrost. Sulfur dioxide is an important constituent of many volcanic eruptions, allowing the AIRS/AMSU sulfur dioxide product to track volcanic emissions. Carbon monoxide is a common constituent in fires, allowing the AIRS/AMSU carbon monoxide product to track the spread of smoke from major fires around the globe. Ozone in the upper atmosphere helps protect life at the surface from excessive ultraviolet radiation, while ozone at ground level is a pollutant. The AIRS/AMSU ozone record is a welcome complement to the well-established, longer records of ozone from ultraviolet measurements, as the AIRS/AMSU records—in contrast to the ultraviolet ones—include periods of darkness as well as daylight.

Aerosols and Other Particulate Matter in the Atmosphere

At ground level, particles in the atmosphere tend to be irritants, and abundant amounts tend to be quite unpleasant for humans, especially for people with asthma or other breathing difficulties. However, particles in the atmosphere have many additional effects, some of which are crucial for such processes as the transport of nutrients from one region to another.

"What is really rewarding is the large variety of practical uses to which MODIS data are applied, including fires, oil spills, volcanic eruptions, weather forecasting, and floods, as well as the expected climate observables."
*—**Michael King** [University of Colorado—MODIS Science Team Leader]*

In terms of the global energy budget, particulate matter has the strong reputation of providing a countereffect to the warming promoted by greenhouse gases. It is not the case, however, that all particulate matter has a cooling effect, as some particle types actually promote warming, one prominent example being black carbon.

Particles get into the atmosphere through both natural means and human activities, and the AIRS/AMSU and MODIS instruments make a variety of measurements of particles from both these sources. AIRS/AMSU and MODIS imagery show volcanic emissions clearly, with the AIRS/AMSU sulfur dioxide product also highlighting that particular emission from volcanoes. MODIS imagery further gives clear depictions of large dust storms and fires; and the AIRS/AMSU data have contributed to an improved understanding of how hurricane formation and intensification have been impacted by the dust in the Saharan Air Layer.

The MODIS aerosol calculations have expanded over time in their regions of applicability, with the early algorithms appropriate only for aerosols above dense vegetation and oceans. The *deep-blue algorithm* in particular has enhanced the MODIS calculations by also allowing calculations for aerosols over bright reflecting surfaces, such as deserts. The MODIS aerosol products include aerosol optical thickness, aerosol size distribution, and even a distinction between fine and coarse particles. The latter is particularly noteworthy because the emissions from anthropogenic sources tend to be weighted far more toward fine particles than do the emissions from natural sources.

Aqua measurements include water in the atmosphere (water vapor, clouds, precipitation), water on land (soil moisture, lakes, rivers, land ice, snow cover), and water in the oceans (surface waters, sea ice), fully justifying the "Aqua" name.

Water in the Earth System

Among the extremely important factors in the Earth's energy budget and in the Earth system as a whole, especially in all forms of Earth-based life, is the water cycle. In the water cycle, water evaporates from the surface, taking in energy as it does so, enters the atmosphere as water vapor, moves from place to place in the atmosphere, transporting the energy that it absorbed during evaporation, and releases the energy when it condenses into liquid droplets or solid ice particles. The droplets or particles eventually fall to the surface, often as precipitation. This is one important way in which the water cycle affects the energy transports and budgets within the Earth system. Another way is through the previously mentioned fact that water vapor is the most abundant greenhouse gas, hindering the Earth's radiation from escaping from the Earth system. Water in its solid form is also critically important to the energy budget, as it reflects solar radiation back to space.

Aqua measurements include water in the atmosphere (water vapor, clouds, precipitation), water on land (soil moisture, lakes, rivers, land ice, snow cover), and water in the oceans (surface waters, sea ice), fully justifying the "Aqua" name. Aqua standard products regarding water in the Earth system are listed in **Table 1** (next page).

Table 1. Aqua standard products of water in the Earth system.

