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Editor's Corner

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I am happy to report that the Jason-3 satellite successfully launched on January 17, 2016 at 10:42 AM Pacific Standard Time from Vandenberg Air Force Base in California onboard a Space-X Falcon 9 rocket. Minutes after Jason-3 separated from the rocket's second stage, the spacecraft unfolded its twin sets of solar arrays and ground controllers successfully acquired the spacecraft's signal. All indications are that the satellite is in good health.

Jason-3 will extend the multidecadal time-series of sea surface height measurements began by TOPEX/Poseidon [1992–2005] and continued with the Jason-1 [2001–2013] and OSTM/Jason-2 [2008–present] missions. Knowledge of ocean surface topography provides scientists with crucial information about ocean currents, interannual phenomena (e.g., El Niño Southern Oscillation), global and regional changes in sea level, and their climate implications for a warming world.

Jason-3 will have a period of overlap with the ongoing Jason-2 mission. Such measurement overlap is highly desirable to help ensure the continuity of long-term satellite records of climate variables. Jason-3 entered orbit

continued on page 2

A SpaceX Falcon 9 rocket carrying the U.S.-European Jason-3 satellite launches from Vandenberg Air Force Base Space Launch Complex 4 East on January 17, 2016. Jason-3, an international mission with NASA participation, will continue a 23-year record of monitoring global sea level rise. **Image credit:** NASA/Bill Ingalls

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In This Issue

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about 25 km (16 mi) below Jason-2. Over the next month, the new spacecraft will gradually raise itself into the same 1336-km (830-mi) orbit and position itself to follow somewhere between 1 and 10 minutes behind Jason-2's ground track. The two spacecraft will then fly in formation, making nearly simultaneous measurements, for about six months to allow scientists to precisely calibrate Jason-3's instruments.

The primary instrument on Jason-3 is a radar altimeter—essentially an identical copy of the instrument that flew on Jason-2—that will measure sea-level variations over the global ocean with very high accuracy. Scientists and operational agencies (e.g., NOAA, European weather agencies, marine operators) will use the data for a variety of scientific research topics and operational oceanography applications that benefit society.

Both TOPEX/Poseidon and Jason-1 were cooperative missions between NASA and CNES. Additional partners in the Jason-2 mission included NOAA and EUMETSAT. Jason-3 continues the international cooperation, with NOAA and EUMETSAT leading the efforts, along with partners NASA and CNES. More information about Jason-3 can be found at *sealevel.jpl.nasa.gov/missions/jason3*.

In other news, January 10, 2016, marked the one-year anniversary of the launch of the Cloud–Aerosol Transport System (CATS) that flies on the International Space Station. (February 12 marked the one-year anniversary for science operation.) Data users, especially those seeking to use CATS data to improve aerosol modeling forecasts (e.g., Air Force, GMAO, NRL) are beginning to ingest and interpret the CATS profile data. The volume of CATS data now collected are sufficient to allow researchers to begin statistical studies of cloud and aerosol coverage.

The CATS team has implemented a new feature on their webpage (*cats.gsfc.nasa.gov*), called *Image of the Week*. The aim is to show some interesting image or science result each week. Level 1 data products are available from the ASDC DAAC (follow links on the CATS web page), and the team has a goal of releasing Level-2 data products by March 1.

On December 23, 2015, the CLARREO Team received notification of an FY16 appropriation to begin the CLARREO Pathfinder project. The CLARREO Team includes scientists from LaRC, GSFC, JPL, seven universities, and other government partners (e.g., NIST). The objective of the CLARREO

Pathfinder project is to demonstrate essential measurement technologies of the CLARREO mission[1] via the International Space Station. The CLARREO Team has begun to refine high-level project plans and budget profiles for the CLARREO Pathfinder mission with NASA Headquarters and the Earth Systematic Missions Program Office. A CLARREO Pathfinder project execution team has been identified and is currently in formation.

In our last issue, we reported that November 21, 2015, marked the fifteenth anniversary of the launch of the Earth Observing-1 (EO-1) mission, which began as a sensor and spacecraft bus technology testbed in support of NASA's New Millennium Program, but evolved into much more. Following the 2015 Earth Science Senior Review, it was decided that in October 2016, EO-1 will end its run after nearly 16 years. While the decision is bittersweet, the entire EO-1 team should be immensely proud of their accomplishments. EO-1's hardware was innovative—the Advanced Land Imager (ALI) multispectral instrument was the prototype for Landsat 8's Operational Land Imager (OLI) instrument, and Hyperion was the first civilian hyperspectral instrument in orbit. Lessons learned from the instruments onboard EO-1 are being incorporated into the planning for and design of the proposed Hyperspectral Infrared Imager (HyspIRI) mission, which includes a scanning visible-to-shortwave infrared imaging spectrometer. Turn to page 23 to read a summary of the most recent HyspIRI Science and Applications Workshop.

Over the years, EO-1 moved far beyond its initial testbed status, taking on additional tasks and duties—all the while performing beyond design expectations. The satellite is a leader in acquiring quick-response disaster imagery around the globe. It was used to test the concept of *SensorWebs*, where independent sensors can trigger satellite image acquisitions. Hyperion and ALI have taken images all over the world, amassing a library of over 165,000 images, including time-series over many calibration sites. Turn to page 4 to read more about the remarkable EO-1 mission.

[1] The National Research Councils's *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (2007), a.k.a., the "2007 Earth Science Decadal Survey", identified CLARREO as a *Tier 1* (highest priority) mission. The report can be found at *nap.edu/catalog/11820/earth-science-and-applications-from-space-national-imperatives-for-the.*

Since it launched in 2003, NASA's SORCE mission has advanced our understanding of the total and spectral solar irradiance while maintaining continuity of solar climate data records from space that were initiated in the late 1970s. In an effort to continue this crucial long-term time series without interruption, the 2015 Earth Science Senior Review approved the extension of the SORCE mission to 2018 to allow overlap with the NASA Total and Spectral Solar Irradiance Sensor (TSIS-1) that is scheduled for deployment on the International Space Station in late 2017. SORCE instruments now make routine measurements in a daytime-only operations mode in order to compensate for reduced battery capacity. SORCE continues to function well and has far exceeded its planned mission. However, in the event the venerable mission must end prior to the launch of TSIS-1, there is a "backup" to insure continuity in the total solar irradiance (TSI) calibration scale between SORCE and TSIS. The Joint Polar Satellite System (JPSS) TSI Calibration Transfer Experiment (TCTE) was launched onboard the U.S. Air Force Space Test Program Satellite-3 (STPSat-3) in 2013. TCTE has been extended to 2017 in order to overlap with TSIS. On page 29 of this issue we report on the November 2015 Sun-Climate Symposium on multi-decadal variations in the Sun and Earth during the space era. Over 80 scientists and students from around the world gathered in Savannah, GA to discuss a broad range of topics related to solar variability and climate change. Observations from SORCE were highlighted in many of the presentations.

For more than 10 years, the Science Program Support Office (SPSO) at GSFC has organized and supported the NASA exhibit at the American Geophysical Union (AGU) Fall Meeting. For the last few years, the SPSO has also organized and hosted a one-day Annual Communication Meeting the weekend before the start of AGU. Even in an era of near instantaneous communication via the Internet and social media, there is still value in face-to-face contact. The annual communication meeting provides such an opportunity for the NASA outreach community, which includes management, public engagement personnel, and the like from several NASA centers. On page 20 of this issue, we provide a glimpse of what took place at the Annual Communication Meeting along with details about recent NASA exhibits at AGU, GEO-XII, and COP-21. ■

Note: List of undefined acronyms from the *Editor's Corner* and the *Table of Contents* can be found on **page 41**.

EO-1: 15 Years After the Start of Its "One-Year Mission"

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Introduction

Originally planned as a "one-year mission," NASA's Earth Observing-1 (EO-1) satellite celebrated the fifteenth anniversary of its launch on November 21, 2015. EO-1 was originally a technology testbed satellite, built quickly and inexpensively. EO-1 is finally heading for the end of its mission, which is projected for October 2016. While the platform and its instruments are operating well, fuel reserves have been exhausted and the satellite has lost its orbital maintenance ability. The impressive milestone of reaching its 15-year anniversary, coupled with the impending end of the mission, provides an excellent time to review EO-1's origins and goals, its expanded mission, and the utility of the data acquired so far. For more specific details on EO-1, visit *eo1.gsfc.nasa.gov*.

EO-1's Beginnings—NASA's New Millennium Program

The story of EO-1 begins with the Land Remote Sensing Policy Act of 1992, which required NASA to continue collecting Landsat data through the use of two technologies: *multispectral imaging* for "traditional" Landsat end-users, and *hyperspectral imaging* for Landsat's research data users (with a requirement for backward compatibility with older Landsat images). The differences in these types of sensors are shown in **Figure 1**, which compares the spectral coverage of multi- and hyperspectral imagers in the visible through shortwave infrared wavelengths.

In 1995 NASA recognized that more-complex space missions would require increasing levels of technology development. Rather than attempt to implement cutting-edge technologies in the new missions themselves, NASA's Office of Space Science and the

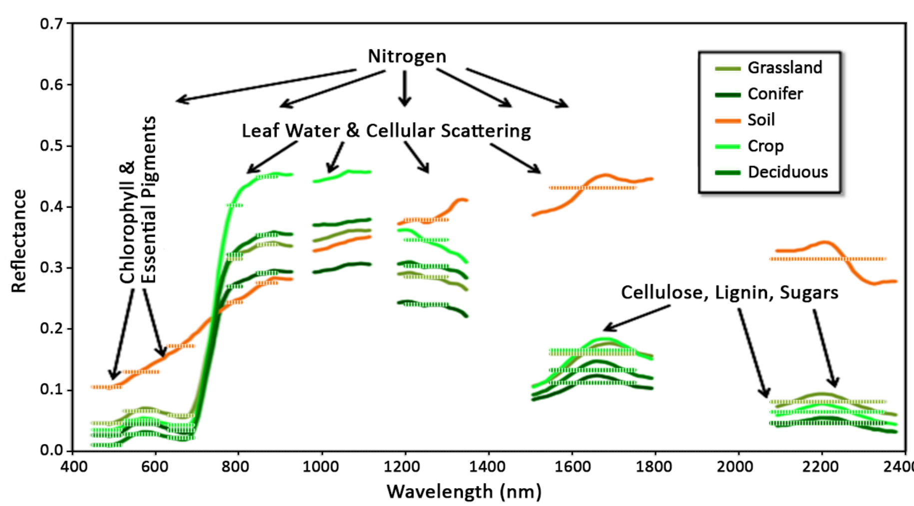

Figure 1. The horizontal lines indicate the spectral coverage of EO-1's multispectral Advanced Land Imager (ALI) instrument, which samples selected regions of the electromagnetic spectrum like Landsat 7 and 8. The smooth curves show the spectral coverage of the imaging spectrometer Hyperion, which acquires images over the visible-to-shortwave-infrared spectrum (0.4-2.5 μm). The gaps are due to atmospheric absorption. The arrows indicate the sections of the spectra where the listed biological features can be detected. **Image credit:** K. Fred Huemmrich

Office of Earth Science established the New Millennium Program (NMP[1]). The NMP was to act as a real-world, space-based testbed for new technologies before their use in large-scale space missions. These technologies focused on autonomous activity, higher data communication rates, reduced size, reduced power use, reduced number of moving parts, and significant cost reductions.

In keeping with the goals of the NMP, the EO-1 mission was designed to extend the technology of Landsat 7 while reducing cost and power usage. New technologies were designed for data correction, calibration, formation flying with other satellites, inter-satellite and lunar calibration, atmospheric correction, and autonomous navigation and instrument operation. In 1996 an NMP technology team recommended that a test hyperspectral imager be flown as a possible prototype for future Landsat missions, which led to the rapid development and launch of the Lewis hyperspectral satellite in August 1997[2]. Unfortunately however, just one month after launch, the satellite spun out of control and reentered the atmosphere. After that, the proposed NMP hyperspectral imager became a priority. Massachusetts Institute of Technology (MIT)'s Lincoln Laboratory had developed hyperspectral add-ons for EO-1, but they ran into technical problems. The decision was therefore made to switch EO-1 to a TRW[3]-proposed hyperspectral imager that could be built quickly, as it was based on a design modified from the Lewis mission. This new imager, Hyperion, was merged into the EO-1 design and constructed in nine months.

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The Baseline EO-1 Mission

The final EO-1 design included a Landsat-like multispectral imager, a hyperspectral imager, a radiometric calibration testbed to improve radiometric accuracy, an atmospheric correction sensor, and a number of advancements in the spacecraft bus. This assemblage was all testbed hardware, so without EO-1 these designs would not have flown in space for many years.

Advanced Land Imager

The Advanced Land Imager (ALI) is a follow-on to Landsat 7's multispectral Enhanced Thematic Mapper Plus (ETM+) imager. The instrument is based on sequential-sampling pushbroom detector technology (i.e., scans along the line of flight), with a wide-field (15°) silicon carbide telescope that has one-fifth of the field-of-regard of Landsat, providing a 37-km (~23-mi) ground swath. ALI acquires data in nine multispectral bands [six in the visible/near infrared (VNIR) and three in the shortwave infrared (SWIR)], with 30-m (~98-ft) spatial resolution (matching the spatial resolution of ETM+) and one panchromatic band with 10-m (~33-ft) resolution for image sharpening. ALI is 25% of the mass, uses 20% of the power, and takes up 14% of the volume of ETM+, with an increase in instrument performance. Unlike the ETM+, however, ALI has no thermal infrared band.

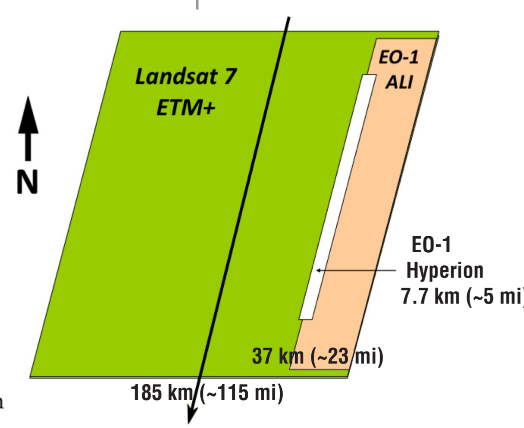

Figure 2. EO-1's ground footprint (ALI and Hyperion) as compared to that of ETM+ on Landsat 7. **Image credit:** NASA

Hyperion

Hyperion is an imaging spectrometer providing 30-m (~98-ft) spatial resolution (like Landsat and ALI) and 10-nm (0.010 μm) spectral resolution across 242 contiguous channels that cover the spectral range from 0.400 to 2.500 μm, with a 7.5-km (~5-mi) wide swath. It uses convex grating spectrometers with a charge-coupled-device (CCD) detector for VNIR data and a mercury-cadmium-tellurium (Hg-Cd-Te) detector for SWIR acquisitions. Pixels in Hyperion's field-of-view are coregistered with those of ALI for full-spectrum cross-calibration of Earth scenes, in their common 7-km (~4-mi) swath region—see **Figure 2**.

[1] For more on the New Millennium Program, visit *nmp.jpl.nasa.gov*.
[2] Named after the nineteenth century U.S. explorer Meriwether Lewis, the mission was developed under Mission to Planet Earth's Small Satellite Technology Initiative.
[3] TRW is a major aerospace company; the abbreviation is a truncation of the last names of its founders: Thompson, Ramo, and Wooldridge.

Linear Etalon Imaging Spectrometer Array Atmospheric Corrector

The Linear Etalon Imaging Spectrometer Array (LEISA) Atmospheric Corrector (LAC) was included in EO-1 to test the idea of using dedicated hardware for atmospheric correction of images. The LAC uses wedge-filter technology to provide high-resolution spectral coverage at the full Landsat swath width of 185 km (~115 mi). After the mission check-out period in 2001, the LAC was not used due to performance problems.

Spacecraft Bus

EO-1 includes a single, lightweight, high-output, articulating solar array feeding power into a rechargeable super nickel-cadmium battery. Onboard hardware provides almost 50 gigabits of data storage using a solid-state, high-throughput (400 Mbps) Wideband Advanced Recorder and Processor (WARP). Spacecraft-to-ground data transfer is *via* a high-data-rate (105 Mbps) X-band phased array antenna, which eliminates deployable structures, associated moving parts, and torque-generating displacements. Early in the mission, the EO-1 team experimented with a pulse plasma thruster for satellite orientation during the initial phase of the mission, but ultimately they opted not to use it due to the possibility of the plasma thrust contaminating the instrument optics.

