Summarizing the First Ten Years of NASA's Aqua Mission

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***Abstract*—The Aqua spacecraft was launched on May 4, 2002 with six Earth-observing instruments on board to collect data on a wide variety of Earth system variables. After ten years of on-orbit operations, Aqua has provided data that have contributed to over 2 000 scientific publications, with new results on the Earth's energy budget, trace gases and particulate matter in the atmosphere, vegetation on land and in the oceans, and many aspects of the water cycle, including evaporation and transpiration, water vapor, cloud cover, precipitation, the oceans, sea ice and land ice, snow cover, and soil moisture. Additionally, Aqua data have been used to assist in practical applications ranging from weather forecasting to the deployment of firefighters and the routing of aircraft. Although the six-year design life of the satellite has been successfully completed and exceeded, enough fuel remains on Aqua for approximately another ten years of operations.**

***Index Terms*—Satellite Earth observations, Aqua, global energy budget, water cycle.**

I. Introduction

NASA's Earth-orbiting Aqua spacecraft (Fig. 1) was launched at 2:55 a.m. on May 4, 2002, from Vandenberg Air Force Base in California. It soon was maneuvered to its desired near-polar, sun-synchronous orbit at an altitude of 705 km, crossing the equator going north at 1:30 in the afternoon and south at 1:30 in the morning, local time [32]. At 705 km, Aqua orbits the Earth every 98.8 minutes. Aqua has now exceeded ten years of on-orbit operations, with a wealth of scientific output resulting at least in part from the use of Aqua data.

Aqua was specifically named for the significant amount of information that it collects regarding water in the Earth system, 'Aqua' being Latin for 'water'. Aqua measurements include water in the atmosphere, on land, and in the oceans, and water in each of its three states: gaseous, liquid, and solid. The Aqua measurements, however, include other aspects of the Earth system as well, and this paper highlights a selection of the key results obtained from the extensive Aqua datasets, doing so in sections on: the global energy budget; water vapor, clouds, and precipitation; other atmospheric trace gases; particulate matter in the atmosphere; ice and snow; vegetation and other life forms; and temperature. The science results are followed by a section on practical applications. First, though, comes a section describing the complement of Aqua's Earth-observing instruments.

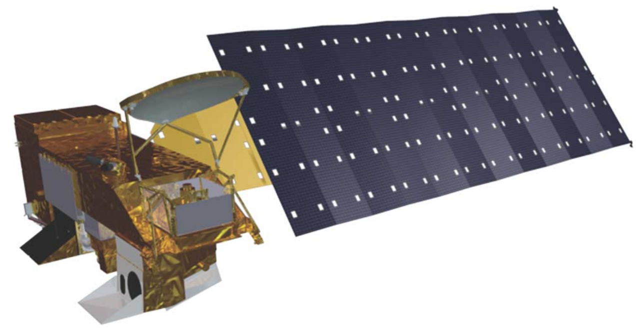

Fig. 1. Artist's rendition of the Aqua spacecraft in orbit. (Rendering by Marit Jentoft-Nilsen, based on an earlier version by TRW/Northrop Grumman.)

II. Aqua's Earth-Observing Instruments

Aqua has on board six Earth-observing instruments: 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). HSB was provided by the Brazilian Institute for Space Research, AMSR-E was provided by the Japan Aerospace Exploration Agency (JAXA), and the remaining instruments and the spacecraft were provided by the United States National Aeronautics and Space Administration (NASA).

AIRS, AMSU, and HSB together constitute a sophisticated sounding system centered on AIRS. AIRS makes measurements at 2378 infrared and 4 visible/near-infrared channels and is unique to the Aqua platform. The 2378 infrared channels on AIRS far exceed the number of channels on previous satellite sounders and enable the determination of atmospheric temperature, moisture, and key trace gases in the atmosphere as well as cloud and surface parameters.

In contrast to the uniqueness of AIRS, both AMSU and HSB are near-identical copies of instruments flown also on satellites of the National Oceanic and Atmospheric Administration (NOAA). AMSU is a 15-channel microwave sounder used in the Aqua sounder system to facilitate cloud clearing of the AIRS observations and to provide, for instance, cloud liquid water and vertical temperature profiles in the presence of clouds. HSB is a four-channel microwave sounder that obtained valuable information about atmospheric humidity and cloud liquid water in the early portion of the Aqua mission

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although ceased operations in February 2003. Algorithms for the AIRS/AMSU/HSB sounding system were adjusted to enable the AIRS/AMSU system to continue to produce the full suite of AIRS/AMSU/HSB data products.

CERES is a 3-channel radiometer measuring reflected shortwave radiation exiting the Earth system 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. Outgoing longwave radiation is calculated from the CERES measurements by a simple subtraction of the reflected shortwave radiation from the total outgoing radiation. Aqua has two CERES sensors on board, each of which is capable of operating in either of two modes, cross-track scanning or rotating-azimuth-plane scanning. Cross-track scanning allows imaging of the entire Earth and continuity with previous satellite instruments focused on the Earth's radiation budget, whereas rotating-azimuth-plane scanning allows sampling from different viewing angles, providing more complete information and improving the accuracy of the derived products.

The two CERES on Aqua are the fourth and fifth CERES in orbit, the first CERES having been launched on November 27, 1997 on the Tropical Rainfall Measuring Mission (TRMM) satellite and the second and third CERES having been launched on December 18, 1999 on the Terra satellite. A sixth CERES was launched on October 28, 2011 on the Suomi National Polar-orbiting Partnership (NPP) satellite, and a seventh CERES is scheduled for a 2016 launch on the Joint Polar Satellite System (JPSS). The two CERES on Aqua are labeled FM-3 (for Flight Model 3) and FM-4. (The TRMM CERES was the Proto Flight Model, while the two Terra CERES are FM-1 and FM-2.)