Standard Product	Instruments Involved
Evapotranspiration	MODIS
Atmospheric Water Vapor	AIRS/AMSU, AMSR-E, and MODIS
Precipitable Water	AIRS/AMSU and MODIS
Cloud Products	AIRS/AMSU, AMSR-E, CERES, and MODIS
Rainfall	AMSR-E
Sea Ice Concentration and/or Extent	AMSR-E and MODIS
Sea Ice Drift	AMSR-E
Snow Depth on Sea Ice	AMSR-E
Snow Depth on Land and Snow Water Equivalent	AMSR-E
Fractional Snow Cover and Snow Albedo	MODIS
Surface Soil Moisture	AMSR-E

Although water vapor in the lower atmosphere had been derived from satellite measurements for decades prior to the Aqua launch, Aqua's AIRS/AMSU water vapor measurements provide increased accuracies and include upper-atmosphere water vapor as well as the lower-atmosphere product. Somewhat similarly, although the TRMM satellite had already provided impressive rainfall measurements for low latitudes, the AMSR-E instrument has extended these rainfall measurements to high latitudes.

Cloud measurements from the Aqua and Terra MODIS instruments have yielded fundamental new information about the Earth's cloud cover, including that average global cloud coverage is about 67% and that this is true both for the early afternoon measurements collected by Aqua and for the mid-morning (about 10:30 AM) measurements collected by Terra. As expected, cloud coverage is greater over oceans, at about 72%, than over land, at about 55%. Additionally, the Terra mid-morning ocean cloud cover values are slightly higher than the corresponding Aqua early afternoon values, whereas land cloud-cover values are slightly higher from Aqua than from Terra.

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AMSR-E and MODIS both provide measurements of sea ice and snow cover, with the AMSR-E measurements particularly useful for climate studies because they provide data throughout the year, irrespective of sunlight conditions and cloud coverage. MODIS, on the other hand, has the advantage of finer resolution, providing greater spatial detail for the times when cloud cover is not an issue. The AMSR-E measurements follow a long tradition of passive-microwave instrumentation but with finer spatial resolution than previous passive-microwave imagers, making them particularly valuable, for instance, in depicting a record minimum Arctic sea ice extent that occurred in 2007—see **Figure 4** (next page)—and held until 2012, when yet another new record was reached. In fact, in contrast to the data from previous passive-microwave imagers, the AMSR-E data have sufficient resolution to resolve *leads*—narrow stretches of open water between ice floes—in the sea ice, allowing satellite-based, all-weather studies of heat fluxes in sea-ice fields.

Temperature in the Atmosphere and at the Surface

A net result of all the various energy sources, sinks, and flows to, from, and within the Earth system is the temperature structure within the system, along with its continual changes. AIRS/AMSU measurements are particularly important for obtaining vertical temperature profiles throughout the atmosphere, whether in the presence of clouds or cloud-free. Improved temperature profiles for weather forecasting was one of the primary goals of the AIRS/AMSU efforts, with the very specific goal of 1-K accuracies in 1-km (~3280 ft) layers in the atmosphere, a goal that was met early in the Aqua mission. In fact, the AIRS/AMSU data get near-radiosonde accuracies

Figure 4. Arctic sea ice coverage on September 14, 2007, as derived from AMSR-E data. Until 2012, this was the date of the record minimum sea ice coverage over the period of the satellite record since late 1978. Note in particular the easy Northwest Passage through the Canadian Archipelago. Greenland is prominent in the center of the upper portion of the image; Siberia, the Bering Strait, and Alaska are at the bottom of the image. **Image credit**: NASA Scientific Visualization Studio (SVS), employing AMSR-E data courtesy of JAXA.

(see **Figure 5**), despite the fact that radiosondes measure temperature *in situ* whereas AIRS and AMSU measure from quite a considerable distance, at Aqua's altitude of 705 km (~438 mi).

Both AMSR-E and MODIS data are used to derive global sea surface temperatures (SSTs), but, as with sea ice and other surface measurements obtained by both instruments, the two sets of measurements are nicely complementary. MODIS obtains higher spatial resolution, thereby providing more geographic detail, but AMSR-E data can be used to obtain SSTs under almost all weather conditions, thereby providing much more thorough coverage than the MODIS SST data, which are largely restricted to cloud-free conditions. MODIS additionally gets land surface temperatures, and gets them both for daytime and nighttime, using thermal infrared measurements. An annual identification of the "hottest place on Earth" as obtained from the MODIS data has generated some public interest in recent years, with the "winner" of this unenviable status often being the Lut Desert of Iran.