The One-Year Mission (November 2000 to 2001)

On November 21, 2000, EO-1 was launched on a Boeing Delta II vehicle from Vandenberg Air Force Base in California. Unlike the NASA/U.S. Geological Survey (USGS) Landsat missions and NASA's Terra and Aqua platforms, EO-1 has no requirement or data storage for continuous global coverage. Rather, EO-1 is a "tasked" satellite, where the instruments point toward targets to collect individual images along the orbit. It is a polar orbiter, following a descending, north-to-south path during daylight with an original equatorial overpass time of 10:00 AM, and ascending at night when hot/bright targets can be imaged. The instruments are *nadir-viewing*, meaning they point straight down, and can be reoriented to point east or west by up to two ground tracks [over 500 km (~310 mi) on the ground]. As a testbed mission, EO-1 originally had a small data archive system, and data product distribution was limited to NASA researchers and collaborators.

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After launch, EO-1 was placed in a 705-km (~438-mi) circular, sun-synchronous orbit at an inclination of 98.2°, and operated as part of NASA's Morning Constellation. It flew one minute "behind" Landsat 7 and one minute "ahead" of Terra—see **Figure 3**. This configuration allowed all three satellites to view the same

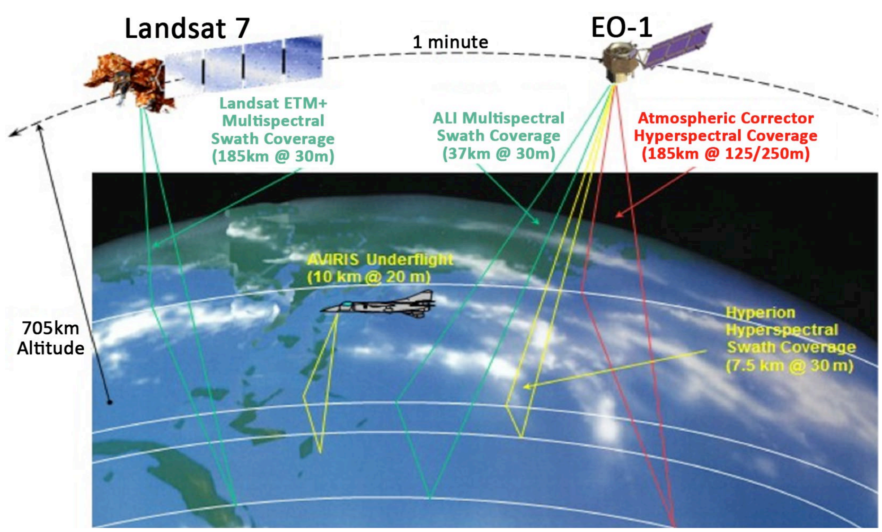

Figure 3. Representation of Landsat 7 and EO-1 formation flying in the Morning Constellation. Also shown are the relative swath widths, including that of the airborne Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) instrument. **Image credit:** NASA

area on Earth's surface in near-synchronous mode, thereby allowing comparison and cross-calibration of terrestrial phenomena.

In 1999 **Stephen J. Ungar** [GSFC], the EO-1 Mission Scientist, created the EO-1 Science Validation Team, responsible for validating the instruments and technologies on EO-1. There were concerns that something on the satellite might fail quickly, so ground validation was planned for the first months after launch, giving this phase the nickname "accelerated mission." One month after launch, a joint validation activity in Argentina with the the Argentine Space Agency [Comisión Nacional de Actividades Espaciales (CONAE)], began with ground teams taking measurements while a de Havilland Canada DHC-6 Twin Otter aircraft flew overhead, carrying the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), the data from which could be compared to Hyperion. The Australians were also involved in the EO-1 validation effort. They coordinated with the Science Validation Team and took ground measurements at a variety of sites across Australia with corresponding EO-1 overpasses.

By all metrics, the initial one-year mission of EO-1 was a success. From the forward-looking concepts for new technologies—both sensor and spacecraft—and the implementation of applications in hardware and software, EO-1 exceeded every expectation.

Findings of the Initial Mission

After analysis of the ground validation data, ALI's advanced SWIR and VNIR technology was able to identify crop and forest species, classify coastal regions, and provide aerosol characterizations. ALI demonstrated the utility of pushbroom detector technology, and showed significant improvement over ETM+ because of the additional bands, increased dynamic range, and higher signal-to-noise ratio (SNR). Hyperion showed that a spaceborne hyperspectral imaging spectrometer has significant utility in identifying many ecosystem components such as vegetation species, canopy nitrogen concentrations, allocation of total carbon in both live and dead biomass, and in detecting drought stress. On the thermal side, Hyperion was able to resolve and map the temperatures of active lava flows and forest fire hot spots and determine fuel types with extremely high accuracy. In general, as compared with ALI and ETM+, Hyperion's performance showed better land-type and -use classification, better detection of invasive species, and better discrimination for geological mapping, including hydrothermal rock alteration.

All of the spacecraft's technologies showed clear benefits for future missions. Specifically, the high-data-rate antenna and solid-state recorder were shown to be viable and valuable, as were error detection and correction hardware. Autonomous formation was clearly useful for satellite constellations, and station-keeping *via* the pulsed plasma thruster was shown to be viable. Especially vital to longer-term use and wide distribution of the data was the reduction in the cost of imagery from $7500 per scene in the mission's first month to $1100 by the sixteenth month. This cost reduction was due to new technologies and ongoing improvements in operations. Over the same period, EO-1 data were collected at a rate four times faster than at the outset.

Judging the Success of the Initial Mission

By all metrics, the initial one-year mission of EO-1 was a success. From the forward-looking concepts for new technologies—both sensor and spacecraft—to the implementation of applications in hardware and software, EO-1 exceeded every expectation. It is to the full credit of the planners and designers that the return on investment on EO-1 has been so high, and its technological achievements are still being used in the design of current and new missions. A summary of EO-1 "firsts" is found in the **Table** on page 8.

Table. List of EO-1 "firsts".

Hyperion was first to:

- acquire hyperspectral observations of Earth with Landsat spatial resolution (30 m) and AVIRIS spectral resolution (10 nm) over the entire Landsat reflective range;
- demonstrate that spaceborne hyperspectral sensors can identify and map vegetation species (including invasive species), canopy nitrogen concentrations, and minerals;
- track regrowth in partially logged Amazon forests and reliably estimate Amazon forest drought stress;
- accurately map and characterize temperature distributions of active lava flows and forest-fire "hot spots" from space;
- map several fire fuel classes from space at very high accuracies, including senesced grass and soil;
- separate total carbon into living biomass, dead biomass, and soil background with high accuracy; and
- perform hyperspectral lunar and solar calibration.

ALI (relative to Landsat) was first to:

- demonstrate sequentially sampled pushbroom detector array technology;
- provide superior signal-to-noise (SNR) ratio and 12-bit analog-to-digital conversion to capture the full dynamic range of Earth imagery;
- provide panchromatic-band-enhanced imagery of exceptional quality;
- provide an additional shortwave infrared band (Band 5p; 1.200-1.300 µm) to supply new information for identifying forest and crop types;
- provide an additional visible/near infrared blue band (1p; 0.433-0.453 µm) to supply new information for coastal studies and aerosol estimation; and
- provide improved SNR to track subtle changes in ice sheet flow velocities.

EO-1 Mission was first to:

- reduce cost of imagery 7-fold in the first 16 months of operation;
- generate a comprehensive spaceborne hyperspectral imagery archive;
- implement an onboard cloud detection algorithm;
- demonstrate use of onboard autonomy and autonomous ground coordination to enable SensorWeb capabilities;
- experiment with adaptive algorithms coupled to a low-cost, ground-based scanning antenna array to dramatically lower the cost of communicating with low-Earth-orbiting satellites;
- use onboard feature detection to autonomously modify onboard imagery tasking decisions; and
- get a waiver from NASA to continue operations after fuel exhaustion in order to study the effects of orbital precession on image data.

The EO-1 Spacecraft Bus was first to:

- use a high-data-rate (105 Mbps), electronically steerable antenna at X-band frequency;
- use a high-data-rate, solid-state recorder (> 1 Gbps);
- use Reed-Solomon error detection and correction chip that operates at 1 Gbps;
- validate nonlinear autonomous formation flying and the use of fuzzy logic software;
- use a pulsed plasma thruster as precision attitude control actuator;
- use a shape memory alloy for system hinge and deployment mechanisms; and
- use a panel with carbon-carbon facesheet material to act both as a radiator and as part of the spacecraft's primary structure.

The Extended Mission (2002-2008)

The original plan was to shut down EO-1 after 12 to 18 months of operation, as it was expected that by that time, *something* would have broken down. Yet, with the exception of the LAC, the satellite continued to operate flawlessly, even though there was only a shoestring budget to continue the mission. Several strategies were used to supplement the budget to keep the satellite operating. EO-1 management approached the U.S. Air Force and the National Reconnaissance Office (NRO) about the possibility of taking over control of EO-1. This did not happen because the data stream from the satellite was not secure, but NRO did agree to purchase over 1000 EO-1 scenes, thereby giving the mission a small additional revenue stream. NASA's Earth Science Mission Operations (ESMO) Project agreed to download data from the EO-1 satellite for free, using any excess capacity in their ground station links (i.e., taking advantage of unused time allocated to Aqua). To further save money, the USGS took over processing and archiving of EO-1 data.

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With entry into this Extended Mission phase, EO-1 data were now made available to individuals and organizations outside those originally charged with mission activities. Even public requests for the imaging of specific ground targets were allowed. The USGS created and distributed standardized data products—but only to authorized users. Beginning in 2002, EO-1 began to host other research efforts, totaling more than $15 million over the next 13 years. These efforts included:

- the Autonomous Science Experiment (ASE), which created "onboard intelligence" and allowed EO-1 to perform onboard science processing, respond to user goals, and make independent decisions on actions that the satellite would perform;
- testing Livingstone[4] onboard model-based diagnostic software to track the satellite's health;
- developing the Delay Tolerant Network (DTN[5]) using EO-1 as one of multiple in-orbit nodes, lowering the risk of data being lost as it is downloaded from space; and
- conducting seven different Advanced Information System Technology (AIST) projects, which would later result in Earth Science Technology Office (ESTO) awards on various SensorWeb topics (described in the next section).

The EO-1 team conducted experiments in accelerating onboard science data processing using various parallel processing techniques and advanced processing. One set of experiments showed that Landsat *multispectral spectral bands*[6] could be synthesized from Hyperion's hyperspectral images, paving the way for the creation of future multimission satellites that could produce a wide variety of image products, including Landsat-like multispectral images.

In 2004 a devoted EO-1 Special Issue was published by Institute of Electrical and Electronics Engineer's *Transactions on Geoscience and Remote Sensing*, which provided 27 papers that addressed EO-1's scientific and technical achievements from the early-mission years.

SensorWeb Testbed

Another achievement of the Extended Mission was the development of *SensorWebs*, which provide the ability to create combined data products from multiple sensors, as observations by one sensor are used to trigger observations by another. Starting in 2003 EO-1 became a SensorWeb testbed. This enabled research in combining satellite

[4] For more information on Livingstone, visit *www.nasa.gov/centers/ames/research/technology-onepagers/livingstone2-modelbased.html*.
[5] For additional information on the DTN, visit *www.nasa.gov/content/disruption-tolerant-networking/#.VmXl9riDGko*.
[6] *Multispectal spectral bands* were created by averaging the hyperspectral bands that lay within each ETM+ band.

sensors with airborne and ground sensors to create better coverage and faster response to disasters. The ability to detect the presence of clouds and other potential problems (e.g., snow, ice, sand) was of key value, as this allowed the system to automatically update the satellite acquisition to a later time when conditions were forecast to improve. These technologies were applied to various disasters, and data products were rapidly and automatically created to assist disaster responders. The team's first experiments were conducted with the U.S. Forest Service to provide situational awareness data products to assist in wildfire response.

Another key result of SensorWeb was EO-1's transformation into an automated mission. Advanced users were able to task EO-1 to collect images and automatically receive additional data products (such as a fire or flood map). The combination of onboard flight software and Web-based automation with Open Geospatial Consortium (OGC) SensorWeb Enablement (SWE) standards and social media created a user-driven system focused on data products. SensorWeb components hide the details of tasking the satellite and multiple data processing steps, enabling users to easily acquire and create data products for decision support.

The New Mission (2008 onward)

In 2005 NASA created the Senior Review process for Earth-observing satellite missions that had gone past their baseline budgets, to decide which to fund for continued operations. The EO-1 team submitted a proposal that resulted in an increase in funding. The Senior Review panel also stated that EO-1 was being vastly underutilized by the scientific community due to project underfunding and the high cost of purchasing scenes.

In 2008 **Elizabeth "Betsy" Middleton** became the EO-1 Mission Scientist—replacing Stephen Ungar. Under Middleton's leadership, time-series data acquisitions became a priority, with repetitive Hyperion collections over science validation sites (e.g., CO_2, energy exchange flux networks) and calibration sites. Middleton also pushed for producing prototype atmospheric correction routines using Hyperion's own spectral atmospheric features and standard algorithms, including standard data products to increase the user base.

In 2009, with Landsat 7 having inflight technical problems and the delayed building of the Landsat Data Continuity Mission (now named Landsat 8), EO-1 was given a specific task of taking Landsat-style images all around the globe. This would "fill in" the Landsat data archive until Landsat 8 could be launched.

Figure 4. An ALI image of Maupiti Island in the South Pacific Ocean. **Image credit:** NASA's Earth Observatory

In 2009, with Landsat 7 having inflight technical problems and the delayed building of the Landsat Data Continuity Mission (now named Landsat 8), EO-1 was given a specific task of taking Landsat-style images all around the globe. This would "fill in" the Landsat data archive until Landsat 8 could be launched. But EO-1 had never been an operational satellite with a data system for processing images, nor did it provide fixed products created from those images. The new budget did not allow these systems to be created, but it did allow for increased software development for faster image processing, and the implementation of ground systems that streamlined image scheduling and downlinking.

While Landsat collects continuous images over land, it does not image over the ocean. Therefore, many small islands had never been imaged at 30-m resolution. For the 2005 and 2010 Global Land Surveys (GLS[7]), EO-1 was tasked with taking images of many islands in the Pacific Ocean—see example in **Figure 4**. These were often the first detailed space-based images of these locations.

At the end of 2001 each EO-1 scene cost consumers $1100. By 2009 the price had dropped to $750—but that cost still limited access by agencies and academia, especially those interested in doing analysis of multiple images. In 2009 all of the EO-1 data were made available through USGS at no cost to the user. After that, in 2010 the

[7] For more on GLS, visit *lta.cr.usgs.gov/GLS.*

downloads of EO-1 data spiked and the data have remained very popular with scientific researchers ever since—see **Figure 5**.

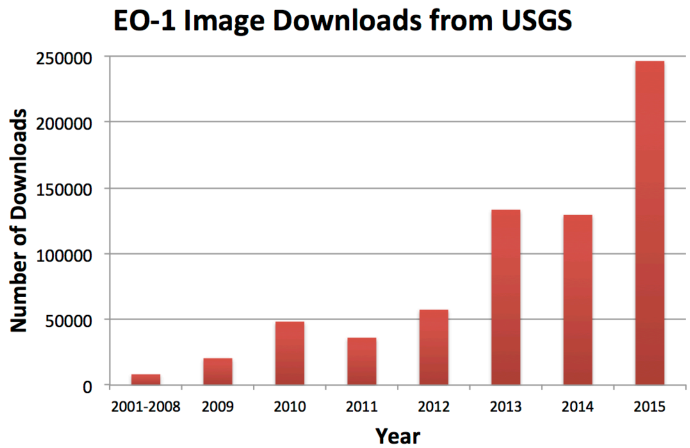

Figure 5. The number of EO-1 images downloaded through USGS. Note the spike in usage in 2010 after the EO-1 data became free to use in 2009. **Image credit**: USGS

Since EO-1 is a pointable satellite and not taking continuous images of the ground, the satellite has become a favorite for rapid-delivery of disaster images. Using the autonomous systems, the EO-1 team can usually add disaster targets to the imaging queue within four hours of target overflight. This allows EO-1 to acquire the image and get the requested data to the disaster relief people within eight hours of the overpass. And with 10-m effective resolution on ALI (due to pan-sharpening), useful images can be delivered very quickly—see **Figure 6**. In fact, EO-1 can usually observe disaster events one-to-two days earlier than the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), onboard NASA's Terra satellite, and Landsat 8, and can provide a second observation of the site within three-to-six days.

Figure 6. The Japanese city of Sendai was one of the hardest hit by the tsunami on March 11, 2011. EO-1's ALI instrument captured this image of the area soon after. Note that the snow cover shows exactly how far the tsunami wave reached inland [over 3 km (~1.9 mi) in some areas]. **Image credit:** NASA's Earth Observatory

With ALI's success producing Landsat-like images with less weight and power usage than Landsat 7 required, author edit than Landsat 7 required, the Landsat 8 team used ALI as the baseline design for the new Landsat instrument, the Operational Land Imager (OLI). Then, with the successful launch of Landsat 8 in February 2013, EO-1 had another task, that of on-orbit calibration with OLI, the "big brother" of ALI. This process saved NASA a great deal of time and money in calibrating OLI for general use.