MODIS is a 36-band multi-purpose radiometer that provides visible and infrared measurements of many atmospheric, ocean surface, and land surface properties, including properties of land and ocean vegetation. MODIS has the finest spatial resolution of any of the Aqua instruments, with resolutions of 250 m to 1 km, depending on the spectral band.

The MODIS on Aqua is one of two MODIS instruments, the other being on Terra. Having MODIS and CERES sensors on both Aqua and Terra increases the MODIS and CERES data density and specifically allows more complete coverage of the daily cycle of variables measured by those two instruments. Terra crosses the equator at approximately 10:30 a.m. and 10:30 p.m., complementing the 1:30 a.m. and 1:30 p.m. equatorial crossing times of Aqua.

Finally, AMSR-E is a 12-channel passive-microwave radiometer that measures a wide variety of atmospheric and surface variables fundamental to weather and climate, especially water-based variables, such as water vapor, cloud water, rainfall, sea ice, snow water content, and soil moisture (or soil surface wetness). Because it measures at microwave wavelengths, AMSR-E is overwhelmingly measuring radiation from within the Earth system and hence does not require sunlight. Further, some of the AMSR-E channels are largely unaffected by clouds, allowing observations of surface variables even in the presence of a substantial cloud cover.

Several of the surface variables measured by AMSR-E, including sea ice, snow cover, and sea surface temperature (SST), are also measured by MODIS, allowing valuable comparisons, especially given their complementary advantages. MODIS provides greater spatial detail, but AMSR-E is able to obtain data on these variables under almost all weather and lighting conditions, whereas many of the MODIS surface measurements are restricted to cloud-free conditions. After a highly successful run of over nine years of high-quality data collection—far exceeding its design lifetime—AMSR-E experienced a major anomaly on October 4, 2011, and it is unlikely that the instrument will ever be restored to full functionality.

AMSR-E was the first AMSR in orbit. Another AMSR, AMSR-2, was launched on the Shizuku satellite in Japan's Global Change Observation Mission-Water (GCOM-W) on May 18, 2012. On June 29, 2012, Shizuku was maneuvered into position in front of Aqua in what is known as the 'A-Train' or 'Afternoon Constellation' of satellites. This constellation began with Aqua in May 2002, after which Aqua was joined by: Aura following its July 15, 2004 launch; the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL), launched on December 18, 2004; CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, launched on April 28, 2006; and Shizuku. The current configuration of the A-Train has Shizuku at the front, then Aqua, CALIPSO, CloudSat, and Aura. The coordinated orbits of these five satellites (and earlier of PARASOL as well) facilitates synergistic use of their many Earth science datasets. The A-Train is a multinational endeavor, with Shizuku from JAXA (Japan), Aqua, CloudSat, and Aura from NASA (United States), PARASOL from the Centre National d'Etudes Spatiales (CNES; France), and CALIPSO jointly from NASA and CNES (United States and France).

Further technical details about the Aqua Earth-observing instruments can be found in prior publications: AIRS/AMSU/HSB [1], AMSR-E [19], CERES [48], and MODIS [2]. The status of the instruments as of late 2012 can be summarized as follows:

- AIRS continues to perform well, with by far the majority of its 2382 channels continuing to operate.
- HSB has not operated since February 5, 2003.
- AMSU continues to perform well except for channels 4 and 5, both of which have degraded to the point where the data from these channels are no longer being used in the generation of AIRS/AMSU geophysical products. The algorithms that had used these channels have all been accordingly revised.
- All three channels on CERES FM-3 and two of the three channels on CERES FM-4 continue to perform well. The shortwave channel on CERES FM-4 failed abruptly on March 30, 2005, and has not operated since that time.
- MODIS continues to perform well, although since the start of the Aqua mission, one of its 36 bands, band 6 (wavelengths 1628–1652 nm), has performed decidedly sub-optimally, with 14 of the 20 band-6 detectors either not operating or producing excessively noisy data. Nonetheless, despite the extra effort involved, at least three different algorithms have been developed to retrieve useful data from the flawed band 6 [35], [40], [47].

- AMSR-E ceased routine operations following its October 4, 2011 anomaly. It was turned off from that date until February 6, 2012, when it was turned back on although without rotation of the antenna. Rotation is required for high-quality science data from AMSR-E, and the antenna had been rotating at 40 revolutions per minute (40 rpm) until the 2011 anomaly. After much analysis and planning, six short spin-up/spin-down tests, lasting less than 10 minutes each, were conducted in September 2012 and established that despite the apparent depletion of lubrication and apparent bearing degradation, the antenna can still rotate, although at a reduced rate. Following analysis of the test results and evaluation of potential consequences of further operations, the rotation was restarted on December 4, 2012, for a planned extended period, the primary purpose being to allow cross-calibration between the AMSR-E and AMSR-2 instruments. This rotation, however, is at approximately 2 rpm, not 40 rpm, and will not allow the same high-quality science data as were obtained previously.

III. Science Advances

Aqua data have been used by hundreds of scientists around the world, studying topics as diverse as individual trichodesmium blooms [15] and the Earth's energy budget [26]. The resulting scientific output includes over 2 000 publications incorporating Aqua data. This section provides a sampling of what has been obtained, starting with the largest scale, the global energy budget.