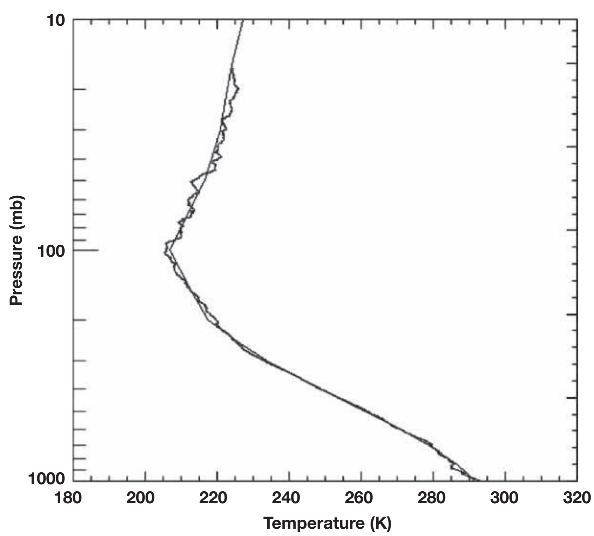

Figure 5. AIRS temperature profile over Chesapeake Bay (smooth curve) overlaid with a radiosonde profile (more-jagged curve) over Chesapeake Bay for the same date, September 13, 2002. Despite the fact that AIRS collects data from an altitude of 705 kilometers (~438 mi), the temperatures derived from the AIRS data match closely with the *in situ* measurements of the radiosonde. **Image credit**: **Wallace McMillan** and the AIRS Science Team, with relabeling.

Land Vegetation and Marine Life

In addition to the wealth of information the Aqua data are providing about the non-biological aspects of the Earth system, Aqua data, especially from the MODIS instrument, are providing information about land vegetation and multiple measures of marine life. In terms of land vegetation, MODIS-derived variables include leaf area index, photosynthetically active radiation, evapotranspiration, the well-established Normalized Difference Vegetation Index (NDVI) that has been used for decades with data from NOAA's Advanced Very High Resolution Radiometer (AVHRR) sensors, and the MODIS Enhanced Vegetation Index (EVI). The EVI has enhanced sensitivity over the NDVI, particularly in areas of dense vegetation, and also reduces the effects of soil variations on the calculations. The MODIS land-vegetation data are used to create global images that show clearly the major deserts and forested areas of the Earth [see **Figure 6** (next page)], but they are also used for local and regional studies—e.g., for examining the drought sensitivity of the Amazon rainforest.

MODIS-derived marine-life datasets include such variables as particulate organic carbon (POC), chlorophyll-*a* concentration, and fluorescence. The MODIS POC product gives the near-surface concentration of organic particles in the water. The MODIS chlorophyll-*a* measurement is an indicator of phytoplankton biomass, chlorophyll-*a* being the main plant pigment involved in photosynthesis. The MODIS measurements