Since EO-1 is a pointable satellite and not taking continuous images of the ground, the satellite has become a favorite for rapid-delivery of disaster images.

EO-1's Scientific Accomplishments

EO-1 has contributed greatly to the understanding of the problems and possibilities of hyperspectral observation of Earth and its moon. By evaluating the usefulness and limitations of ALI and Hyperion and the EO-1 acquisition strategy, the mission continues to contribute to future Earth-science mission needs (e.g., desired spectral and spatial resolution, SNR, frequency, and time and geometry of acquisition).

Hyperion Spectral Enabling Studies

A key EO-1 mission goal has been to evaluate the ability of satellite hyperspectral imaging to characterize terrestrial surface states and processes. Hyperion (and any visible/shortwave infrared hyperspectral imager) provides several advantages over multispectral satellite systems: spectral information critical for atmospheric correction of top-of-atmosphere radiances, to derive surface reflectance; the ability to create a broad array of spectral indices and parameters for land-cover characterization; and the ability to simulate the wider spectral bands used in multispectral systems. For characterizing vegetation condition and function, Hyperion is providing unique global spectral sampling that captures key vegetation traits such as canopy chlorophyll, water, and cellulose. Hyperion can also retrieve spectral indices related to photosynthetic function and plant stress—making use of spectral bands that are unavailable on current multispectral satellites. Researchers engaged in NASA's Terrestrial Ecology, Carbon Science, Land-Cover and Land-Use Change, and other programs have used Hyperion data to achieve land-cover classification accuracies and measures of vegetation biogeochemistry that far exceed those reached with the current spaceborne fleet of multispectral sensors. Hyperion has demonstrated the value of imaging spectroscopy in many science applications, including mining, geology, forestry, agriculture, environmental management, invasive species identification, desertification, land use, volcano studies, natural and anthropogenic hazards, and disaster assessments.

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Hyperion Time Series and Calibration Studies

Since 2008 Hyperion has collected repeated observations over a selection of flux tower and other ground validation sites around the globe—see **Figure 7**. Recent results demonstrate the close link between Hyperion's spectral descriptors (e.g., derivative indices) and carbon flux measurements, and their potential for scaling ground measurements to local, regional, and potentially global levels. Hyperion has also collected time series of nighttime imagery over volcanoes, describing activity changes.

The Committee on Earth Observing Satellites (CEOS) has suggested a number of sites as standard references (*pseudo-invariant calibration sites*) for the post-launch calibration of all space-based optical imaging sensors (as shown in **Figure 7**); these sites were added to the EO-1 spectral time-series collection. The spectral stability of Hyperion's reflectance time series at these CEOS sites was evaluated repeatedly and found usable as long-term spectral and spatial descriptors for these sites. Hyperion's long-term reflectance measurements at the CEOS sites support cross-comparison with other optical sensors through Hyperion's ability to simulate the spectral response of different multiband sensors. Further, once per month since 2001, Hyperion and ALI have each collected lunar images, and the lunar responses are compared with the USGS RObotic Lunar Observatory (ROLO) lunar model to monitor EO-1 lifetime trends and to improve the use of lunar observations for calibration of other sensors.

Calibration of old and new sensors against each other over a common set of targets is a key requirement for maintaining long-term usable data series, which are needed to

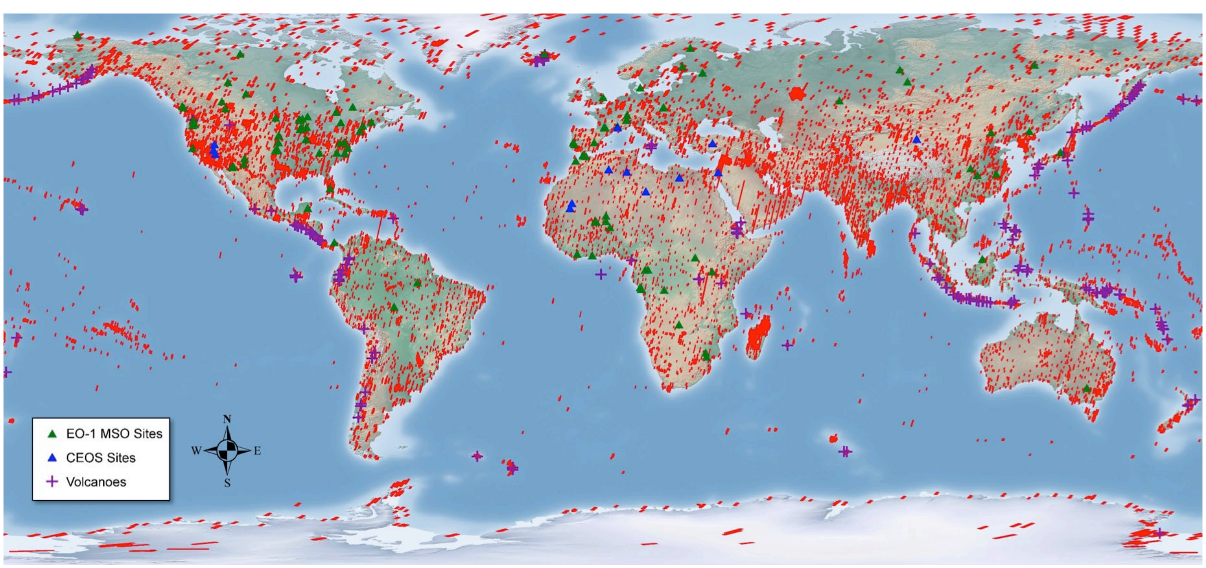

Figure 7. EO-1's global coverage of over 165,000 images, including the Hyperion spectral time series sites. **Image credit:** Petya K. Campbell

study climate change. The Landsat archive contains the longest continuous record of the Earth's surface as viewed from space. Recently, Hyperion facilitated the radiometric cross-calibration of ETM+ on Landsat 7 and OLI on Landsat 8. Cross-calibration of multispectral sensors with hyperspectral instruments, such as Hyperion, could allow retroactive data processing to calibrate the entire Landsat archive to the same standards for direct comparison of images from 1973 to 2016.

Many of these EO-1 scientific results were described in the IEEE EO-1 Special Issue of the *Journal of Selected Topics in Applied Earth Observations and Remote Sensing* (JSTARS), titled "The Earth Observing One (EO-1) Satellite Mission: Over a Decade in Space[8]." This 2013 publication contained 20 papers on the science and technology of EO-1 after its (then) 12 years in space.

EO-1 Adrift

Staying in formation behind Landsat 7 required EO-1 to perform periodic inclination maneuvers using the onboard thrusters. After almost seven years in formation, there was only enough fuel left to de-orbit the spacecraft, so EO-1 began a series of maneuvers designed to drop it out of formation and bring it back to Earth over the ocean. But a month later, in October 2007, it was decided that EO-1 should continue operation. The mission was granted an orbital debris re-entry waiver and its remaining re-entry fuel was allocated to maintaining its current orbit with a 10:00 AM Mean Local Time (MLT). In February 2011, after over three years in this orbit, the spacecraft ran low on fuel; since then it has drifted, the orbit slowly lowering and precessing to earlier and earlier MLTs. Normally, an out-of-fuel satellite is decommissioned, but EO-1 was given a second waiver to continue operations as it drifted. This was done to study how lower orbits and earlier imaging times (dropping from 10:00 AM toward 8:00 AM) would affect the usefulness of the image data. No earlier satellite had been allowed to do this, so this was unknown territory.

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One of the key effects of EO-1 drifting to earlier MLTs has been a lowering in the solar elevation angle during imaging. This decreases the solar energy density, which, in turn, decreases the reflected radiance. The lower solar elevation also increases the size of ground shadows being cast by objects such as trees, also acting to decrease reflected radiance. Yet, because the solar angles change seasonally and with latitude, even under nominal MLT (10:00 AM), usable images have been collected under a wide range of solar elevation angles. Analysis shows that energy density is highest for midsummer observations at high latitudes (80% of the incident radiance at 8:00 AM overpass compared to 100% at 10:00 AM overpass). This is a region of particular interest, as high-latitude ecosystems are shifting in response to climate change. EO-1's unique hyperspectral observations have been useful in describing variations in tundra ecosystems. EO-1 data are being collected to support NASA's Arctic-Boreal Vulnerability Experiment (ABoVE), which begins fieldwork in Alaska and western Canada in summer 2016. An in-depth analysis of the earlier overpass data has shown very little degradation; the early overpass time has not impeded EO-1's ability to collect useful data.

The EO-1 mission team is now preparing for the satellite to be decommissioned at the end of September 2016 when the MLT will be 8:00 AM. Since there is no fuel left to de-orbit the satellite, EO-1 will remain in a slowly degrading orbit for many years. There are proposals to turn the satellite into a dedicated lunar observatory, where the MLT over Earth will not matter. So, the fate of EO-1 is not yet sealed, and the mission may yet find a way to contribute more to science.

[8] IEEE JSTARS, Vol. 6, No. 2, April 2013, ISSN-1939-1404.

Conclusion

By any measure, EO-1 has been a very successful mission. From its earliest hardware testbed status to its more recent software and ground upgrades, the entire mission has shown innovation and ingenuity in getting the most out of a small "one-year mission" satellite. EO-1 has met its initial mission goals as a technology demonstrator. In addition to the earlier-described improvements over Landsat 7's ETM+, the LAC, while not used for long on EO-1, provided the basis for an instrument on NASA's New Horizon flyby mission to Pluto in 2015. EO-1 has also been a leader in the development of SensorWeb technology, allowing independent sensors to automatically trigger satellite acquisitions.

EO-1 has proved itself to be more than an engineering testbed, as its data have proven quite popular. For fifteen years, Hyperion and ALI have taken images all over the globe, amassing a library of over 165,000 images[9]. "Landsat-like" images kept the Landsat dataset continuity intact, and the satellite has been incredibly valuable to the disaster response community. EO-1's ALI was used as the basis for the design of OLI on Landsat 8, a multispectral instrument with much smaller mass and power usage than its predecessor (ETM+). EO-1 has proved the value of hyperspectral imagery to the scientific community and has acted as the precursor to the upcoming HyspIRI Hyperspectral Imager mission[10]. It has produced a unique archive of globally-sampled multispectral and hyperspectral images—an important legacy that will continue to be used long after EO-1 is gone.

The EO-1 mission has been a testament to the inventiveness and forward-thinking of the team in finding new challenges to tackle—keeping this "one-year mission" successful and productive for over fifteen years.

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Acknowledgements

So many people have worked on EO-1 over the years that it would not be possible to list them all here. The people mainly responsible for the existence of EO-1 are **Stephen Ungar**, *retired*, **Gran Paules**, *deceased*, and **Bryant Cramer,** *retired*, all of whom worked at NASA Headquarters and/or NASA's Goddard Space Flight Center (GSFC) during their careers; **Fuk Li** from NASA/Jet Propulsion Laboratory (JPL); as well as several hundred more.

With that being said, we wish to specifically acknowledge the individuals keeping EO-1 going as of today, which include: **Elizabeth Middleton**, *EO-1 Project Scientist*, **Daniel Mandl**, **Stephen Ungar**, and **Chris Neigh** [all from GSFC]; **Steve Chien** and **Daniel Tran** [both from JPL]; **Ray Burnes** [U.S. Geological Survey]; **Stuart Frye** [Stinger Ghaffarian Technologies], **Petya Campbell** and **Fred Huemmrich** [both from UMBC/JCET]; **David Landis** [Global Science and Technology, Inc.]; **Lawrence Ong**, **Vuong Li**, and **Nathan Pollack** [all from Science Systems and Applications, Inc.]; **Pat Cappelaere** [Vightel Corp.]; **Larry Alexander** [Raytheon]; **Ben Holt**, **Rishabh Maharaja**, **Steve Etchison**, **Dave Bradley**, and **Stuart Newman** [all from Honeywell]; **Jeff D'Agostino** [Hammers]; **Bruce Trout** [Microtel]; and **Mike Flick** [Columbus Technologies]. ■

[9] The images are available at the USGS EarthExplorer at *earthexplorer.usgs.gov*.

[10] A summary of the recent HyspIRI Science and Applications Workshop can be found on page 23 of this issue.

DEVELOP Project Uses NASA Data to Assess Landslide Characteristics in Rwanda and Uganda

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Introduction

Rainfall-triggered landslides are estimated to have caused over 32,000 deaths between 2007 and 2010 worldwide. This number is thought to be conservative, as many countries do not report landslide deaths.

Predicting landslide occurrence is a challenge. Often, emergency management officials use a combination of geographic and climatological variables, such as topography (specifically, slope), rainfall amounts, and land-cover and land-use types to pinpoint areas where landslides are possible. Unfortunately, however, these variables are less accurate at predicting when a particular landslide might actually occur.

Developed nations have better access than those less-developed to remote sensing data such as topography and analytical techniques that allow them to concentrate on forecasting and relief efforts. In contrast, emergency managers in less-developed countries tend to rely on historical and anecdotal evidence when deciding where to focus their efforts. As a result, less-developed nations are often unable to respond effectively to landslide events, and are thereby more susceptible to the harmful impacts of landslides, and less able to limit loss of life and property.

This article describes a project conducted by NASA's DEVELOP program[1], using recently released data of higher resolution than had previously been available from Shuttle Radar Topography Mission version 2 (SRTM-v2) digital elevation models (DEM). Data from both resolutions were combined with road, soil, topography, and population density data to determine areas susceptible to landslides and to show where populations are at risk of being affected by a landslide and to see what effect using the higher-resolution data might have on the overall utility of the respective datasets. The resulting maps provide end-users concrete locations to apply appropriate policies and mitigation efforts rather than sometimes naïve reliance on anecdotal evidence.

This article describes a project conducted by NASA's DEVELOP program, using recently released data of higher resolution than had previously been available from Shuttle Radar Topography Mission version 2 (SRTM-v2) digital elevation models (DEM).

To carry out the study, DEVELOP participants partnered with the Regional Visualization and Monitoring System (SERVIR[2]) and the Regional Centre for Mapping of Resources for Development (RCMRD[3]).

Study Area: Rwanda and Uganda

Landslides are common in the East African nations of Rwanda and Uganda due to steep topography, rainfall patterns, and loose soils (mainly derived from schistose, sandstones, quartzite formations, granite and gneissic formations, and old volcanic materials). Locations such as Southwestern Uganda, Western Rwanda, and the Mt. Elgon region of Eastern Uganda have a particularly high landslide incidence rate. For

[1] The NASA DEVELOP National Program fosters an interdisciplinary research environment where applied science research projects are conducted under the guidance of NASA and other partner science advisors. The program began in 1999 and originally was called the Digital Earth Virtual Environment Learning Outreach Project (DEVELOP). However, the acronym was dropped after the first year. For more information, visit *develop.larc.nasa.gov/about.html*.
[2] SERVIR is a joint NASA and U.S. Agency for International Development (USAID) effort that provides analyses and applications from space-based, remotely sensed information to help developing nations in decision-making processes that address natural disasters, climate change, and other environmental threats. SERVIR is not an acronym; it means "to serve" in Spanish.
[3] RCMRD is an intergovernmental organization of 20 Contracting Member States in Eastern and Southern Africa that promotes sustainable development through generation, application, and dissemination of geo-information and allied information and communications technologies, products, and services.

example, a landslide in the Mt. Elgon region on March 1, 2010, is estimated to have killed over 300 people.

Currently, information on landslides in Rwanda and Uganda from remote sensing platforms is limited. While general knowledge exists of where landslide-prone areas are located in both countries, more precise mapping and a more thorough investigation of landslide characteristics in the region will help disaster-management officials implement preventative measures regarding rainfall-triggered landslides.

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Shuttle Radar Topography Mission Data

A key tool in this work was data from the SRTM payload, which launched onboard Space Shuttle Endeavour February 11, 2000. With its radars sweeping most of Earth's surface, SRTM acquired enough data during its ten days of operation to obtain the most complete, near-global, high-resolution database of Earth's topography.

Until recently, publicly available SRTM-v2 data had been confined to 90-m (~295-ft) spatial resolution for all areas of the globe other than the U.S., which was provided at 30-m (~98-ft) resolution. In September 2014 the White House announced that they would release 30-m resolution SRTM-v2 data for the entire globe to aid international efforts in understanding natural processes and preparing for natural disasters.

Creating Landslide Susceptibility and Hazard Maps

The team used recently released 30-m and older 90-m SRTM-v2 data to derive a number of physical characteristics known to be correlated to the occurrence of landslides across the study region, including elevation, slope, plan curvature, profile curvature, distance from streams, distance from ridges, topographic wetness index (TWI), and terrain roughness. They used the Global Roads Open Access Data Set (gROADS[4]) to determine distance from roads, and the International Soil Reference and Information Center (ISRIC[5]) to determine depth to bedrock.