A. The Global Energy Budget

The three channels on the CERES sensors were carefully selected to obtain critical information regarding the Earth's energy budget. In particular, CERES measurements allow determination and mapping of the solar radiation reflected from the Earth/atmosphere system back to space and the Earth's longwave radiation emitted to space (e.g., Fig. 2).

Combining CERES data on reflected and emitted radiation with data on the incoming solar radiation allows a quantification of the net radiation at the top of the Earth's atmosphere. Specifically, CERES data from Aqua and Terra have been used with incoming solar radiation data from the Total Irradiance Monitor (TIM) on the Solar Radiation and Climate Experiment (SORCE) to calculate that the Earth has been accumulating energy at a rate of approximately 0.50±0.43 Wm^{-2} over the course of the 10-year period 2001–2010 [26]. This slight imbalance at the top of the atmosphere, with more energy entering than leaving the Earth system, induces overall warming.

There are many forcing factors affecting the Earth's energy budget and creating the current slight imbalance. Aqua measurements are contributing new information on many of these, including ones that tend to enhance the warming, such as greenhouse gases, which promote warming by readily allowing solar radiation through to the Earth's surface while hindering terrestrial radiation from leaving the Earth system, and others that tend to dampen the warming, such as certain types of aerosols.

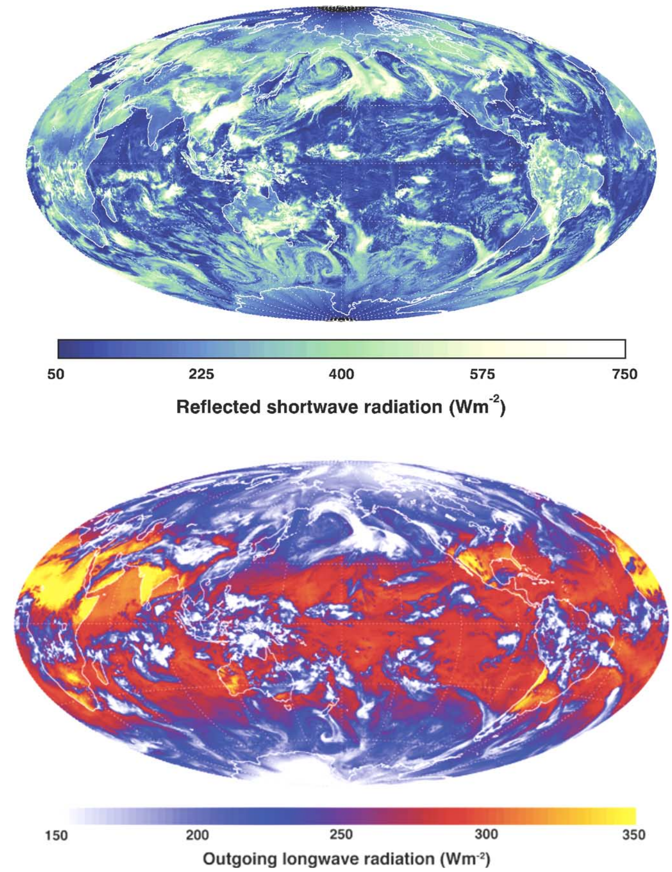

Fig. 2. Reflected shortwave radiation (top) and outgoing longwave radiation (bottom), March 18, 2011, as derived from Aqua CERES data. Longwave radiation is particularly low over the ice sheets of Antarctica and Greenland, plus where clouds block radiation from the surface from exiting to space. (Images from Tak Wong and the CERES Science Team, with relabeling.)

B. Water Vapor, Clouds, and Precipitation

AIRS/AMSU, AMSR-E, and MODIS data have all been used to derive information on water vapor, which although it is not a major contributor to the current energy imbalance, is the Earth's most abundant greenhouse gas, while also being critically important in the water cycle and critically important to life on Earth, transporting water and energy throughout the atmosphere.

Although water vapor had been derived for decades from satellite data, the high accuracy of the AIRS/AMSU water vapor products [11] and the fact that they include water vapor in the upper atmosphere (e.g., Fig. 3) as well as in the lower atmosphere has made them particularly useful. This includes use for atmospheric monitoring, for data assimilation, and for validating other observations and numerical models. For instance, the AIRS/AMSU water vapor products reveal much larger tropospheric moisture perturbations than depicted in widely-used reanalyses, suggesting that those reanalyses underestimate the impact of convection-induced downdrafts on the atmospheric boundary layer [12]. Also, comparisons of the AIRS/AMSU water vapor with six coupled climate models has identified the vertical moisture transport as a particular area for model improvements [34]. Further, the AIRS/AMSU data have been used to connect changes in water vapor, temperature, and

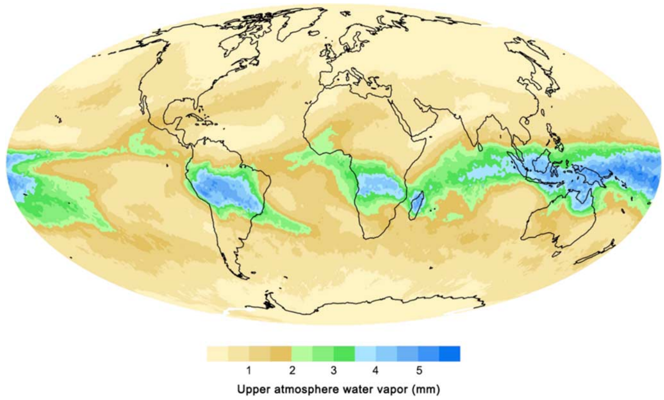

Fig. 3. Average January 2003 upper atmosphere water vapor (above the 500 mb level), as derived from AIRS/AMSU data. (Image from the AIRS Science Team.)