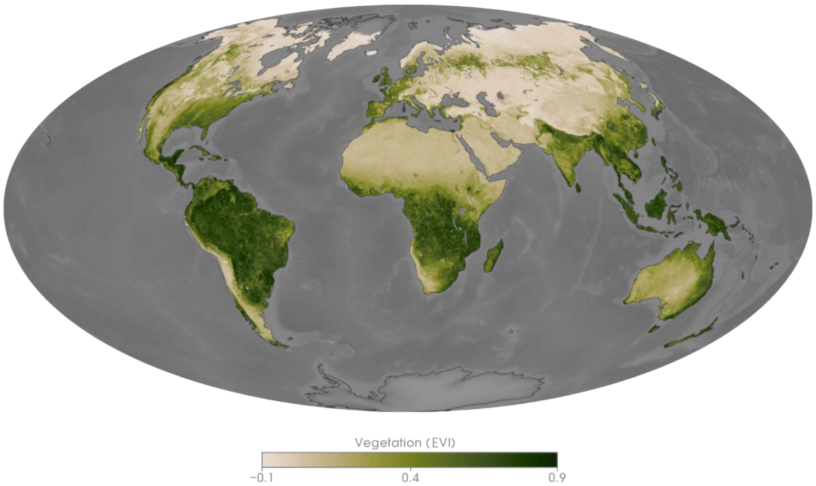

Figure 6. Global image of the MODIS Enhanced Vegetation Index (EVI), averaged over the 16-day period February 10-25, 2012, as derived from Aqua MODIS data. Deep greens highlight the rainforests of the Amazon, equatorial Africa, Indonesia, and Central America; and browns highlight such desert areas as the Sahara Desert in northern Africa, the Gobi Desert in central Asia, the Great Victoria and Great Sandy Deserts of Australia, the Atacama Desert along the west coast of South America, and the Sonoran and Mojave Deserts in the southwestern United States. **Image credit**: **Marit Jentoft-Nilsen**, with data provided by **Kamel Didan** and the MODIS Science Team.

continue the chlorophyll-*a* record from the Sea-viewing Wide-Field-of-view Sensor (SeaWiFS), launched in 1997 on the Orbview-2 satellite. In contrast, the fluorescence measurements are new with the Aqua MODIS and provide the first satellite-derived large-scale view of the physiological stress undergone by ocean phytoplankton. This is an exciting new capability of the Aqua MODIS, providing information about the health of phytoplankton to complement the earlier and continuing information about the phytoplankton biomass. Phytoplankton account for approximately half of the photosynthetic activity on the planet, and they consume carbon dioxide as they do so.

Practical Applications

Although the Aqua mission was developed largely for its many anticipated scientific contributions, from the beginning it was also hoped and expected that the mission would have value in the realm of practical applications. Well before launch, researchers recognized that the high accuracy of the AIRS/AMSU temperature and water vapor measurements would have value in weather forecasting, and indeed since launch the measurements from AIRS/AMSU have been used in many weather forecasting models around the world, with resulting measurable improvements in forecast skill.

Others of the Aqua instruments have also contributed to improved forecasts. In particular, the AMSR-E sea surface temperature, water vapor, and precipitation data have been used by hurricane prediction centers; and incorporation of MODIS polar wind data in computer models has resulted in measurably improved weather forecasts in the polar regions and beyond. Also of importance for forecasting is the large-scale view that satellites provide of hurricanes and typhoons as they form, develop, and approach land—e.g., see **Figure 7**.

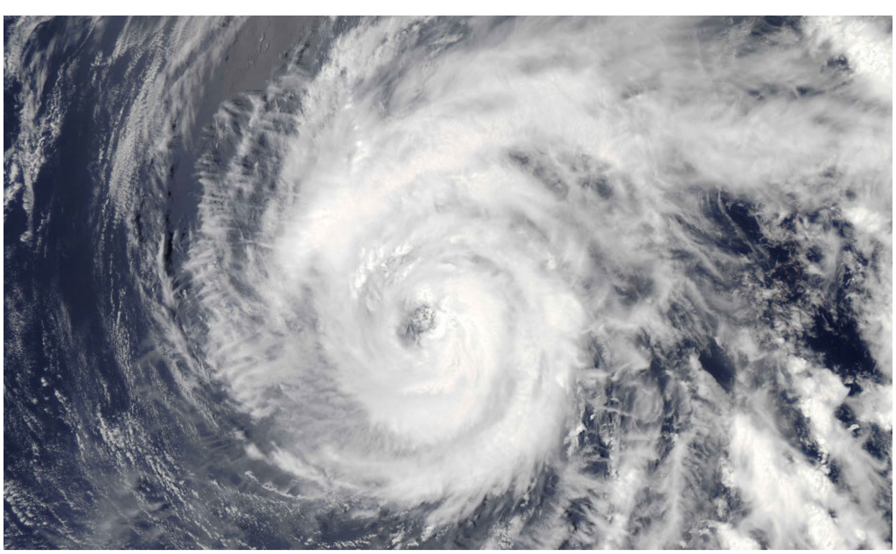

Figure 7. Typhoon Sanvu over the western Pacific, roughly 185 km (~115 miles) southwest of Iwo Jima, Japan, on May 25, 2012, as imaged by the Aqua MODIS. Sanvu had gusts of up to 185 km/hr (~115 mi/hr) and sustained winds of 150 km/hr (~93 mi/hr). **Image credit**: **Jeff Schmaltz** of the MODIS Rapid Response Team at NASA's Goddard Space Flight Center.