To identify landslide points within the study period of January 2010 to February 2015, the team used Google Earth's historical time slide viewer to compare aerial photographs from various dates, and generated an error matrix to represent the models' predictive accuracies.

Susceptibility Mapping

Because the specific causes of individual landslides can be difficult to pinpoint, the team created a Landslide Susceptibility Map using a *heuristic approach*[6]. This approach required the use of a Fuzzy Logic Model[7] in the commercially available *ArcMap* geospatial processing program developed by ESRI, version 10.2.1. In this case, 0 represented the lowest landslide susceptibility and 1 represented the highest landslide susceptibility for each variable. The program compiles the values of all variables and then shows what the overall likelihood of a landslide is (on a "yes-no" basis) in a particular location based on the combined input of all the variables. This method works well for this type of analysis because it consolidates several variables that normally cannot be compared. The 90- and 30-m Landslide Susceptibility Maps are shown in the top panels of **Figures 1 and 2,** respectively, where regions

[4] gROADS is a global dataset of roads, developed under the auspices of the Socioeconomic Data and Applications Center, hosted by the Center for International Earth Science Information Network at Columbia University, in NY.

[5] ISRIC in an independent science-based foundation, and is the accredited World Data Centre for Soils. The goal of ISRIC is to spread information about the world's soil resources globally, which helps to address global environmental issues.

[6] A heuristic approach is one that uses practical methods without guarantee of exactness. In this case, a list of causative effects was drawn up as a combination of expert opinion from scientific journal articles and the team's own educated guesses.

[7] Fuzzy logic computing uses values of any real number between 0 and 1, unlike the "true or false" (1 or 0) Boolean logic on which computing is more commonly based.

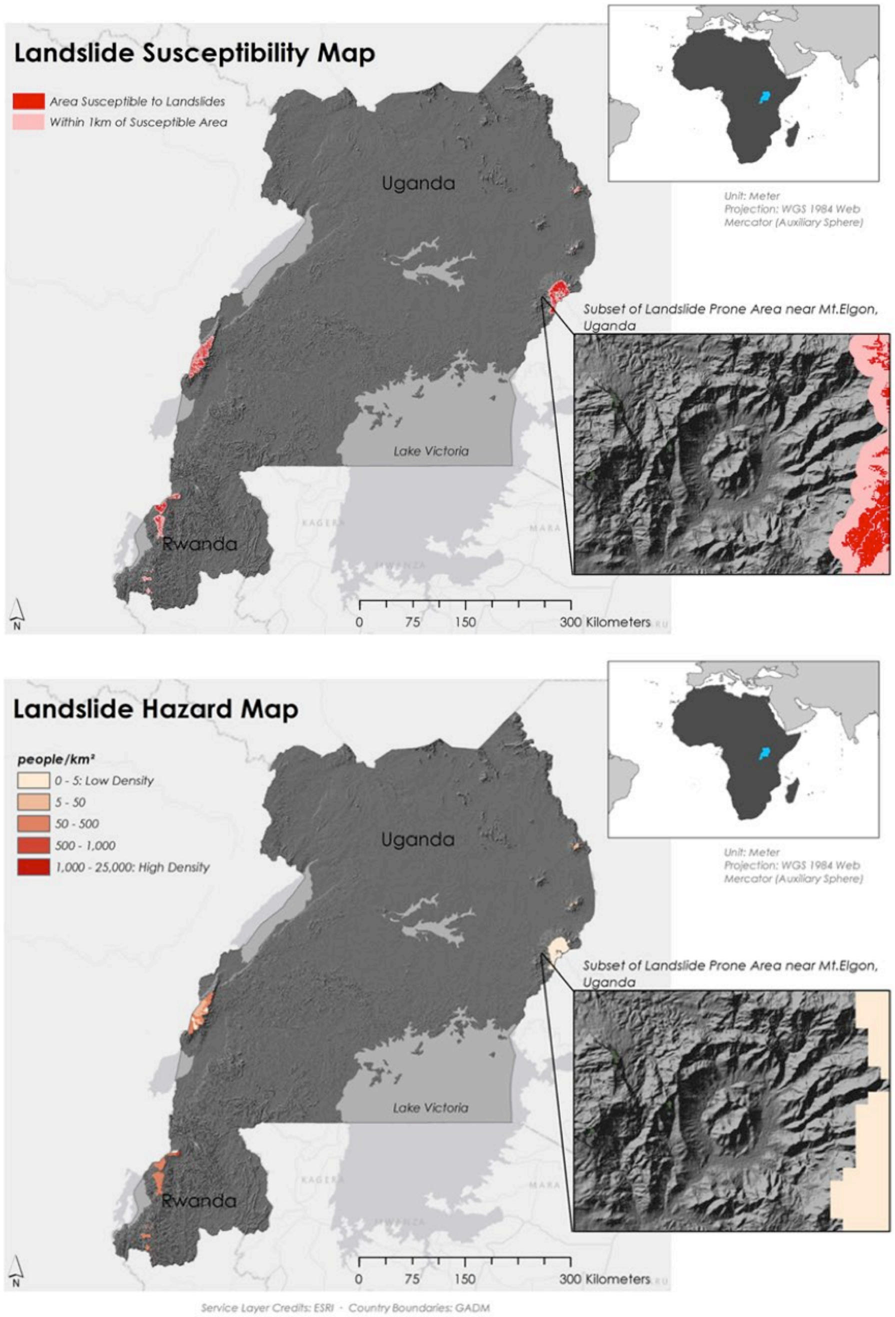

Figure 1: Low-resolution, finalized susceptibility [*top*] and hazard [*bottom*] maps generated using fuzzy logic on a SRTM-v2 90-m resolution image. In the top panel, red highlights areas with higher incidences of landslides, and pink represents a 1-km "buffer" zone around these activity centers. Data analysis of the low-resolution data predicted known landslide points with an accuracy of only 4%—and completely missed a known event near Mt. Elgon, Uganda (close-up shown in the inset panels). The bottom panel shows the population density in susceptible areas. When matched with the results in the top panel these data clearly demonstrate—and, as shown in Figure 2, clearly underestimate—how many people would be affected by outflows from landslides. **Image credit:** DEVELOP National Program

susceptible to landslides by these criteria are represented by dark shades, and those within 1 km of these "hot spots" are represented by light shades. This 1-km (~0.6 mi) "buffer" zone was generated around the highly susceptible areas—that is, those with values of 0.5 or greater—to include places that could be affected by the outflow of a worst-case-scenario landslide event, as represented in the associated hazard map, shown in the bottom panel of the figures, and generated using techniques described in the next section.

Hazard Mapping

The next step was to combine population data from the Socioeconomic and Applications Data Center (SEDAC) with the Landslide Susceptibility Map to show landslide hazard—that is, how many people within a defined area would be affected by a landslide in that area. People living in these areas are considered to be "at risk,"

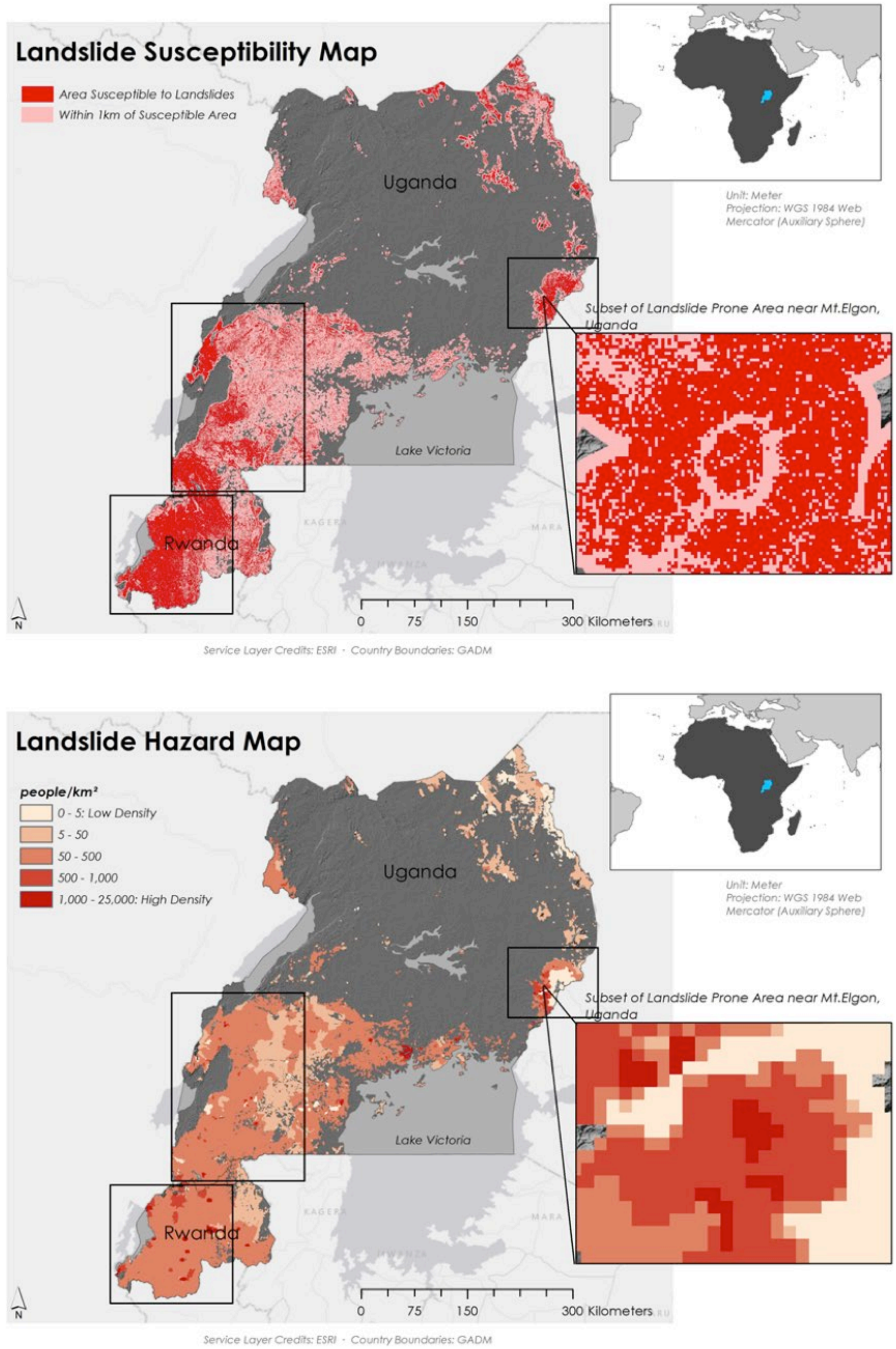

Figure 2: High-resolution, finalized susceptibility [*top*] and hazard [*bottom*] maps generated using fuzzy logic on a SRTM-v2 30-m resolution image. The color scale is the same as described in the caption for Figure 1. Notice the marked improvements using high-resolution data. Locations such as Southwestern Uganda, Western Rwanda, and the Mt. Elgon region of Eastern Uganda [*boxed regions*] have a particularly high landslide incidence rate. The analysis does a much better job capturing the event at Mt. Elgon and, overall, correctly predicts known landslide points with ~84% accuracy—considered highly accurate for this type of prediction. As in Figure 1, the bottom panel indicates the number of people potentially impacted, likely much more accurately than from the lower-resolution estimates. **Image credit:** DEVELOP National Program

which is reflected spatially in both the 90- and 30-m Landslide Hazard Maps—shown in the bottom panels of Figures 1 and 2, respectively. The lower-resolution (90-m) data Landslide Hazard Map identified approximately 560,000 people within 1-km of a landslide prone area. The use of the higher-resolution (30-m) Landslide Hazard Map significantly increased that number, finding that over 16 million people—or about one-third of the combined population of these two countries—are within 1 km of a landslide prone area.

Mathematical Validation

To put this analysis on a firmer basis—and because of the importance of a well-defined potentially hazardous condition—the team developed an error matrix to determine the accuracy of the maps using the landslide location points collected using the Google Earth historical tool and an equal number of randomly generated "absence" data points. The team examined these points in Google Earth to determine if any landslides were recorded within 100 m (~328 ft) of the absence point. If there was a landslide within 100 m of the absence point, then they replaced the absence point with a new point. This new point would not be a *false negative* as these points are considered to be true data points. Based on this analysis the team could construct and analyze a matrix of four possible outcomes:

- *true positives*: actual landslide points inside predicted landslide susceptibility;
- *false positives*: actual landslide points outside predicted landslide susceptibility;
- *true negatives:* absence points outside predicted landslide susceptibility; and
- *false negatives*: absence points inside predicted landslide susceptibility.

The error matrix of the lower-resolution (90-m) Landslide Susceptibility Map shows that the model produced an overall accuracy[8] of 51% and a misclassification rate of more than 48%. The true positive was less than 4%. As might be expected, the error matrix for the higher resolution (30-m) Landslide Susceptibility Map shows a marked improvement in model performance. In this case, the overall accuracy increases to greater than 87%, and the misclassification rate lowers to less than 12%. The true positive, or accuracy when predicting susceptibility for areas with known landslides, was greater than 82%.

Incorporating high-resolution data into the analysis described herein clearly led to a much more accurate assessment of the number of people threatened by landslides in the study region. When such information is made available to emergency managers it will allow them to more effectively allocate resources and help with mitigation efforts.

A comparison of the top panels of Figures 1 and 2 illustrates the improvements achieved when higher-resolution data is incorporated into the analysis. In particular, notice that the lower-resolution data (Figure 1) shows an almost complete lack of predicted landslides around Mt. Elgon—the region where the most severe landslides occurred. The high-resolution run, on the other hand, does a much better job predicting landslides in this area, and overall, performs well for a model examining a complex natural phenomenon.

Summary

This NASA DEVELOP project provided Landslide Susceptibility Maps and Landslide Hazard Maps for Rwanda and Uganda at 30- and 90-m resolutions to help identify areas prone to landslides and to estimate the number of people that could potentially be affected. Higher-resolution, 30-m STRM-v2 data product analysis predicted the location of landslides far more accurately than the 90-m-resolution data. Further, the more-accurate 30-m Landslide Hazard Map identified over 16 million people who are within 1 km of a landslide prone area—more than twice as many as the lower-resolution version identified.

This enhanced utility strongly supports NASA's decision to release worldwide 30-m-resolution SRTM-v2 data. Incorporating high-resolution data into the analysis described herein clearly led to a much more accurate assessment of the number of people threatened by landslides in the study region. When such information is made available to emergency managers it will allow them to more effectively allocate resources and help with mitigation efforts. These end products will be used by SERVIR and RCMRD to aid disaster risk management efforts and land-use planning in the region, and to increase understanding of the conditions required to trigger a landslide, with potential to mitigate deleterious effects.

While this analysis focused on a specific region of East Africa, the results are likely to have applicability elsewhere. Future research could test the technique in other landslide-prone areas around the globe. Although it is not yet possible to predict the timing of a landslide with any substantial accuracy, techniques such as those outlined herein offer the potential for emergency managers to more effectively predict where landslides might occur, which leads to more effective preparation and planning in landslide-prone regions. ■

[8] This overall accuracy describes when the map correctly predicted the susceptibility for areas with known landslides and when it correctly predicted no susceptibility for absence points.

Delivering NASA Science Face-To-Face to the World

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The Science Program Support Office (SPSO) is the primary point of contact for NASA's Science Mission Directorate, for science exhibit outreach and product development. During fiscal year 2015 (FY2015[1]) the SPSO supported 24 domestic and international science conferences and public events[2]. At such events the SPSO provides an inspiring and interactive venue, using a unique storytelling approach that allows a variety of audiences worldwide to connect in a personal way with NASA's science activities.

Continuing this trend, already in FY16, the SPSO has supported five scientific conferences before the close of 2015:

- Digital Earth, held October 5-9, 2015, in Halifax, Nova Scotia, Canada;
- the Geological Society of America (GSA) Annual Meeting, held November 1-4, 2015, in Baltimore, MD;
- the Twelfth Plenary Session of the Group on Earth Observations (GEO-XII), held November 11-12, 2015, in Mexico City, Mexico;
- the twenty-first Conference of Parties (COP-21) to the United Nations Framework Convention on Climate Change, held November 30 - December 11, 2015, in Paris, France; and
- the American Geophysical Union (AGU) Fall Meeting, held December 14-18, 2015, in San Francisco, CA.

This article provides a glimpse of what took place at the last three events in 2015: GEO-XIII, COP-21, and AGU. To view additional photos from these and other events, visit *www.flickr.com/photos/eospso/sets*.