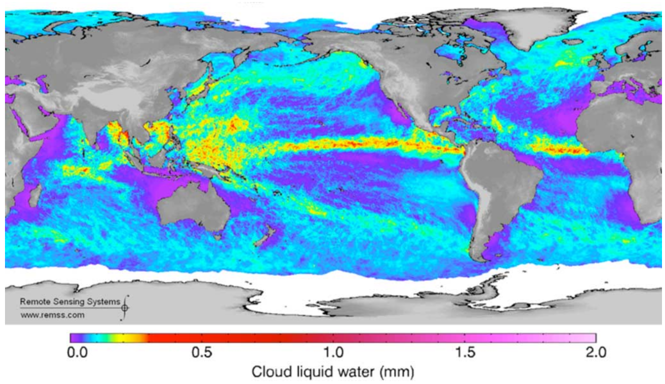

Fig. 4. Average September 2011 cloud liquid water over the oceans, as derived from AMSR-E data. (Image from Remote Sensing Systems, with relabeling.)

precipitation to the Madden-Julian Oscillation (MJO) [44] and are helping to reveal new insights into the water-vapor/climate feedback [10].

Like water vapor, clouds and precipitation are critical elements in the water and energy cycles. Clouds form as water vapor condenses to liquid droplets and/or ice particles, releasing to the atmosphere the energy that the water vapor gained during the process of evaporation from water on land, ocean, plant, or other surfaces. Precipitation returns the water to the Earth's surface. Among their impacts on the energy budget, clouds reflect solar radiation back to space, which taken by itself produces a cooling influence on the climate; but they also trap some of the outgoing terrestrial radiation, which provides a countering warming influence.

Aqua measurements include considerable information about clouds, including cloud liquid water from AMSR-E (Fig. 4), fractional cloud cover from AIRS/AMSU and MODIS, cloud-top height from AIRS/AMSU, cloud-top temperature from AIRS/AMSU and MODIS, and cloud top pressure, cloud particle phase, cloud effective radius, cloud optical thickness, cloud integrated water path, and effective emissivity from MODIS.

Two key results regarding the Earth's cloud cover obtained through the combination of data from the Aqua MODIS and the Terra MODIS are that: (1) average global cloud coverage is about 67%, and (2) this is equally true of conditions in the early afternoon, as seen from Aqua measurements, and conditions at approximately 10:30 a.m., as seen from Terra measurements [22]. Furthermore, over oceans cloud coverage averages about 72%, with slightly higher Terra values, from about 10:30 a.m., than the early afternoon Aqua values, while over land cloud coverage averages about 55%, with slightly higher values in the early afternoon [22].

The Aqua data are also used to derive rainfall rates, using the passive-microwave AMSR-E measurements (Fig. 5). The AMSR-E rainfall data extend to high latitudes the impressive low-latitude rainfall product from the Tropical Rainfall Measuring Mission (TRMM). Also, by providing critical early-afternoon data for the blended rainfall dataset of the University of Maryland's Cooperative Institute for Climate Studies, they allow improved monitoring of rainfall throughout the course of a day [18].

C. Other Atmospheric Trace Gases

In addition to water vapor, AIRS/AMSU data have been used to calculate and map several other prominent trace gases, including the Earth system's second and third most abundant greenhouse gases, carbon dioxide (CO_2) and methane, respectively, plus ozone, carbon monoxide, and sulfur dioxide. Of these, the CO_2 measurements have generated particular interest.

Despite water vapor's being more abundant, CO_2 is the greenhouse gas most frequently discussed in the context of global warming, the reason being the prominent increase in atmospheric CO_2 in the past two centuries due to human activities. The longest high-quality record of atmospheric CO_2 is from the Mauna Loa Observatory in Hawaii and dates back to late 1957. This record shows a large seasonal cycle in CO_2, with atmospheric CO_2 decreasing during the Northern Hemisphere spring and summer, as plants take in CO_2 for photosynthesis, then rising during the fall and winter. Combined with the seasonal cycle is a prominent and systematic upward trend [20]. The Mauna Loa record has become extremely important—even iconic—in illustrating changes in atmospheric composition over the past half century. It is, however, restricted to a single location.

The first satellite-based global maps of mid-tropospheric CO_2 were derived from the AIRS/AMSU data (e.g., Fig. 6). These maps have been calibrated with in situ data from Mauna Loa and elsewhere and have revealed the CO_2 distributions to be strongly influenced by the mid-latitude jet streams, synoptic weather systems, and the strength of the Northern Hemisphere annular mode [6], [17]. Furthermore, when animated through a several-year period, they give a powerful global depiction of both the seasonal cycle of atmospheric CO_2 and the overall upward trend (animation available at http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003562/index.html).