"Launched in May 2002 as a six-year mission, Aqua is still an excellent performer. It has met the challenges imposed on it by the science community with distinction and has contributed to the development of climate data records of unprecedented quality. Operational agencies around the world are using Aqua data to improve weather prediction. The six Aqua instruments were carefully selected to make measurements for the improved characterization and understanding of atmospheric temperature and humidity profiles, clouds, global precipitation, and Earth's thermal radiation balance; terrestrial snow and sea ice; sea surface temperature and ocean productivity; and soil moisture. The Aqua sounding instruments and imaging radiometers have considerably higher volume resolution (vertical resolution X footprint area) than the corresponding predecessor instruments. The synergy generated by the Aqua instruments along with other A-train components is allowing us to make extraordinary space-based measurements to study complex and interrelated systems of land surface, biosphere, atmosphere, and oceans. To keep pace with the improved spatial and temporal resolution of the global models, the satellite instruments of the future will continue to improve the volume resolution and find innovative ways to tackle the time resolution horizon. However, the performance provided by the Aqua satellite will be a tough act to follow."

*—**Ramesh Kakar** [NASA Headquarters—Aqua Program Scientist]*

In addition to their value in weather forecasting, Aqua data are proving of practical value in numerous other arenas. Data from the MODIS instruments on both Aqua and Terra show forest fires with great clarity, allowing the U.S. Forest Service and other forest services around the world to see the locations and expanse of forest fires, thereby helping them in their very practical determination of where best to deploy firefighters.

In a different realm, the AIRS/AMSU and MODIS data are used to track and monitor volcanic emissions. Because airborne volcanic ash can pose significant dangers to airplanes, monitoring volcanic emissions has been of great value to airplane pilots and aviation administrations, helping them to steer planes clear of the volcanic ash.

In addition to their value in weather forecasting, Aqua data are proving of practical value in numerous other arenas.

Other practical uses of Aqua data include the use of:

- AIRS/AMSU and MODIS data in air-quality analyses;
- CERES data by utility companies for energy management;
- MODIS data by the U.S. Department of Agriculture for monitoring crop yields and drought;
- CERES data by the Department of Agriculture in its analyses of the factors affecting crop yields;
- AMSR-E SST data by the Japanese fishing industry to help analyze local and regional fishing conditions;
- AMSR-E and MODIS data for monitoring floods and their aftermath;
- MODIS data for monitoring oil spills and dust storms, both of great relevance for people in the path of the oil and dust;
- MODIS data for monitoring phytoplankton blooms and hence identifying ocean regions that abound with life; and
- AMSR-E and MODIS data for sea ice monitoring, helping crews of ships maneuvering in polar oceans to be aware of hazardous conditions.

When Aqua launched in May 2002, it was unclear how much value the Aqua data would have for immediate practical applications beyond weather forecasting. However, in part because of Aqua's direct broadcast capability, whereby the spacecraft routinely broadcasts its real-time data, the value of the Aqua mission for practical applications has exceeded almost all initial expectations.

Ten Singled-Out Achievements (a qualified 'Top Ten' List)

The many and varied contributions made so far with Aqua data make it difficult to identify which contributions are the most important. However, with the help of **Joao Teixeira** [JPL— *AIRS Science Team Leader*], **Roy Spencer** [UAH—*U.S. AMSR-E Science Team Leader*], **Norman Loeb** [LaRC—*CERES Science Team Leader*], **Bruce Wielicki** [LaRC—*Former CERES Science Team Leader*], **Michael King** [University of Colorado—*MODIS Science Team Leader*], **Vince Salomonson** [University of Utah—*Former MODIS Science Team Leader*], other members of the science teams, and **Ramesh Kakar** [NASA Headquarters—*Aqua Program Scientist*], the Aqua Project Scientist has compiled a list of ten contributions singled out as Ten Top Achievements of Aqua's First 10 Years of Observations. These are not presented as necessarily the "Top Ten," but rather as ten that are near the top, fully recognizing that there are other major achievements as well. With that qualification, here is the list of Ten Top Achievements (not ordered by importance):

1. Aqua and Terra data from CERES, in conjunction with incoming solar radiation data from the Solar Radiation and Climate Experiment (SORCE), have been used to quantify changes in the energy imbalance at the top of the atmosphere, determining that the Earth system has been accumulating energy at an overall rate of 0.5 W/m^2.