Representing the U.S. at GEO

Representatives from the SPSO traveled to Mexico City, Mexico, to participate in the U.S. GEO exhibit at GEO-XII. GEO is a partnership of governments and organizations that coordinates comprehensive and sustained Earth observations for the benefit humankind. The activities at the booth were the results of an interagency effort that collectively represented research activities at each U.S. agency. This year the exhibit featured a 70-inch plasma screen at which four programmatic talks took place. During times when there were no live presentations, participants could view ultra-high-resolution (4K) NASA visualizations that were displayed on the screen, interspersed with other visual content from the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS). **Sally Jewell** [U.S. Secretary of the Interior], who led the U.S. delegation, and **Kathryn Sullivan** [NOAA Administrator], U.S. Co-chair of GEO, spoke with visitors about the visualizations at the U.S. GEO booth—see **Photos 1-2**. Both Sullivan and Jewell thanked NASA for their excellent work supporting the booth.

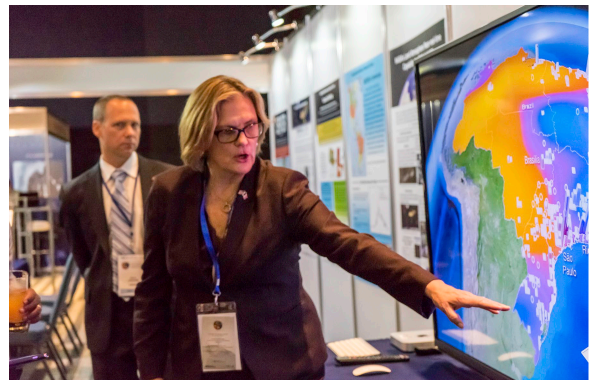

Photo 1. Kathryn Sullivan explained global visualizations to GEO-XII attendees at the U.S. GEO booth. **Photo credit:** NASA

Photo 2. Sally Jewell [*left*] and **Kathryn Sullivan** [*right*] discussed several visualizations. **Photo credit:** NASA

Inside the U.S. Center at COP-21

The SPSO supported the twenty-first Conference of Parties (COP-21) to the United Nations Framework Convention on Climate Change in Paris, France. The U.S. Department of State was the host of the *U.S. Center* at COP-21, which was a major public outreach initiative to inform attendees about key U.S. climate initiatives and scientific research. As has been the standard for past COP meetings[3], representatives from NASA, other U.S. government agencies, academic institutions, nongovernmental organizations, private-sector companies, and other stakeholders convened in the U.S. Center to highlight key climate programs and relevant scientific research. The NASA Hyperwall was used for 30-minute single-presenter talks as well as *side-event presentations*—60-90-minute talks

[1] FY2015 ran from October 1, 2014 to September 30, 2015.
[2] For details, read the SPSO FY2015 Annual Report at *go.nasa.gov/1Mxomqw*.

[3] To read about NASA's involvement in COP-20, see "NASA's Hyperwall: Around the World in 2015," in the January-February 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 1**, pp. 20-23].

generally given by a small panel—all of which took place inside the U.S. Center.

Jack Kaye [NASA Headquarters (HQ)—*Earth Science Associate Director for Research*], **Michelle Gierach** [NASA/Jet Propulsion Laboratory (JPL)—*Marine Scientist*], **Steven Pawson** [NASA's Goddard Space Flight Center (GSFC)—*Chief of the Global Modeling and Assimilation Office*], and **Patrick Taylor** [NASA's Langley Research Center—*Climate Scientist*] traveled to Paris to participate in the two-week event by delivering a variety of NASA Hyperwall and side-event presentations—see **Photos 3-4**. A brochure containing the science stories that were shown on the Hyperwall is available online at *go.nasa.gov/1MxnLoM*.

Photo 3. Patrick Taylor discussed a visualization that showed annual minimum Arctic sea ice extents from 1979 to 2014. The visual material included a graphic overlay that revealed a downward trend in minimum extents over this period. **Photo credit:** NASA

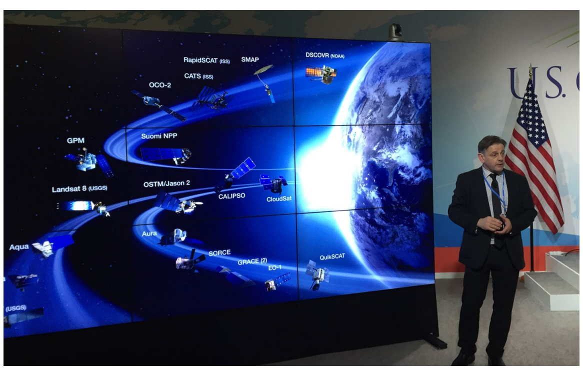

Photo 4. Steven Pawson began his Hyperwall presentation with a graphic showing the current fleet of NASA's Earth-observing satellite missions. **Photo credit:** NASA

AGU Fall Meeting

For more than 10 years, the SPSO has organized and supported the NASA exhibit at the American Geophysical Union (AGU) Fall Meeting. For the last few years, the SPSO has also organized and hosted a one-day Annual Communication Meeting the weekend before the start of AGU. Even in an era of near-instantaneous communication via the Internet and social media, there is still value in face-to-face contact. The annual communication meeting provides such an opportunity for the NASA outreach community, which includes management, public engagement personnel, and the like from several NASA centers. The community came together on the Sunday afternoon before AGU for an opportunity to hear from and talk directly with management and to interact with colleagues—see *2015 Annual Communication Meeting at AGU* on page 22.

This year's exhibit hall at the forty-eighth annual Fall AGU meeting opened on December 14, and continued through December 18. An opening reception took place on Monday evening. **John Grunsfeld** [NASA HQ—*Associate Administrator for the Science Mission Directorate*] provided opening remarks and welcomed participants to the exhibit. Hyperwall presentations from three of the four

Photo 5. Michael Freilich gave the first talk on opening night titled *NASA's Earth Observation Capabilities: Meeting the Challenges of Climate and Environmental Change*. **Photo credit:** NASA

SMD division directors followed: **Michael Freilich** [NASA HQ—*Director of the Earth Science Division*]—see **Photo 5**; **Jim Green** [NASA HQ—*Director of the Planetary Science Division*]; and **Steven Clarke** [NASA HQ—*Director of the Heliophysics Division*]. Over the next four days there were 40 additional Hyperwall presentations and 33 in-booth *Science Flash Talks*—7-minute talks in which representatives of NASA provide an overview of a particular science topic and/or data processing tool or service—see **Photos 6-8**. This year's AGU meeting coincided with the premiere of *Star Wars*, Episode VII "The Force Awakens," so even the "droid" R2-D2 visited the Hyperwall—see **Photo 9**. A schedule of the events that took place at the booth is available online at *go.nasa.gov/1jK1r3i*.

In addition to these talks, the exhibit offered a wide range of printed materials—including mission brochures, story booklets, fact sheets, lithographs, and the 2016 NASA Science calendar—that represent NASA Earth science, planetary science, and heliophysics activities. A *Tree of Knowledge* located at the booth allowed attendees to "leaf" their thoughts about NASA science—see **Photo 10**.

As always, there was something for just about everyone at the NASA booth at AGU.

Conclusion

In 2016 the SPSO plans to support an increasing number of scientific conferences and events. Currently, the Hyperwall continues to provide an exciting platform for NASA to communicate its science in a face-to-face fashion that is unlike that provided by any other space

2015 Annual Communication Meeting at AGU

The Science Program Support Office supported the NASA Science Mission Directorate (SMD)'s 2015 Annual Communication Meeting, Sunday, December 13, at the San Francisco Marriott Union Square. With 83 participants representing various NASA centers, this was the largest communication gathering held at AGU. The meeting opened with discussions from SMD communication leaders and division directors from Earth Science, Planetary Science, and Heliophysics divisions. These and other presentations during the meeting will help to shape communication strategies and guide the workflow for the coming year. The Share-a-thon, combined with the many informal conversations throughout the meeting, provided an excellent forum for learning. Participants left well informed about NASA's wide range of communication activities.

Photo 6. Bill Putman [GSFC—*Research Scientist for the Global Modeling and Assimilation Office*] showed several global climate simulations in ultra-high-resolution (4K). **Photo credit:** NASA

Photo 7. Jake Kaye showed several examples of how "human footprints" can be seen from space. In this photo, Kaye is showing Landsat images that show the rapid urbanization in Las Vegas. **Photo credit:** NASA

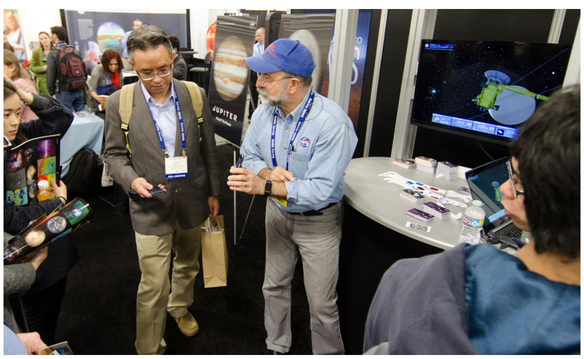

Photo 8. Kevin Hussey [JPL—*Visualization Technology Applications and Development Manager*] demonstrated NASA's *Eyes on the Earth* interactive web applications. **Photo credit:** NASA

Photo 9. R2-D2 seems infatuated with this Hyperwall image of the Mars Curiosity Rover. **Photo credit:** NASA

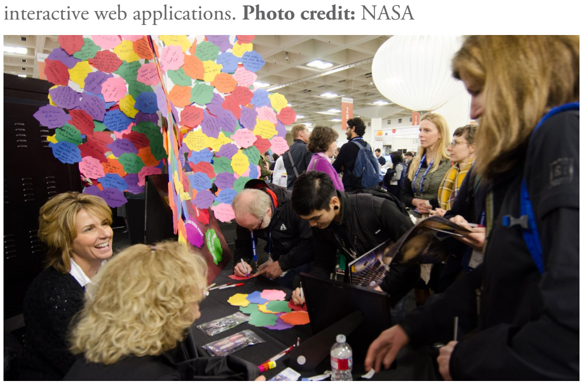

Photo 10. AGU attendees were invited to write and pin their comments about NASA on a five-foot-high display tree dubbed *The Tree of Knowledge*. **Photo credit:** NASA

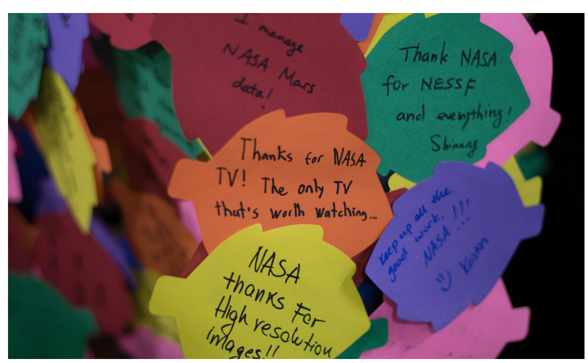

Photo 11. Participants were asked to "leaf" their thoughts about NASA on *The Tree of Knowledge*. **Photo credit:** NASA

agency in the world. Looking ahead, the office remains committed to implementing "next-generation" communication platforms as they become available. The SPSO will continue to provide and strengthen visibility for the agency, inspiring a new generation to pursue topics and careers that are relevant to NASA's many missions, and continuing to demonstrate NASA's role as a leading research agency. ■

2015 HyspIRI Science and Applications Workshop Summary

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Introduction

The proposed NASA Hyperspectral InfraRed Imager (HyspIRI) will address urgent Earth Science and applications challenges through a global-mapping satellite mission. The planned payload includes a scanning visible-to-shortwave infrared imaging spectrometer (VSWIR), covering a range between 380 and 2500 nm in 10-nm bands, and a scanning multispectral thermal infrared imager (TIR), with eight discrete bands between 3 and 12 µm.

HyspIRI was identified as a Tier 2 priority in the National Research Council's (NRC) 2007 Decadal Survey: *Earth Science and Applications from Space*[1]. Since then, the HyspIRI mission and its research community have worked to highlight and demonstrate how such a mission would fill critical measurement gaps and significantly improve our understanding of global biodiversity (including terrestrial, aquatic, and coastal ecosystems), volcanology, ecosystem function, and other critical science themes. Moreover, HyspIRI-like data have also been collected (via aircraft campaigns, mentioned below) and used to support multiple science applications, such as wildfire behavior, drought incidence, and snowpack characteristics. HyspIRI's mission concept also seeks to respond to the need for data consistency and continuity with the combined NASA/U.S. Geological Survey (USGS) Sustainable Land Imaging (SLI) program; for example, the team worked to update HyspIRI requirements for improved spatial and temporal resolution. In its current configuration, HyspIRI would provide global VSWIR and TIR coverage at 30 to 60 m (~98 to 177 ft) per pixel, every 5 to 16 days.

The HyspIRI community has demonstrated that technologies and the research and applications communities are ready for the HyspIRI mission. There have been several HyspIRI Airborne Campaigns aimed at reducing risks and uncertainties associated with the upcoming mission. These include a series of airborne missions in California (between 2013 and 2015) that studied terrestrial ecosystems, land use and land cover change, oceanography, geology, and atmospheric composition. A similar upcoming campaign in Hawaii (planned for 2016–2017) will use HyspIRI like instruments mounted on NASA's high-altitude ER-2 aircraft to study coral reefs and volcanoes. In addition, there have been calibration/validation studies for the Hyperion instrument onboard NASA's Earth Observing-1 (EO-1[2]). Risk reduction is also being achieved by leveraging resources such as the Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR), which is now being integrated into the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission, scheduled to be launched and installed on the International Space Station in 2018.

Meeting Overview

In support of the mission, the 2015 HyspIRI Science and Applications workshop was held at the California Institute of Technology from October 13-15, 2015, with 118 attendees. The workshop was arranged into multiple thematic sessions that allowed participants to receive updates on various aspects of the status of HyspIRI science and applications research. The sessions included:

- Technology;
- Volcanoes and Wildfires;
- Aquatic Systems;
- Terrestrial Ecology;
- Methane and Atmosphere;
- Cryosphere; and
- Surface Composition and Geology.

In addition to these sessions related to HyspIRI, there was a special session on the ECOSTRESS mission—see *Special Session on ECOSTRESS* on page 25.

Outside of the sessions, participants had ample opportunities to meet with one another for informal discussions. Also, the workshop dedicated at least two hours

[1] See *www.nap.edu/catalog/11820/earth-science-and-applications-from-space-national-imperatives-for-the.*

[2] To learn more about EO-1 please see "EO-1: 15 Years After the Start of Its 'One Year Mission'" on page 4 of this issue.

Table. Breakout session leaders and topics. Note that some of these topics are the same as the Thematic Sessions, which are summarized in the body of the article.

Lead [Affiliation]	**Topic**
Day One	
Kevin Turpie [NASA's Goddard Space Flight Center (GSFC)]	Aquatic Studies
Josh Fisher [NASA/Jet Propulsion Laboratory (JPL)]	Evapotranspiration and Agriculture
Rob Wright [Hawaii Institute of Geophysics]	Volcanoes
Sander Veraverbeke and **E. Natasha Stavros** [both at JPL]	Wildfires
Day Two	
Eric Hochberg [Bermuda Institute of Ocean Sciences]	Aquatic Benthic Habitats
Wendy Calvin [University of Nevada, Reno]	Surface Composition and Geology
Andrew Thorpe [JPL]	Methane and Atmosphere
Ryan Pavlik [California Institute of Technology]	Biodiversity
Day Three	
Phil Townsend [University of Wisconsin, Madison]	Terrestrial Ecology and Plant Physiology
Jeff Luvall [NASA's Marshall Space Flight Center]	Human Health and Water Quality
Tom Painter [JPL]	Cryosphere Science

each day to *white paper* breakout sessions—see **Table**. The objective of these discussions was to bring together representatives of the research and applications community so that they might collaborate on the development of white papers in response to the 2017 Earth Science Decadal Survey's request for input[3]. The lead or co-leads for each breakout session were tasked with capturing the discussions' contents and developing the white papers. Ultimately, this feedback will be used to help the Steering Committee succinctly identify and discuss critical science and applications challenges for the 2017 Decadal Survey.

Please visit *hyspiri.jpl.nasa.gov* to access presentations and posters presented during the workshop and links to white papers developed during breakout sessions. These white papers were all submitted to the Decadal Survey Request for Information.

Day One

The workshop began with a series of programmatic presentations. **Woody Turner** [NASA Headquarters—*Program Manager for Ecological Forecasting and Biological Diversity*] began with an overview of HyspIRI and its many potential contributions to the science and applications landscape. A series of presentations from the HyspIRI mission leads followed: **Robert Green** [NASA/Jet Propulsion Laboratory (JPL)] and **Simon Hook** [JPL] discussed the status of the HyspIRI Mission Concept and reviewed Level 1 data requirements, and **Elizabeth Middleton** [NASA's Goddard Space Flight Center (GSFC)] summarized the June 2015 HyspIRI Science Data Products Symposium[4].

After these overview presentations, the remainder of the first day was devoted to three of the thematic sessions, followed by breakout sessions (see Table).