Interest in AIRS/AMSU maps of atmospheric methane, the third most abundant greenhouse gas, could increase if, as predicted, the north polar region continues to warm and decaying permafrost releases substantial amounts of methane to the atmosphere [51]. AIRS/AMSU ozone retrievals include information on the conditions of the Antarctic ozone hole during polar

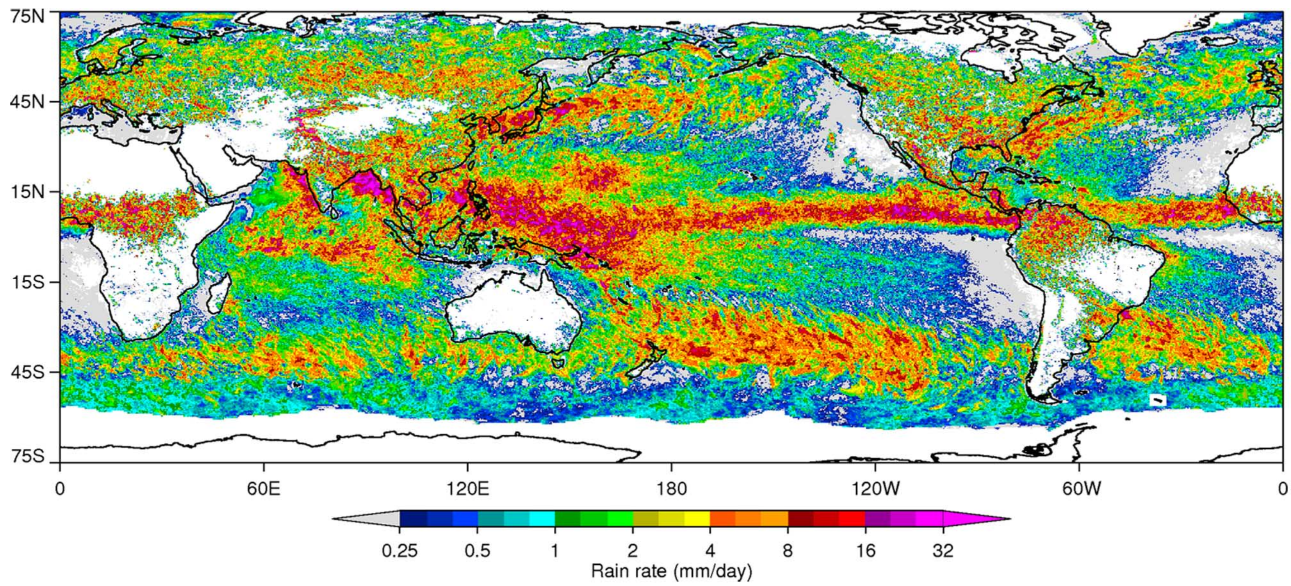

Fig. 5. Average rainfall rates (mm/day) in July 2009, as derived from AMSR-E data. White signifies areas of no rain. (Image from Dave Randel and the AMSR-E Science Team.)

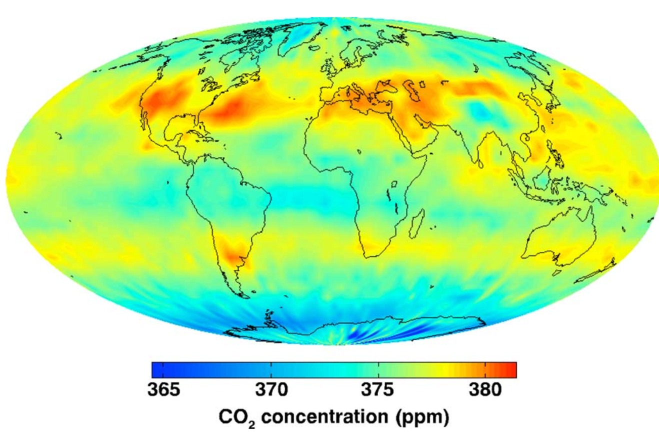

Fig. 6. Mid-tropospheric CO_2 concentrations (ppm) for July 2003, as derived from AIRS/AMSU data. (Image from Moustafa Chahine and the AIRS Science Team.)

night, when information is not available from satellite ultraviolet data, a mainstay of global ozone measurements. Among the results obtained from the AIRS/AMSU ozone retrievals is the finding that intraseasonal ozone variations are tied to the Madden-Julian Oscillation (MJO) [43].

The AIRS/AMSU carbon monoxide product has facilitated the tracking of emissions from fires, including emissions from wildfires (see Section IV-B) and biomass burning [27]. Similarly, the AIRS/AMSU sulfur dioxide product has facilitated the tracking of emissions from volcanoes.

D. Particulate Matter in the Atmosphere

Much (but not all) of the particulate matter in the atmosphere has an effect on the Earth's radiation budget that is opposite to the warming effect of greenhouse gases. The cooling effect from much of the particulate matter is due in part to the fact that particles reflect solar radiation. AIRS/AMSU and MODIS measurements of particulate matter include significant information on volcanic emissions, dust storms (e.g., Fig. 7), fire emissions, and other natural and anthropogenic aerosols.

For two examples, AIRS/AMSU data have led to improved understanding of the impact of the Saharan Air Layer on hurricane formation and intensification [41], and an enhanced MODIS aerosol algorithm called the 'deep-blue algorithm' allows derivation of aerosol properties over bright reflecting surfaces, such as deserts, overcoming a limitation of earlier algorithms that were appropriate only for aerosols above dense vegetation and oceans [14], [25]. Further, the MODIS aerosol products include a distinction between fine particles, which are often associated with anthropogenic sources, and coarse particles, which are more likely to be from natural sources.

MODIS aerosol data have been combined with CERES radiative data to quantify the direct radiative effect of atmospheric aerosols on top-of-the-atmosphere, within-the-atmosphere, and surface radiative fluxes.

CERES data have also been used with aerosol data from CALIPSO, for further examination of the radiative effects that aerosols have. Specifically, in a case study of the influence of African dust and smoke on cloud radiative effects over the tropical Atlantic Ocean, a pronounced effect was found, with absorption by aerosols above the clouds reducing the outgoing shortwave radiation at the top of the atmosphere [49].

E. Ice and Snow

Despite the warming that has occurred during recent decades and centuries, the Earth continues to have a substantial expanse of ice, spreading over approximately 15×10^6 km^2 of land area and approximately 22×10^6 km^2 of ocean area, the latter varying seasonally. In the Northern Hemisphere winter, snow can cover an even greater area of the globe than ice does, although to a far lesser depth.