2. Aqua data from AIRS/AMSU have been used to produce the first global maps from space of mid-troposphere carbon dioxide concentrations and have revealed the influence of large-scale dynamics on carbon dioxide distributions.

3. Aqua radiance data from AIRS provide an unprecedented accuracy and stability that makes them ideal for climate studies, leading to the confirmation of previous estimates of the sign and magnitude of the water vapor feedback and to the creation of novel ways of evaluating climate models.

4. Aqua data from CERES and MODIS have been used to quantify the direct radiative effect of atmospheric aerosols on top-of-the-atmosphere, within-the-atmosphere, and surface radiative fluxes.

5. Aqua data from AMSR-E have been used to extend to high latitudes the high-quality precipitation retrievals from the Tropical Rainfall Measuring Mission (TRMM).

6. Aqua data from AMSR-E have provided near-all-weather global monitoring of a variety of surface variables, including sea surface temperature and sea ice, allowing the observation and analysis of such occurrences as the August 2005 sea surface cold wake following the passage of Hurricane Katrina and the September 2007 then-record minimum (later surpassed) in Arctic sea ice coverage.

7. Aqua data from MODIS have included the first global observations of ocean chlorophyll fluorescence, providing a synoptic view of phytoplankton physiological stress.

8. Aqua data from MODIS have provided the first global annual measure of ecosystem disturbance, a key component for quantifying deforestation and desertification.

9. Aqua and Terra data from MODIS have provided the first decade-long dataset of global evapotranspiration, a key variable in drought monitoring.

10. Aqua data from AIRS/AMSU, MODIS, and AMSR-E have all helped in weather forecasting, and AIRS in particular has been found in several sensitivity studies to be the single most important satellite instrument in improving global weather forecasts during the last 10 years.

The A-Train Constellation of Satellites

Aqua is not alone in its orbital track around the Earth. Instead, it was the first in what became a sequence of satellites launched into a line-up popularly known as the "A-Train" and more formally known as the "Afternoon Constellation." The second satellite into the A-Train was NASA's Aura satellite, launched on July 15, 2004, and placed well behind Aqua. A few months later, on December 18, 2004, the French Centre National d'Etudes Spatiales (CNES) launched a satellite with the acronym PARASOL (standing for Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar) and then maneuvered it into position between Aqua and Aura. Next came NASA's CloudSat and the joint NASA/CNES Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), launched together on April 28, 2006, and placed between Aqua and PARASOL.

The variety of instruments on the A-Train satellites greatly enhances the science that can be done with the A-Train data, and indeed the Aqua science teams are working with science teams from the other A-Train missions to make effective use of the complementary datasets.

The Orbiting Carbon Observatory (OCO) and Glory were both intended for the A-Train, but in both cases the launch sadly failed, OCO on February 24, 2009, and Glory on March 4, 2011. These major disappointments were followed on May 18, 2012 by JAXA's successful launch of the Global Change Observation Mission–Water (GCOM-W), or "Shizuku," and its successful maneuvering into place in the A-Train in front of Aqua on June 29, 2012. Shizuku carries on board an AMSR2 follow-on to Aqua's AMSR-E instrument.

PARASOL was shifted to a lower orbit on December 2, 2009, and is no longer orbiting in the A-Train. CloudSat was temporarily outside of the A-Train but was repositioned back into the A-Train behind CALIPSO on May 15, 2012. The result is that the A-Train is now led by GCOM-W, followed by Aqua, then CALIPSO, CloudSat, and Aura—see **Figure 8**.