Technology

Dan Mandl [GSFC] provided updates on recent technology developments including the Intelligent Payload Module, which will improve data latency and allow additional capabilities that will benefit both science and applications. **Bill Johnson** [JPL] and **Pantazis Mouroulis** [JPL] then gave presentations about TIR activities and the VSWIR Dyson Imaging Spectrometer, respectively. **Steve Chien** [GSFC] and **Sergio Cogliati** [University of Milano-Bicocca, Italy] also provided updates on technologies, including onboard instrument processing demonstrations from the EO-1 mission and automated field systems for collecting spectrometer measurements for calibration and validation.

Volcanoes and Wildfires

This session featured presentations from **Chad Deering** [Michigan Technological University], **Michael Ramsey** [University of Pittsburgh], and **Vince Realmuto** [JPL], all of whom have been recently selected as science team members for the upcoming 2016 coral reef and

[3] The next Earth Science Decadal Survey for Earth Science and Applications from Space (ESAS2017), covering the period 2017-2027, is now underway; it is again sponsored by NASA, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey. A website for the Decadal Survey (*www.nas.edu/esas2017*) has been created to provide a link for communications from the research community.

[4] To learn more about this meeting, visit *hyspiri.jpl.nasa.gov/events/2015-hyspiri-science-symposium.*

volcanoes airborne campaign in Hawaii, mentioned previously. (A separate *Planning Meeting for the HyspIRI Airborne Campaign: Volcanoes and Coral Reefs* took place on October 16 and is described in the sidebar on page 26.) Also during this session, **E. Natasha Stavros** [JPL] presented examples of synergistic uses of the AVIRIS and MASTER[5] sensors to document the 2014 California King Fire, and **Neil Pearson** [University of Nevada, Reno (UNR)] summarized work conducted over the Mono Basin and Long Valley Caldera.

Aquatic Systems

This session included presentations from **Eric Hochberg** [Bermuda Institute of Ocean Sciences—*Principal Investigator (PI) for COral Reef Airborne Laboratory*[6]] on monitoring kelp forests; **Tom Bell** [University of California (UC), Santa Barbara] on identifying phytoplankton functional types; **Liane Guild** [NASA's Ames Research Center (ARC)] on harmful algal bloom monitoring in Lake Erie; **Jeff Luvall** [NASA's Marshall Space Flight Center (MSFC)] on water quality studies; and **Steve Ackleson** [Naval Research Laboratory] on coral reef studies. In addition, **Kevin Turpie** [GSFC] summarized the HyspIRI Aquatic Studies Group (HASG) report (*go.nasa.gov/1RpHoX6*), which provides a review of critical areas in aquatic and coastal ecosystems studies that would be significantly advanced with the HyspIRI mission.

Day Two

The second day began with a presentation from **Ian McCubbin** [JPL] on field campaigns for HyspIRI airborne instruments in California and upcoming campaigns focusing on Hawaiian coral reefs and volcanoes. **Andre Hollstein** [GeoForschungsZentrum (GFZ), Potsdam, Germany] described a German hyperspectral mission, Environmental Mapping and Analysis Program (EnMAP). **Robert Green** [JPL] reported on the planned AVIRIS-Next Generation airborne campaigns in Asian Environments.

Special Session on ECOSTRESS

The special session on ECOSTRESS provided an opportunity to explore the status of the mission, instrument, and science objectives. As members of the ECOSTRESS Science Team, **Simon Hook** [JPL—*PI for ECOSTRESS*], **Joshua Fisher** [JPL—*Science Lead for ECOSTRESS*], and **Glynn Hulley** [JPL—*Science Team Member*] discussed topics such as how ECOSTRESS will be used to study vegetation water stress and to understand diurnal variability of evapotranspiration, as well as how data products (such as Level 2 land surface temperature and emissivity) will be developed. **Johan Perret** [EARTH University] described a partnership in which his institution could assist with calibration and validation activities and other application development in support of ECOSTRESS. **Bill Johnson** [JPL] closed the session with a discussion of instrument design. More information about this mission can be found at *ecostress.jpl.nasa.gov*.

Terrestrial Ecosystems

Greg Asner [Stanford University (SU)] gave a keynote presentation on the Carnegie Airborne Observatory, a three-dimensional laser imager[7]. **Dana Chadwick** [SU] then summarized findings on imaging spectroscopy of canopy nutrients in the Amazon. The session also included presentations from **Paul Gader** [University of Florida], **Wei Yao** [Rochester Institute of Technology], and **Karine Adeline** [UC, Davis] on processing methods, evaluating vegetation structure, and characterizing canopy chemistry, respectively. Additionally, **Dar Roberts** [UC, Santa Barbara], **Phil Townsend** [University of Wisconsin, Madison], and **John Gamon** [University of Alberta] presented information on vegetation distribution in anthropogenic landscapes, ecosystem physiology, and assessing biodiversity and productivity, respectively. **Matthew Clark** [Sonoma State], **Amin Tayyebi** [UC, Riverside], and **Paul Moorcroft** and **Stacy Bogan** [both from Harvard University] touched on a variety of topics such as land cover, climate change adaptation, vegetation signatures, ecosystem composition, and plant functional types. **Dongdong Wang** [University of Maryland, College Park] concluded the session with a presentation on land surface radiation and the energy budget.

Poster Session

The second day also included a lunchtime poster session, with fourteen posters covering several thematic areas. The poster session allowed for direct interaction with speakers and provided an additional medium to present research for those who did not give an oral presentation.

Day Three

The third day began with talks on methane and aerosols followed by talks on the cryosphere. Next, there was a special session on the upcoming ECOSTRESS mission, as described in the box above. There were also several talks on surface composition and geology and an Applied Sciences working lunch, led by **Christine Lee** [JPL], to explore processes for HyspIRI and ECOSTRESS

[5] AVIRIS stands for Airborne Visible InfraRed Imaging Spectrometer; MASTER stands for the MODIS/ASTER airborne simulator.

[6] CORAL is a sub-orbital mission, one of the winning selections from the Earth Venture Sub-Orbital-2 (EVS-2) Announcement of Opportunity.

[7] To learn more, please visit *carnegiescience.edu/projects/uncovering-canopy-chemistry-carnegie-airborne-observatory*.

Planning Meeting for the HyspIRI Airborne Campaign: Volcanoes and Coral Reefs

Following the HyspIRI Science and Applications Workshop, the HyspIRI Hawaii Principal Investigator (PI) team held a meeting at NASA/Jet Propulsion Laboratory (JPL). In addition to the members of the PI team, members of the HyspIRI Steering Committee from NASA Headquarters, GSFC, and JPL participated. Members of the instrument and aircraft teams gave presentations for MASTER, AVIRIS, and NASA's ER-2 aircraft. The PI(s) gave a presentation on the goals of their specific projects, planned field activities, and desired data collection dates. There was also discussion to work out the schedule for the campaign and collaborative validation activities.

applications through an Early Adopter program. Several more breakout sessions took place in the afternoon—refer again to the Table on page 24. The meeting ended with two presentations and a discussion about how to summarize advances in science and applications research and technology as a potential reference for the 2017 Earth Science Decadal Survey.

Methane and Atmosphere

This session included talks from **Jun Wang** [University of Nebraska] and **Andrew Thorpe** [JPL], who discussed methods for assessing aerosol properties and using AVIRIS-Next Generation (learn more at *avirisng.jpl.nasa.gov*) for mapping methane emissions, respectively.

Cryosphere

This session featured presentations from **Felix Seidel** [JPL] on snow properties in the Sierra Nevada and Rocky Mountains using AVIRIS and from **Tom Painter** [JPL] on snow and ice radiative forcing and albedo using the Airborne Snow Observatory imaging spectroscopy measurements.

Surface Composition and Geology

Dutta Dubsunder [University of Illinois], **Gwen Davies** [UNR], **Robert Green**, **Bernard Hubbard** [USGS], and **Wendy Calvin** [UNR] delivered presentations on soil properties, acid mine drainage, mineral dust source composition, mineral maps for landslide and debris flow studies, and resource exploration, respectively.

Concluding Presentations and Plans for the 2017 Decadal Survey

Two presentations ended the day. **Robert Green** described the Tetracorder 5 software program for improved imaging spectroscopy data processing, and **Miguel Velez-Reyes** [University of Texas, El Paso] reported on how to better separate signal and noise in hyperspectral data signatures.

Woody Turner and the HyspIRI team leads then led a closing discussion of the proposed HyspIRI mission and its potential consideration in the 2017 Earth Science Decadal Survey. They underscored the mission's unique capability to address a wide variety of science and applications questions such as global biodiversity, terrestrial ecosystems and disturbances, aquatic studies and benthic habitats, geological surface composition, and other areas. Participants identified "next steps" to keep the community active and engaged in the process. In particular, the community summarized key science and application challenges *via* white papers for the Decadal Survey's request for information.

Summary

The HyspIRI community continues to describe the fundamental science- and applications-related contributions that this mission could provide in the future, through HyspIRI airborne campaigns, flights of opportunity, technology demonstrations, domestic and international partnerships, or Earth Venture missions such as CORAL and ECOSTRESS. HyspIRI has the unique capability to address urgent, widespread, and diverse science questions and societal needs. ■

Summary of the 2015 NASA Sounder Science Team Meeting

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Introduction

The NASA Sounder Science Team Meeting (STM) took place October 13–16, 2015, in Greenbelt, MD. The Atmospheric Infrared Sounder (AIRS) project at NASA/Jet Propulsion Laboratory (JPL) hosted the meeting. The overarching theme throughout the three days was the science being produced from atmospheric sounder observations.

Space agencies around the world—including the U.S.-based NASA and National Oceanic and Atmospheric Administration (NOAA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)—currently operate four hyperspectral infrared sounders and several lower-spectral-resolution infrared and microwave sounders. The hyperspectral infrared instruments discussed at the STM included the AIRS onboard NASA's Aqua satellite, launched in 2002; two Infrared Atmospheric Sounding Interferometer (IASI) instruments onboard EUMETSAT's MetOp-A and MetOp-B satellites, launched in 2006 and 2012, respectively; and the Cross-track Infrared Spectrometer (CrIS) onboard NASA's Suomi National Polar-orbiting Partnership (NPP) satellite, launched in 2011. Additional infrared and microwave sounding instruments are carried on aircraft.

Observations from the satellite sounding instruments already in operation have led to significant weather forecast improvements. In addition to providing up-to-the-minute forecast information, data from these sounders have produced a detailed record of weather and climate phenomena over a 13-year period. To extend these records, several other satellite-borne instruments are already in development or planned. Since many sounder-observed phenomena are not fully represented in weather and climate models, existing and future sounder records will provide challenging and important scientific insights in the coming decades. Sounder Science Team Meetings provide a forum to communicate progress on meeting these challenges with an eye toward future data acquisitions.

Toward that end, the meeting summarized here was organized into eight thematic sessions:

- Atmospheric Physics and Climate;
- Applications;
- Algorithm Development;
- Weather;
- Validation;
- Atmospheric Composition and Aerosols;
- Data Systems and Services, and
- Instrument Calibration and Level 2B Products.

Speakers shared results from a broad range of scientific and technical disciplines; in all, there were 72 presentations. The full meeting agenda is available at *airs.jpl.nasa.gov/events/35*, and most of the presentations from this and earlier meetings can be downloaded from *airs.jpl.nasa.gov/resources/presentations.* The remainder of this report highlights some of the key results presented during this meeting.

Highlights

Day One: Atmospheric Physics and Climate; Applications

The first day of the meeting was dedicated to introductory remarks and the first two thematic sessions. **Tsengdar Lee** [NASA Headquarters] described a NASA-organized workshop held in April 2015 to better define outstanding challenges in NASA's Weather focus area, with the expectation that clearer science goals will guide future space and suborbital missions[1]. Using data obtained from instruments on Aqua, **Lazaros Oreopoulos** [NASA's Goddard Space Flight Center (GSFC)] sorted outgoing longwave radiation (OLR) derived from AIRS spectra into *cloud state* as observed by the Moderate-resolution Imaging Spectroradiometer (MODIS). He showed broad agreement with OLR from Clouds and the Earth's Radiant Energy System (CERES) observations. **Jae Lee** [GSFC] compared OLR observations from CERES and AIRS with those from the NASA Modern Era Retrospective-Analysis (MERRA), demonstrating general agreement. **Joshua Roundy** [University of Kansas] and **Stephanie Granger** [JPL] described two efforts to better characterize drought conditions using sounder temperature and water vapor observations—see **Figure 1**.

Day Two: Algorithm Development; Weather

Mathias Schreier, **Robert C. Wilson**, and **Hartmut Aumann** [all from JPL] separately assessed the performance of several radiative transfer models for cloudy conditions. They noted the challenges in selecting a preferred model for retrieval algorithm development or climate studies. **Antonia Gambacorta** [Science and Technology Corp.] described a retrieval algorithm applicable to all satellite hyperspectral sounders and

[1] The full workshop report is available at *science.nasa.gov/earth-science/focus-areas/earth-weather/*.

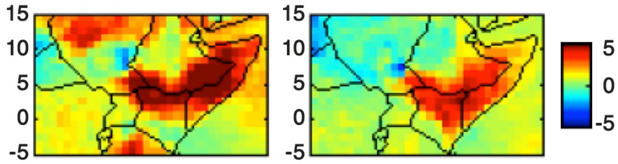

Figure 1. These images show near-surface atmospheric water vapor pressure deficit (VPD) (in hPa, or mb) during November [*left*] and December [*right*] 2011 over the Horn of Africa from AIRS—when this region was experiencing a severe drought and associated political instability. VPD is a measure of the drying capability of the atmosphere, with high values indicating larger drought stress. In the figures VPD is largest along the border between Ethiopia and Somalia, where a large fraction of the population was displaced by food shortages. **Image credit**: Stephanie Granger

their companion microwave instruments that involves exploiting the fundamental similarities of the instruments, namely common spectral coverage and well-characterized resolution. **Daniel Nietfeld** [NOAA's National Weather Service] described the use of retrieved temperature and water vapor from CrIS in improving severe weather forecasts over the Midwestern U.S. He noted the advantages of having early afternoon satellite overpasses, which provide dense coverage via remote sounding observations midway between operational radiosonde launches.

Day Three: Validation; Atmospheric Composition and Aerosols; and Data Systems and Services

Tony Reale [NOAA's Center for Satellite Applications and Research] showed results of comparisons between operational radiosonde temperature and water vapor observations and retrievals from the four current hyperspectral infrared sounder systems listed earlier in this article. This analysis revealed that all sounder systems are meeting their design specifications for these two fundamental quantities. **Sun Wong** and **Peter Kalmus** [both from JPL] gave consecutive presentations, during which they showed comparisons between AIRS temperature and water vapor retrievals with boundary layer structure observed by radiosondes. **Wong** focused on observations over land while **Kalmus** focused on observations over water—see **Figure 2**. **Deijan Fu** [JPL] described a retrieval methodology designed to exploit radiance information in colocated observations from instruments with different orbital characteristics, including those in low-Earth and geosynchronous orbits. **Karen Cady-Pereira** [Atmospheric and Environmental Research] showed global ammonia retrievals from the IASI instruments and noted high values in regions with large aggregations of livestock. **Ding Feng** [GSFC] described data services being provided or developed for users of AIRS and CrIS datasets.

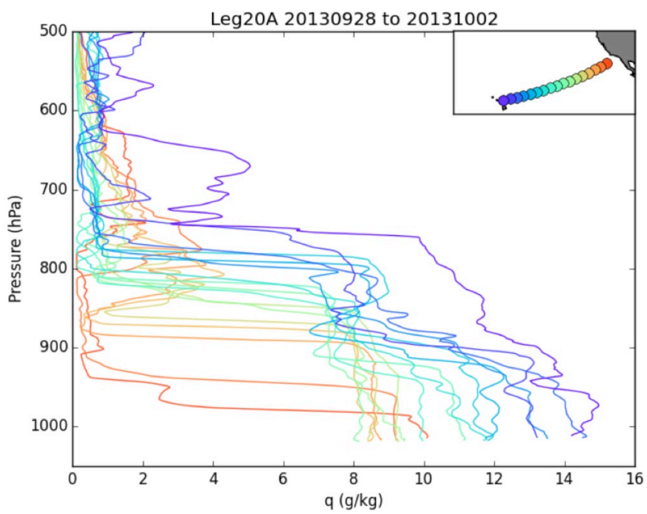

Figure 2. Radiosonde observations of atmospheric water vapor profiles obtained from a ship travelling over the northeastern Pacific Ocean between Los Angeles, CA, and Honolulu, HI during fall 2012. Line colors represent location as shown in the inset map at upper right. The sounder observations resolve some, but not all, of the vertical structure shown here. **Image credit:** Peter Kalmus, JPL

Day Four: Instrument Calibration and Level 2B Products

During the last day's single session, **Chris Hepplewhite** [University of Maryland, Baltimore County] showed comparisons of infrared radiances observed by AIRS, IASI, and CrIS, including spectra placed on a common wavenumber grid. He showed agreement within a few tenths of a Kelvin in brightness temperature. **Thomas Pagano** [JPL] examined the AIRS spatial and radiometric calibration by comparisons with colocated MODIS radiances. He showed that scene inhomogeneity, as measured by the finer fields-of-view of MODIS, has a small but detectable effect on AIRS radiances, and that MODIS data can be used to correct AIRS data.