The expansive global ice and snow covers have major impacts on the Earth's energy budget, being highly reflective of solar radiation and being effective insulators between the ocean

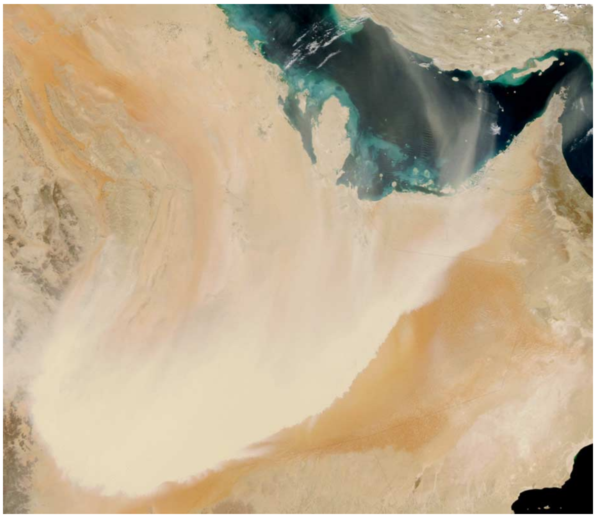

Fig. 7. Aqua MODIS image of a sandstorm over Saudi Arabia and the Persian Gulf on March 26, 2011. (Image from Jeff Schmaltz of the MODIS Rapid Response Team.)

Fig. 8. Arctic sea ice coverage on September 14, 2007, as imaged from AMSR-E data. The September 14, 2007 ice cover was the record minimum for the period of the multi-channel passive-microwave satellite record, starting in late 1978, until August 2012, when a new record was set. Greenland is centered near the top of the image, and an easy route through the Northwest Passage is visible in the right half of the image. (AMSR-E data from JAXA; visualization by the NASA Scientific Visualization Studio.)

or land beneath and the atmosphere above. They also have many practical impacts for humans and other species, for instance hindering ship-based and land-based travel and offering a variety of recreational opportunities.

AMSR-E and MODIS both obtain routine measurements of ice and snow, MODIS with higher spatial resolution and AMSR-E with greater temporal coverage because of being able to obtain measurements under both cloudy and cloud-free conditions and during both darkness and daylight. By taking advantage of the strengths of both instruments, the AMSR-E and MODIS data together can be used to obtain enhanced overall results, for instance more accurate estimates of snow-water equivalent [13].

Despite being coarser resolution than MODIS measurements, AMSR-E all-weather sea ice measurements provide higher resolution than from previous passive-microwave imagers. In fact, the AMSR-E data have sufficient resolution to resolve major leads (approximately linear breaks between ice floes) in the sea ice cover. The high quality of the AMSR-E sea ice measurements have led to their use in studies of the then-record minimum Arctic sea ice extent in 2007 (Fig. 8) [9] and in studies of the large-scale processes governing the seasonal variability of sea ice in the Southern Ocean [21]. Analyses of sea ice concentrations and extents derived from AMSR-E data versus those derived from data from the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSMI) confirm a close match, for both Arctic [8] and Antarctic [33] sea ice.

F. Vegetation and Other Life Forms

MODIS data additionally provide information on land vegetation, ocean vegetation, and select other life forms in the oceans, all of which are critically important to humans both because of their being sources of food and because of their roles in land-based and marine ecosystems. Additionally, vegetation matters to the water cycle and energy budget, for instance through the intake of water and CO_2 for photosynthesis and through its effect on surface reflectance of solar radiation.

MODIS-derived measures of land vegetation include leaf area index, photosynthetically active radiation, evapotranspiration, net and gross primary productivity, and two vegetation indices, the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). The NDVI provides important continuity with long-term measurements from instruments on earlier satellites, particularly the NOAA Advanced Very High Resolution Radiometer (AVHRR), for long-term climate applications, while the EVI (Fig. 9) has enhanced sensitivity in areas of dense vegetation and reduces the effects of canopy and soil variations. The MODIS NDVI and EVI data have been used in global biogeochemical and hydrologic modeling as well as for agricultural monitoring, land cover characterization, and land cover change detection. MODIS products also include a measure regarding vegetation destruction, specifically a measure of biomass burning, which is a process widely recognized as important for its emission of trace gases and particulate matter to the atmosphere and its contributions to radiative forcing [46].

Land vegetation, which uses solar radiation to power photosynthesis, tends to have a different (often lower) albedo than the surrounding ground cover. Hence the presence of vegetation affects the surface reflectivity of solar radiation and thereby the energy budget. In addition to the products already mentioned, MODIS land products include land surface reflectance for individual MODIS bands, corrected for atmospheric influences and used as input for various other MODIS land products [45], and surface albedo [39]. The albedo product is affected by snow and ice (previous section), vegetation (this section), and all other land surface variables. It makes use of high-quality, cloud-free observations from the MODIS instruments on both Aqua and Terra and is now incorporated in various climate models, for its relevance to energy budget considerations [39].