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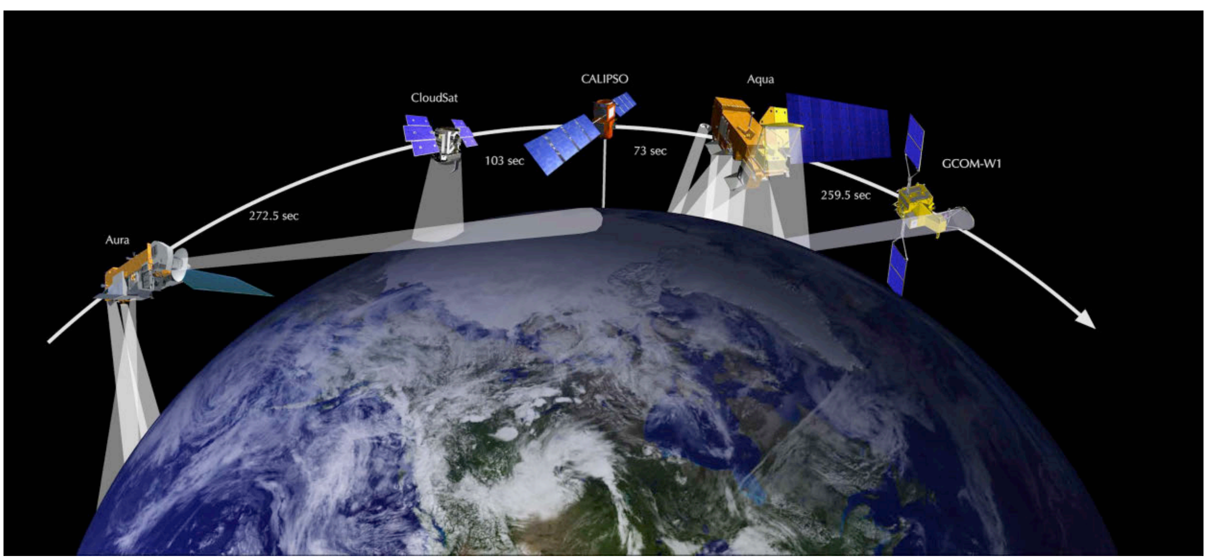

Figure 8. Configuration of the A-Train constellation of satellites as of mid-2012, with GCOM-W in the lead, followed by Aqua, CALIPSO, CloudSat, and Aura. **Image credit**: **Ed Hanka**, **Angie Kelly**, and the A-Train Mission Operations Working Group.

Summary and a Look Toward the Future

Aqua has now exceeded 10 years of on-orbit operations—well beyond its six-year prime mission. The Aqua instruments have gathered information on numerous aspects of the Earth's water cycle, the Earth's energy budget, and such additional components of the Earth system as the vegetative life both on land and in the oceans. These data have enabled the Aqua science teams to successfully accomplish each of the Aqua Mission Success Criteria and proceed far beyond those initial criteria.

With well over 2000 scientific papers now published using Aqua data, any short summary can include only a small sampling of the wealth of scientific output resulting from the Aqua mission. The items highlighted in this article are meant to illustrate the range and value of the Aqua data for science and for practical applications, but much more information can be found on the internet, at *aqua.nasa.gov* and the many links provided there, including to websites for each of the Aqua science teams.

The Aqua spacecraft has enough fuel remaining to last into the early 2020s. At this point, four of Aqua's Earth-observing instruments are still going strong—AIRS, AMSU, CERES, and MODIS—and the hope is that some or even all of them will continue to operate successfully into the next decade.

The hope is also that many of the Aqua datasets will be extended into the future by instruments on other satellites even after the Aqua instruments are no longer operational. For AMSR-E, dataset extensions should come from the Shizuku AMSR2, launched in May 2012. For CERES, dataset extensions can come from the CERES on Suomi NPP, launched in October 2011, and from the CERES planned for eventual launch on JPSS. Many of the MODIS datasets can be extended with data from the Visible Infrared Imaging Radiometer Suite (VIIRS) on Suomi NPP and the VIIRS planned for JPSS; and many of the AIRS/AMSU datasets can be extended with data from the Cross-track Infrared Sounder (CrIS) and Advanced Technology Microwave Sounder (ATMS) on Suomi NPP and the CrIS and ATMS planned for JPSS.

As the currently operating Aqua instruments continue to collect data and instruments on other satellites extend Aqua datasets, the highly successful Aqua mission should continue to have valuable contributions to the advance of Earth system science and practical applications far into the future. ■

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