Summary

The results shared at this meeting showed that observations from the current suite of sounders are a major reason for significant improvements in weather forecast skill over the past decade. The discussions also revealed that observations are providing new scientific insight into weather and climate processes. NASA Sounder Science Team Meetings, held twice a year, give the broad community an opportunity to share important new results and plan for future sounding instruments. The next meeting will be held March 22–24, 2016, in Pasadena, CA. ■

Summary of the 2015 Sun-Climate Symposium

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Introduction

The 2015 Sun-Climate Symposium took place November 10-13, 2015, in Savannah, GA. The Sun-Climate Research Center—established as a collaboration between NASA's Goddard Space Flight Center (GSFC) and the Laboratory for Atmospheric and Space Physics at the University of Colorado (LASP/CU)—organized the meeting. The conference focused on multidecadal variations in several physical phenomena in the sun and the Earth's systems since the early days of satellite-based data retrievals that began in the 1970s. There were eight sessions that covered solar irradiance measurements and modeling, solar influences on Earth's atmosphere and climate, variability observed in sun-like stars, and climate change and its impact on society. Over 80 scientists and students from around the world gathered to present their findings and to engage in spirited discussions. Most of the 2015 Sun-Climate Symposium presentations are available online at *tinyurl.com/qjfx6zh*.

Gary Rottman [LASP/CU], the original Solar Radiation and Climate Experiment (SORCE) Principal Investigator, opened the meeting with a keynote presentation on the solar variability record that began with the sunspot record in the 1600s, progressing to solar irradiance measurements from the ground to the space-based measurements that have continued since 1978—see **Figure 1**.

Acronyms Used in Figure 1: ERB, Earth Radiation Budget (onboard Nimbus 7); ERBS, Earth Radiation Budget Satellite; ACRIM, Active Cavity Radiometer Irradiance Monitor (onboard ACRIM); SOVA, SOlar VAriability experiment (onboard the Picard satellite); NOAA, National Oceanic and Atmospheric Administration; VIRGO, Variability of solar Irradiance and Gravity Oscillations [onboard the SOlar and Heliospheric Observatory (SOHO)]; SOVIM, SOlar Variations and Irradiance Monitor (onboard the International Space Station); SORCE/TIM, Total Irradiance Monitor onboard SORCE; TCTE/TIM, Total Irradiance Monitor for the Total Solar Irradiance Calibration Transfer Experiment onboard the U.S. Air Force's Space Test Program Satellite-3 (STPSat-3); PREMOS, PREcision Monitoring Of Solar Variability (onboard the Picard satellite).

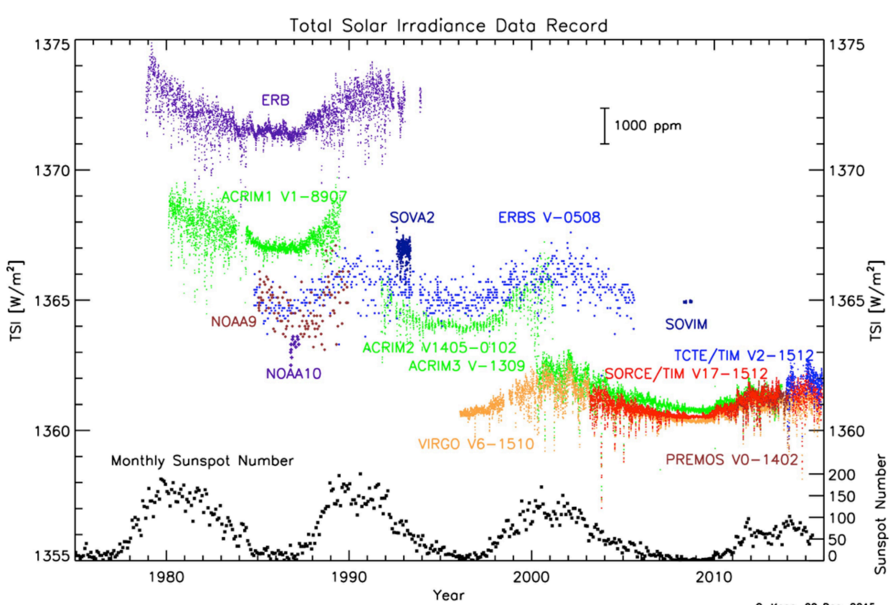


Figure 1. This figure shows 40 years of the solar climate data record. SORCE has had a direct contribution to this record. The SORCE Total Irradiance Monitor (TIM) and other recently calibrated total solar irradiance (TSI) sensors now indicate that the TSI level is near 1361 W/m^2. **Image credit**: Greg Kopp, LASP/CU

Session 1: Total Solar Irradiance Measurements and Modeling

This session focused on the total solar irradiance (TSI) measurements during solar cycles 23 and 24[1]. Included in the session were results from the recently revised Naval Research Laboratory TSI2 (NRLTSI2) empirical proxy model, the semi-empirical Spectral And Total Irradiance REconstruction (SATIRE) model, the San Fernando Observatory's TSI reconstructions using ground-based photometric indices, and historical reconstructions dating back to the Maunder Minimum, an unusually long-lasting period of low solar activity (i.e., as measured by the number of sunspots) lasting from roughly 1645 to 1715 AD. Such reconstructions help determine Earth's climate sensitivity to natural forcing as well as the solar causes of irradiance variations. One topic of discussion during the session was the potential trend in solar irradiance between the 1996 and 2008 solar cycle minima, because of its implications for long-term solar influences on climate change. The different TSI composites from space-borne measurements exhibit changes in minima that range from a decrease of 150 parts per million (ppm) (SATIRE model) to little or no decrease (NRLTSI2 model). Stability uncertainties of about 120 ppm limit the long-term variability results from the current TSI measurements and models, so there is no clear resolution of this important sun-climate issue.

Reconstructions of TSI generally indicate lower values during the Maunder Minimum at the end of what is known as the Little Ice Age[2]. The new Sunspot Index and Long-term Solar Observations (SILSO) sunspot record, released in July 2015, resolves some issues related to how measurements from different observers are combined and provides clarification about the criteria for defining a *sunspot group*. Session speakers estimated TSI levels during the Maunder Minimum to be 0.5 to 1.0 W/m^2 lower than modern cycle minima levels.

A TSI of 1361 W/m^2 has clearly been established over the past several years. The TSI community is now focusing on long-term stability, provided by linking data from temporally overlapping instruments such as those from SORCE's Total Irradiance Monitor (TIM) and other TSI instruments currently flying—see acronym list in Figure 1. International research teams are working to develop a community-composite TSI record. Once complete, this community composite will provide a new TSI record important for both solar and climate researchers.

Session 2: Sun-Climate Connection: Top-Down and Bottom-Up Couplings

This session explored the links between the sun and Earth's climate, including *top-down*—from atmosphere to surface—*and bottom-up*—from surface to atmosphere—couplings, addressing questions about the sun's influence on Earth's atmosphere during the satellite era and the skill of climate models to capture these links. The sun is Earth's primary source of energy, providing a globally averaged irradiance that is four orders of magnitude greater than Earth's interior heat flux—the next largest energy source. Solar spectral variability in the visible (400-700 nm) and near-infrared (700-4000 nm) regions of the electromagnetic spectrum drives the bottom-up couplings, while highly variable ultraviolet (UV) radiation, absorbed in the atmosphere by ozone (O_3) and oxygen, drives the top-down couplings. Even the variability in the sun's total energy over one solar cycle exceeds the energy of all other energy sources by an order of magnitude. Despite this, one of the difficulties in assessing the atmospheric response to solar variability is that several internal modes of variability are present, which may inhibit accurate detection. In particular, assessing and distinguishing between natural climate variability—e.g., the Pacific Decadal Oscillation (PDO) and Quasi Biennial Oscillation (QBO)—and anthropogenic forcing, and quantifying their relative contributions to climate change present formidable challenges.

One of these challenges is that the Whole Atmosphere Community Climate Model (WACCM) simulations do not find a persistent wintertime solar response in the polar vortex[3] when stratifying by QBO phase, but this contradicts observational data from 1953 to 2012. The model simulations also indicate solar cycle influences on gravity waves and wave-driven circulation. At solar maximum, the monthly-mean, zonal mean temperature in the Southern Hemisphere from July to October is between 2 and 5 K lower than the mean value in the stratosphere and between 3 and 6 K higher than average in the mesosphere and lower thermosphere (MLT). Both of these regions of Earth's atmosphere have well-established links to solar forcing. Using the 13 solar cycles from 1869 to 2009, another model study showed significant differences in temperature patterns between the phases for four of the cycles. The clearest pattern of the temperature anomalies is not found during sunspot maximum or minimum, but during the declining phase, when the temperature pattern closely resembles

[1] *Solar cycle 23* and *24* refer, respectively, to the twenty-third and twenty-fourth solar cycles since 1755. Solar cycle 23 ran from 1996 to 2008 with maximum activity in March 2000; solar cycle 24 is the current cycle, which began in 2008 and continues to the present. This solar cycle is on track to be the cycle with the lowest level of solar activity since 1906.

[2] The *Little Ice Age* was not a true "ice age." Rather, it was a longer-duration cooling event that lasted from about 1300 to 1850 AD. A variety of factors, including decreased solar activity, increased volcanic activity, changes in ocean circulation, natural climate variability, and decreases in human population have all been suggested as contributing to this multi-century cooling.

[3] Specifically, it has been suggested that there is a correlation between geopotential heights and the phase of the Quasi Biennial Oscillation.

the pattern found during the positive phase of the North Atlantic Oscillation. In a Goddard Institute for Space Studies (GISS) climate simulation, however, no clear 11-year solar forcing signals are found in surface temperature. Instead, there are large multidecadal surface temperature responses, where the planetary albedo is negatively correlated with the surface temperature. Another study, using the SOlar Climate Ozone Links (SOCOL) model within the framework of the International Global Atmospheric Chemistry/Stratospheric Processes And their Role on Climate, found solar cycle signals in lower-stratospheric temperature and O_3 time series. However, the solar signal could be misattributed to other signals, e.g., volcanic eruptions and the El Niño-Southern Oscillation (ENSO). Proper characterization requires either longer time series or periods that are not contaminated by volcanic aerosols. From these results, it is clear that both top-down and bottom-up couplings play a role, but challenges remain in modeling the solar forcing contributions at the required accuracies.

While solar cycle impacts are greatest in the upper atmosphere, anthropogenic effects also make significant contributions there. Carbon dioxide (CO_2) observations from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on NASA's Thermosphere Ionosphere Mesosphere Energetics Dyanamics (TIMED) satellite shows an increasing trend of ~5% per decade at ~80 km (~50 mi) and below, consistent with the tropospheric trend observed at Mauna Loa from anthropogenic forcing. Above 110 km (~68 mi), the SABER CO_2 trend is as large as ~12% per decade, a result that requires more sophisticated chemistry and transport modeling to fully understand the underlying processes.

Session 3: Climate Changes During the Space Era

The various multidecadal records obtained during the space era help to put current knowledge of climate change, including the sun's role, into perspective. **Drew Shindell** [Duke University] delivered a keynote presentation titled *Solar Forcing of Industrial Era Climate Change,* wherein he discussed the challenges of isolating solar forcing in observations and climate models due to overlapping temporal signals from other known climate drivers, such as volcanic activity. Earth system models have generally improved over time, but not all models fully represent the top-down response of known solar forcing. For example, solar variability in the UV imparts atmospheric temperature gradients that modulate upper stratospheric winds that could potentially impact physical processes in polar regions through dynamical propagation. There is evidence of solar forcing on regional scales in some models used in the Coupled Model Intercomparison Project (CMIP), and some changes, such as those found over Europe, can be much larger than the global average.

Discussion of Earth's radiation imbalance included comparisons of observed and modeled radiative fluxes at Earth's top-of-atmosphere (TOA), and the importance of TSI measurements for estimating the imbalance. The TOA imbalance determined by the Clouds and the Earth's Radiant Energy System (CERES[4]) instrumental record is 0.6 W/m^2 [values between 0.34 and 0.86 W/m^2 are within one standard deviation (1σ) of the mean], with no identifiable long-term trend. Relating the imbalance to atmospheric and surface variables remains a challenge because some climate feedbacks and climate forcings are not well known. Improved understanding requires reducing uncertainty in outgoing fluxes to 0.06% (0.2 W/m^2), comparable to the current uncertainty in TSI of 0.13 W/m^2.

Other presentations provided insights into discrepancies between the observational record and models of long-term trends of density and chemical species in the thermosphere. Increases in CO_2 trends related to the solar cycle from measurements made by SABER (~12% per decade at 110 km, or ~68 mi) were shown to be larger than model estimates from WACCM. This comparison emphasizes the importance of quantifying the solar cycle signal, which may be embedded within the 12 years of CO_2 observations from the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE FTS) launched on the Canadian SCISAT-1 satellite in 2003. These increasing trends, between 8 and 9% per decade in CO_x (the combined total of carbon monoxide (CO) and CO_2) in the mesosphere, exceed the estimated 5% per decade anthropogenic influence of CO and CO_2 at the surface and in the stratosphere. Changing the gravity wave parameterization in the WACCM model had the effect of significantly improving reproduction of SABER CO and CO_2 observations. In the thermosphere, because CO and CO_2 are the dominant infrared (IR) emitters, the thermosphere is cooling as CO and CO_2 increase. Consequently, thermospheric density is dramatically increasing near 400 km (~249 mi) as the thermosphere cools. For example, the 400-km density decreased by about 30% in 2008 relative to the previous solar cycle minimum in 1996. Solar extreme UV variability, geomagnetic activity, and changes in CO and CO_2 composition all help explain these decade-long changes in thermospheric density, but the changes are not all well reproduced by thermospheric models. Improved understanding of the long-term changes of the thermospheric density has a very practical implication for tracking satellites and orbital debris. Currently, there are more than 100,000 objects with sizes between 1 and 10 cm (~0.4 and 4 in)—versus only about 7500 objects larger than 10 cm—in low Earth orbit with perigee altitudes below 2000 km (~1243 mi). Calculating atmospheric drag is key to mitigating satellite collisions with such debris.

[4] CERES flies onboard NASA's Terra and Aqua satellites.

Session 4: Solar Spectral Irradiance Measurements and Modeling

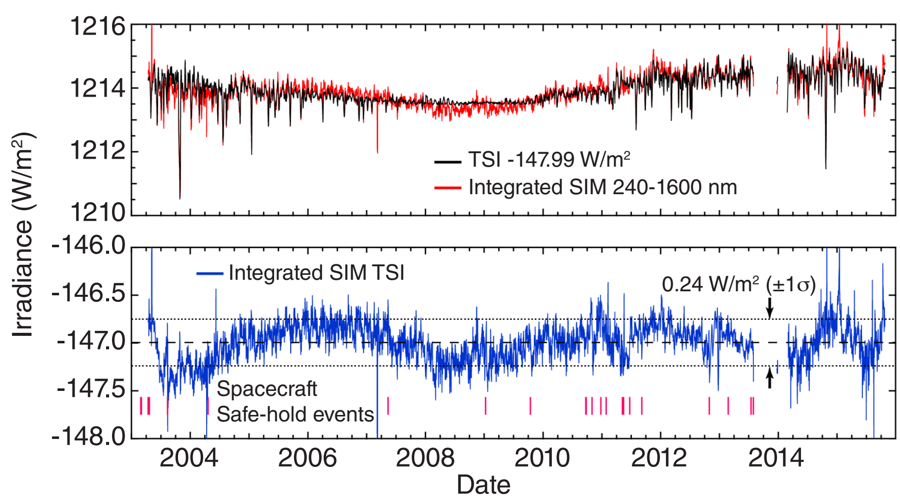
Solar spectral irradiance (SSI) is by far the strongest external forcing to Earth's climate system, so understanding the SSI measurement record is essential to understanding sun-climate connections. The two main themes of this session were modeling the solar physics that produces spectral irradiance variability and understanding uncertainties in the SSI observational record.

The magnitude and sign of SSI solar cycle variability during the SORCE mission has been under debate for several years. Presentations during this session examined the SORCE SSI results along with SSI variability models and other verification techniques such as the trending of O_3 measurements and the relationship between the 27-day rotational and 11-year solar cycle variability. These presentations clarified the range of variability of the SSI as a function of wavelength. Although UV variability is significantly larger than in the visible range, the magnitude of UV variability was debated. While measurements and models both support out-of-phase variability in the near infrared (NIR), they differ in variability trends in the visible—see **Figure 2**.