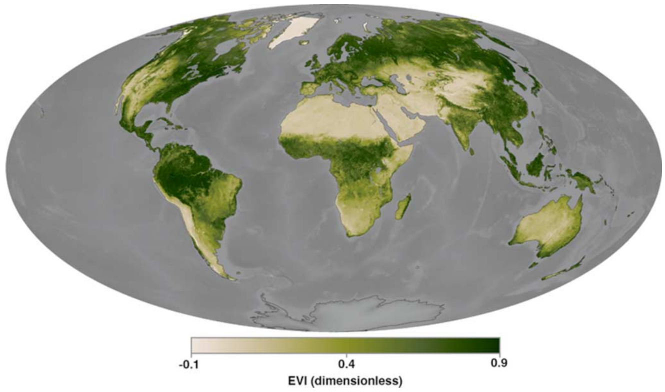

Fig. 9. Global image of the dimensionless Enhanced Vegetation Index (EVI) averaged over the 16-day period August 4–19, 2012, as derived from Aqua MODIS data and clearly showing the Earth's major deserts (including the Sahara, Arabian, and Gobi deserts and desert areas in Australia and the southwestern United States) as low in vegetation and the tropical rainforests as high in vegetation. (Image from Marit Jentoft-Nilsen, based on data from the MODIS Science Team, with relabeling.)

MODIS ocean-color measurements continue the records of chlorophyll-*a* and marine net primary productivity derived from measurements of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), launched in 1997 on the Orbview-2 satellite [31], and also contribute new measurements, most notably of fluorescence. The MODIS 678 nm band was designed specifically to detect the fluorescence signal of chlorophyll-*a*, the main plant pigment involved in photosynthesis. While the chlorophyll-*a* measurements provide an indicator of phytoplankton biomass, the fluorescence data provide the first large-scale, satellite-derived view of the health and physiological stress of ocean phytoplankton [3].

Another example of the use of Aqua MODIS data in studies of marine life is their use in the identification of oceanic blooms of trichodesmium, a species of cyanobacteria that is an important nitrogen fixer and has also been linked to blooms of Kerenia Brevis, a phytoplankton species responsible for many toxic red tides [15]. Interestingly, the trichodesmium identification came about by examining the ocean with two MODIS spectral bands (at 469 and 555 nm) that were originally designed for land and atmosphere observations. MODIS data have also been used in conjunction with data from the Ocean Color Monitor (OCM) on the Indian Oceansat-2 satellite to develop a nitrate algorithm for applications in ocean biogeochemical cycling [38].

G. Temperature

A consequence of all the various energy flows to, from, and within the Earth system is the resultant full-scale temperature structure. Aqua data products include global land surface, sea surface, and atmospheric temperatures.

Prior to the Aqua launch, the single most talked about measurement goal for the Aqua mission was for the AIRS/AMSU sounding system to obtain air temperatures with 1 K accuracy in 1 km layers of the atmosphere [1]. The hope was to obtain radiosonde accuracies from the spacecraft's altitude of 705 km and to do so around the globe, not just at locations with people launching radiosonde balloons. By the time of Aqua's end-of-prime-mission review in 2008, the AIRS Science Team was able to report confidently that this impressive goal had been met.

Land surface temperatures have been derived from AIRS/AMSU and MODIS data; and sea surface temperatures (SSTs) have been derived from AIRS/AMSU, AMSR-E, and MODIS data. MODIS land temperatures have been used to highlight the hottest spot on Earth, with the locations gaining that dubious distinction being in Queensland, Australia in 2003, in the Lut desert of Iran in 2004–2007 and 2009, and in the Turpan Basin of northwestern China in 2008. The highest temperatures in those seven years ranged from 66.8°C in 2008 to 70.7°C in 2005 [28], [29]. For this particular application of examining the highest temperatures, the Aqua MODIS is preferred over the Terra MODIS because the early afternoon timing of the Aqua measurements is close to the timing of when land surface temperatures are typically highest [29].

AMSR-E all-weather surface measurements have provided unprecedented global monitoring of SSTs [7], which, for one example, have been used with AMSR-E ocean surface wind and integrated water vapor measurements to estimate ocean-atmosphere latent heat flux [23]. They have also been used to show large interannual variability in SST, a portion of which is related to El Niño and La Niña events, and to provide data for investigating climate feedback processes [42].

IV. Practical Applications

Although the Aqua mission was developed largely for its scientific value, the Aqua data have proven to be of immense practical value as well. This section discusses several of the practical applications of the Aqua data, beginning with one that affects hundreds of millions of people, namely, weather forecasting.

A. Weather Forecasting

When the AIRS instrument was conceived and developed, one of the primary goals for it was to facilitate improved weather forecasts. As anticipated well before launch, the high accuracies of the AIRS/AMSU temperature and water vapor products (Sections III-B and III-G) have led to measurable improvements in forecast skill when these data are incorporated in weather forecast models [4]. As a result, NOAA and other weather forecasting agencies in North America and in Europe, Asia, Africa, Australia, and South America routinely use at least some of the AIRS data in their forecast models. Some of these agencies, however, use only clear-sky radiances; studies have shown that some forecasts could be improved even further with assimilation of more of the AIRS data [36].

Although less anticipated, MODIS and AMSR-E data have also proven valuable for forecasts. Specifically, incorporation of MODIS-derived polar winds in weather forecast models has resulted in improved forecasts for the polar regions and beyond [24], [37], and AMSR-E sea surface temperature, water vapor, and precipitation data have all been used by hurricane prediction centers. The Japan Meteorological Agency (JMA) has found that assimilation of AMSR-E data has improved the skill of the JMA forecasts of hurricane tracks. Further, the Joint Center for Satellite Data Assimilation has reported that assimilation of AMSR-E radiances over the oceans improves medium-range

Fig. 10. Aqua MODIS image of forest fires in Oregon, in the northwest United States, on August 12, 2002. Such images assist forest services in monitoring forest fires and determining the appropriate deployment of fire fighters.

forecasts in the Southern Hemisphere, although shows neutral impacts for the Northern Hemisphere [30].

The usage of Aqua data in weather forecasts is greatly facilitated by two important services. One is NOAA's National Environmental Satellite, Data, and Information Service (NESDIS), which distributes the AIRS radiance data in near real time. The other is a software package—the International MODIS/AIRS Processing Package (IMAPP)—made available by the University of Wisconsin's Cooperative Institute for Meteorological Satellite Studies (CIMSS). IMAPP converts direct broadcast data from Aqua and Terra into a suite of geophysical data products from the MODIS, AIRS, AMSU, and AMSR-E instruments. This IMAPP software is used not only by weather agencies to support weather forecasting but also for the fog detection and snow/ice/cloud discrimination provided by the MODIS products.

B. Other Practical Applications

The United States Forest Service and other forest services around the world have frequently used MODIS data from the Aqua and Terra satellites to monitor forest fires and assist in the decision of where to deploy fire fighters (Fig. 10). AIRS/AMSU carbon monoxide data have also been useful in monitoring fires, as fires are a major source of carbon monoxide in the atmosphere. For instance, the AIRS/AMSU carbon monoxide data were in demand in July and August 2010 for their depiction of the extent and distribution of a rash of several hundred wildfires that broke out across Russia during the unusually hot and dry summer of 2010.

In another important application of Aqua data, airplane pilots and aviation administrations have used AIRS/AMSU and MODIS data to monitor volcanic emissions and help steer planes clear of volcanic ash [5]. This received particular media attention in spring 2010, when an eruption of the Eyjafjallajökull volcano in Iceland disrupted air traffic to, from, and within Europe, with a large number of flights cancelled particularly in the period April 15–20, 2010. During this period, the AIRS/AMSU and MODIS data were used not only by air traffic controllers but also by the media reporting on the distribution of the emissions.

Among the many other practical applications of the Aqua data, many greatly facilitated by Aqua's direct broadcast capability, are the following: the use of MODIS data by the Environmental Protection Agency for air-quality analyses; the use of CERES data by utility companies in neural network load forecasting tools, for improved energy management; the use of AMSR-E SST data by the Japanese fishing industry in their analyses of local and regional fishing conditions; the use of AMSR-E and MODIS data for monitoring floods and their aftermath; the use of MODIS data for monitoring oil spills and dust storms, including the oil spill from the April 20, 2010 explosion of the Deepwater Horizon drilling rig in the Gulf of Mexico; and the use of AMSR-E and MODIS data for sea ice monitoring by ships maneuvering in polar oceans.

V. Conclusions and Discussion

With well over 2,000 scientific papers having been published using Aqua data, neither this nor any other short summary can include more than a small sampling of the results obtained so far from the Aqua mission. Nonetheless, the sampling presented here illustrates that the Aqua data have proven valuable for a wide variety of scientific studies and many practical applications. More information can be found at the Aqua website http://aqua.nasa.gov and the many links provided therein.

All instruments on Aqua are now well beyond their design lifetimes. However, the continued strong performance of AIRS, MODIS, CERES, and to a lesser extent AMSU, suggests that some or all of these instruments might last many additional years (see the final paragraph of Section II for the current status of each instrument as of late 2012). The same is true of the Aqua spacecraft itself, which has performed almost flawlessly since launch. Further, there is enough fuel on board to last into the 2020s, with approximately half of the initial 225 kg of fuel remaining. Fuel projections are based on anticipated fuel usages for inclination adjust maneuvers, to maintain Aqua at its desired 1:30 a.m. and 1:30 p.m. equatorial crossing times, and for drag-makeup maneuvers, to maintain the altitude (705 km) and ground track requirements. The remaining fuel is expected to suffice at least until 2022, barring an excessive number of unanticipated maneuvers, for instance for avoiding space debris.

The hope is that even after the eventual demise of the Aqua spacecraft, many of the Earth system data records from Aqua will be continued through instruments on other satellites. The AMSR-E records are already being continued through AMSR-2 on Shizuku, and AMSU and HSB instruments have a long and continuing history on NOAA satellites (as AMSU-A and AMSU-B). The Suomi NPP, launched in 2011, carries not only a CERES instrument (as mentioned in Section II) but also the Advanced Technology Microwave Sounder (ATMS), the Cross-track Infrared Sounder (CrIS), the Ozone Mapping and Profiler Suite (OMPS), and the Visible Infrared Imaging

Radiometer Suite (VIIRS). Further, JPSS, with an anticipated launch in 2016, is also expected to have on board ATMS, CERES, CrIS, OMPS, and VIIRS instruments. VIIRS is a 22-band radiometer able to extend many of the MODIS records, and CrIS and ATMS should be able to extend many of the AIRS/AMSU records.

For some variables, Aqua measurements can inform planning for improved measurements on future missions, a primary example being the case of soil moisture, a variable with critical roles in vegetation growth and in water and energy budgets. Valuable soil-moisture information has been obtained from Aqua's AMSR-E instrument, especially in regions with low or no vegetation and without a snow or ice cover [16], [50], but neither AMSR-E nor any of the other Aqua instruments have channels specifically tuned to soil moisture detection. In contrast, NASA's upcoming Soil Moisture Active Passive (SMAP) mission, scheduled for launch in late 2014, will have an L-band radar and an L-band radiometer developed explicitly for soil-moisture monitoring. It is anticipated that SMAP will enable accurate monitoring of soil moisture through low and moderate vegetation and irrespective of cloud cover or day/night conditions. SMAP illustrates the continuing advances in capabilities of observing an ever greater portion of the Earth system from the vantage of space.

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