There were also solar physics presentations during this session ranging from purely theoretical radiative transfer models of the solar atmosphere to analysis of ground-based solar images. One highlight was the report from **Scott McIntosh** [National Center for Atmospheric Research/High Altitude Observatory] about the interaction of bands of activity on the sun over several solar cycles. This work may lead to a better understanding of the cause of the 11-year irradiance cycle and the 22-year solar magnetism cycle.

Session 5: Societal Impacts from Climate Change and Solar Variability

Global impacts on the severity and costs due to deleterious effects of climate change were highlighted in this session. Keynote speaker **Bruce Wielicki** [NASA's Langley Research Center] presented the results of detailed economic analyses using accurate climate monitoring methods, such as those planned for the future Climate Absolute Radiance and Refractivity Observatory (CLARREO), and various response scenarios to estimate the value of climate information. Shortened times-to-detection and earlier mitigation strategies revealed the risks and unrealized costs of delays in establishing a global climate program. A presentation on Atlantic sea-level rise drove home the severity of increased warming, with several examples of impacts around the globe.



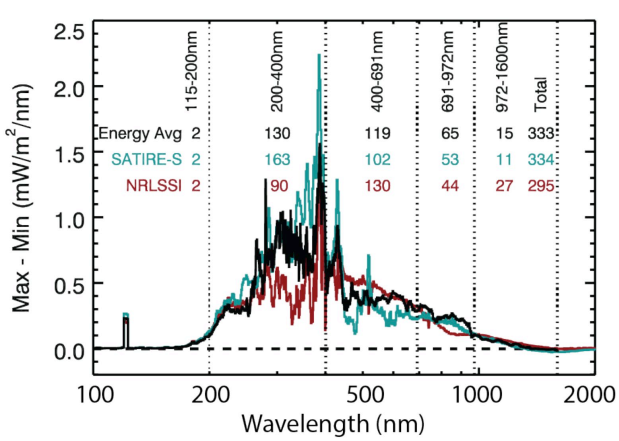


Figure 2. The integrated SSI from the SORCE Solar Irradiance Monitor (SIM) agrees well with the TSI time series from the SORCE TIM, as shown in the top two panels. However, there remain significant differences of the SSI variability between the SORCE measurements (Energy Average) and the SATIRE-S and NRLSSI models, particularly for near UV and visible wavelengths as shown in the bottom panel. **Image credit**: Jerry Harder, Tom Woods, LASP/CU

Session 6: Variability of the Sun-Like Stars

NOTE: *This session stood apart from others by moving outside of the solar-terrestrial domain to look at how the behavior of other stars may improve our understanding of the sun and its variability. By examining sun-like stars we can understand how typical the sun and its cyclic activity are. The recent Kepler mission and ground-based synoptic programs have helped to quantify the total and spectral irradiance variability of sun-like stars and in understanding what controls their cycle length and activity range.*

In his keynote address, surveying 60 years of monitoring sun-like stars via photometry and spectrophotometry, **Jeffrey Hall** [Lowell Observatory], vividly illustrated the importance of advances in observational techniques, including asteroseismology, precision astrometry, and radial velocity studies. The continuity of observing the same objects over the years has been an important lesson in showing that a small number of stars (e.g., 18 Scorpii) can justifably be called "solar twins" based on physical parameters and therefore, merit close study.

Other speakers in this session considered diverse space- and ground-based data acquisitions that reveal the range of behaviors of sun-like stars. Some show cyclic activity on timescales roughly comparable to the sun's, while others show no definite variation or hints of multiperiodicity. Some stars are similar to the sun in that they become brighter at visible wavelengths when they become more active, while others show the reverse behavior, reflecting the relative contributions of bright and dark atmospheric features such as plages and sunspots. Studying the sun alone has not enabled further development of the theory of *regenerative magnetofluid dynamos*—which is thought to underlie the activity of all sun-like stars. For predicting solar activity and space weather, researchers also need to confirm physical understanding of the thermal and velocity structure of the solar interior. As of yet, they have not been able to construct and test a comprehensive dynamo theory from first principles. One specific area of uncertainty surrounds exactly how the sun generates a poloidal (north-south) magnetic field component ("α effect") from the toroidal component generated by differential rotation ("Ω effect"). While there have been several semi-empirical models of the solar activity cycle proposed, the sun alone has not enabled researchers to choose which model most accurately represents reality.

Attendees agreed that combining data from synoptic ground-based programs with multiwavelength data from space missions such as SORCE will allow exploration of the range of activity exhibited by sun-like stars that have somewhat different masses, ages, rotation rates, and chemical compositions. The goal is to narrow the range of semi-empirical variability models to those that are capable of reproducing not only the sun's behavior, but also to describe and predict the behavior of sun-like stars. In this endeavor, it will be important to create a community resource that enables researchers to easily access and combine data from dozens of space- and ground-based observations. It will also be essential to continue synoptic programs and expand the sample of stars that have been tracked over multiple decades. Although synoptic observations have thus far been made mainly with ground-based programs, long-term monitoring of the sun and sun-like stars at soft X-ray wavelengths is also particularly important because these signals exhibit a strong cycle response but do not typically disappear during periods of weak activity.

Session 7: Challenges and Opportunities in Solar Observations

There are a wide variety of upcoming missions, instrument developments, and measurement capabilities that will extend the lessons-learned from previous missions to address needs for sun-climate and solar physics research. Presentations during this session described new sensors. For example, there is the Compact Spectral Irradiance Monitor (CSIM) being developed at LASP, that spans the entire solar spectrum. There are also advanced technologies in a variety of spectrometers, and innovative smaller and lighter CubeSat designs. These latter designs meet the same stringent requirements as existing sensors, such as the Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat mission.

There was a discussion of the status of the Total and Spectral Solar Irradiance Sensor (TSIS) and the Geostationary Operational Environmental Satellites-R Series (GOES-R) missions scheduled for launch within the next two years. These missions will ensure the continuity of climate records from the SORCE and GOES programs. In addition to advances in sensor technology, advances in launch facilities and inexpensive launch vehicles are also required. Aside from these space-based assets, profound improvements in our understanding of the sun will be driven by the sub-arcsecond observation capabilities of the Daniel K. Inouye Solar Telescope (DKIST) now under construction on Haleakala (the East Maui Volcano) in Hawaii.

The session closed with an overview of the NASA Solar Irradiance Science Team (SIST) program that will provide valuable datasets and improved models of TSI and SSI variability for the sun-climate research community. In 2014 NASA selected seven proposals to develop consistent multi-instrument/multi-platform space-based datasets of solar irradiance. Over three years the teams will explore drifts in instrument operation, apply calibration advances for more consistent past and present data records, and compare all solar irradiance measurements to better understand the long-term solar irradiance records. One expected improvement is the establishment of total and spectral irradiance uncertainties

Attendees at the 2015 Sun-Climate Symposium in Savannah, GA. **Photo credit**: Vanessa George, LASP/CU

over multiple datasets, helping to constrain general circulation models and atmospheric chemistry and transport models.

Session 8: Next-Generation Observing Systems for Climate Records

The discussions in Session 3 on *Climate Changes During the Space Era*, and in particular **Norman Loeb's** [NASA's Langley Research Center] presentation on *Earth's Radiation Imbalance Observed from Space*, made clear that next-generation observing systems with advanced sensors and implementation strategies are essential to meet the current and future challenges facing climate change studies. The discussion during Session 8 focused on the broad challenges that will be faced by critical future Earth science observations central to our understanding of the climate system.

Keynote speaker **Hank Revercomb** [University of Wisconsin, Madison] introduced many of these challenges in an overview of the CLARREO Climate Benchmarking Mission. He emphasized the need for increased measurement accuracy and spectral resolution required for climate-trend detection and attribution. Two other examples of next-generation instruments are the Absolute Radiance Interferometer (ARI) to measure spectrally-resolved long-wave IR emissions with increased accuracy (with less than 0.1 K uncertainty in brightness temperature) and the Earth Climate Hyperspectral Observatory (ECHO), a proposed pathfinder mission for CLARREO, to provide a more accurate measurement of the spectrally-resolved Earth-reflected shortwave radiation. These technology advances are proving valuable assets toward final implementation on emerging orbital systems to quantify the full Earth radiation budget across the spectrum, from the UV to the far IR.

SORCE and several other more recently launched missions are already providing important global data to describe Earth's climate system, with unprecedented coverage of the atmosphere, land, sea, and ice. From high-cadence atmospheric-column-CO_2 profiles to reflectance observations of the diurnal variations of aerosols, clouds, and vegetation, scientists are beginning to refine the needed observational and geosampling strategies required of a twenty-first century climate observational system. While the strategies and technology are mature, funding limitations remains the biggest challenge.

Conclusion

NASA Earth Science missions, including SORCE, have been critical for advancing our understanding of Earth's complex systems and their connection with the solar environment in which they are embedded. New climate missions are required to continue these valuable climate records. The 2015 Sun-Climate Symposium underscored this theme by emphasizing solar variability and Earth's climate during the satellite observational era. Although this period covers just a little more than three solar cycles—which by climate standards is but a "snapshot"—the knowledge gained from the vantage point of space has already vastly improved our understanding of how the sun's energy varies and how Earth's systems respond. The Sun-Climate Symposium addressed these issues in the context of present-day climate change and its anthropogenic and natural drivers. The multidisciplinary nature of the meeting brought together specialists in measuring and modeling the sun's output and Earth's radiation budget; climate and atmospheric modelers, who interpret those and other forcings and quantify Earth's changing environment; solar physicists, who study how the sun varies; and other specialists developing new instruments and missions to address a wide range of topics. Overall, the organizers were very pleased with this meeting and look forward to the next, when updates on some of the most vexing issues in Sun-Earth connections will be discussed, and new questions are sure to arise.

To stay up to date on the latest SORCE news and meeting announcements, read the SORCE newsletter at *lasp.colorado.edu/home/sorce/news-events/newsletter*. ■

Study Shows Climate Change Rapidly Warming World's Lakes

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

Climate change is rapidly warming lakes around the world, threatening freshwater supplies and ecosystems, according to a new NASA and National Science Foundation-funded study[1] of more than half of the world's freshwater supply.

Using more than 25 years of satellite temperature data and ground measurements of 235 lakes (see **Figure 1**) on six continents, this study—the largest of its kind—found lakes are warming an average of 0.61 °F (0.34 °C) each decade—see **Figure 2**. The scientists say this is greater than the warming rate of either the ocean or the atmosphere—and it can have profound effects.

As warming rates increase over the next century, algal blooms, which can rob water of oxygen, are projected to increase 20% in lakes. Algal blooms that are toxic to fish and animals are expected to increase by 5%. Emissions of methane, a greenhouse gas 25 times more powerful than carbon dioxide on 100-year time scales, will increase 4% over the next decade, if these rates continue.

"Society depends on surface water for the vast majority of human uses," said co-author **Stephanie Hampton** [Washington State University, Pullman—*Director of the Center for Environmental Research, Education and Outreach*]. "Not just for drinking water, but manufacturing, for energy production, and for irrigation of our crops. Protein from freshwater fish is especially important in the developing world."

Figure 1. A combination of satellite data and ground measurements, such as from instrumented buoys like this one in Lake Tahoe on the California/Nevada border, were used to provide a comprehensive view of changing lake temperatures worldwide. The buoy measures the water temperature from above and below. **Image credit**: Limnotech

Water temperature influences a host of other properties critical to the health and viability of ecosystems. When temperatures swing quickly and widely from the norm, life forms in a lake can change dramatically and even disappear.

[1] The research, published in *Geophysical Research Letters*, was announced December 16, 2015, at the American Geophysical Union meeting in San Francisco, CA.

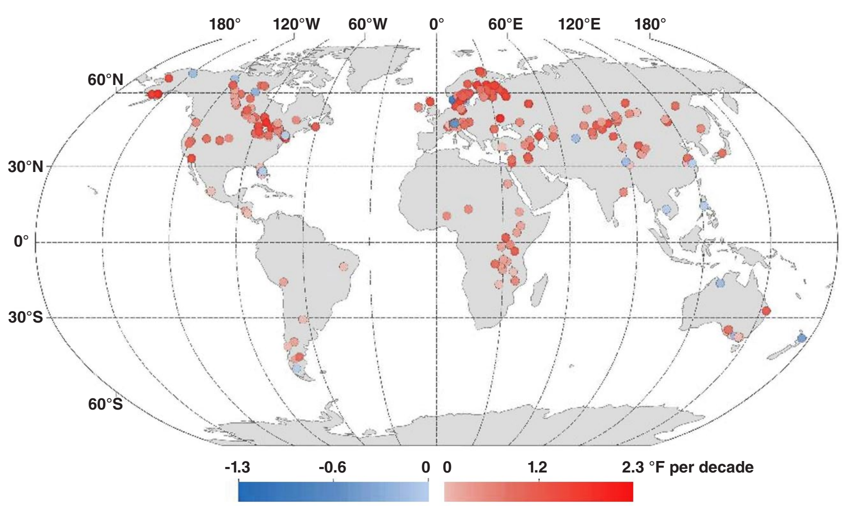

Figure 2. Global changes in lake temperatures over the past 25 years. Red dots indicate warming; blue dots indicate cooling. The study found Earth's lakes are warming about 0.61 °F (0.34 °C) per decade on average—faster than overall warming rates for the ocean and atmosphere. **Image credit**: Illinois State University/U.S. Geological Survey/California University of Pennsylvania

"These results suggest that large changes in our lakes are not only unavoidable, but are probably already happening," said lead study author **Catherine O'Reilly** [Illinois State University, Normal—*Associate Professor of Geology*]. Earlier research by O'Reilly has seen declining productivity in lakes with rising temperatures.

Study co-author **Simon Hook** [NASA/Jet Propulsion Laboratory—*Science Division Manager*] said satellite measurements provide a broad view of lake temperatures over the entire globe. However, satellites only measure surface temperature, while ground measurements can detect temperature changes throughout a lake. Also, while satellite measurements go back 30 years, some lake measurements go back more than a century. "Combining the ground and satellite measurements provides the most comprehensive view of how lake temperatures are changing around the world," he said.

The researchers said various climate factors are associated with the warming trend. In northern climates, lakes are losing their ice cover earlier in the spring and many areas of the world have less cloud cover, exposing their waters more to the sun's warming rays.

In a previous study Hook used satellite data to show that many lake temperatures were warming faster than air temperature and that the greatest warming was observed at high latitudes, as seen in other climate warming studies. This new research confirmed those earlier observations, with average warming rates of 1.3 °F (0.72 °C) per decade at high latitudes.

Warm-water tropical lakes may be seeing less dramatic temperature increases, but increased warming of these lakes still can have significant negative impacts on fish. That can be particularly important in the African Great Lakes, where fish are a major source of food.

"We want to be careful that we don't dismiss some of these lower rates of change," said Hampton. "In warmer lakes, those temperature changes can be really important. They can be just as important as a higher rate of change in a cooler lake."

In general, the researchers write, "The pervasive and rapid warming observed here signals the urgent need to incorporate climate impacts into vulnerability assessments and adaptation efforts for lakes." ■

kudos

Congratulations to AAAS Fellows!

The Earth Observer is pleased to acknowledge researchers in Earth-science disciplines from NASA field centers who have been named Fellows of the American Association for the Advancement of Science (AAAS). Election as an AAAS Fellow is an honor bestowed upon Association members by their peers in recognition for meritorious efforts to advance science or its applications.

Section on Atmospheric and Hydrospheric Sciences

- **Jose Rodriguez** [NASA's Goddard Space Flight Center (GSFC)—*Chief of the Atmospheric Chemistry and Dynamics Laboratory*]
- **Compton "Jim" Tucker** [GSFC—*Senior Research Scientist*]
- **Michael King** [University of Colorado Boulder—*Former EOS Senior Project Scientist*]

Section on Education

- **Lin Chambers** [NASA's Langley Research Center—*Physical Scientist of Climate and Radiation Studies and Director of the CERES S'COOL Project*]

These individuals were recognized for their contributions to science and technology at the Fellows Forum, held on February 13, 2016, during the AAAS Annual Meeting in Washington, DC.

To see the full list of AAAS fellows, visit *www.aaas.org/elected-fellows*.

NASA Finds New Way to Track Ocean Currents from Space

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

A team of NASA and university scientists has developed a new way to use satellite measurements to track changes in Atlantic Ocean currents, which are a driving force in global climate. The finding[1] opens a path to better monitoring and understanding of how ocean circulation is changing and what the changes may mean for future climate.

In the Atlantic, currents at the ocean surface, such as the Gulf Stream, carry sun-warmed water from the tropics northeastward. As the water moves through colder regions, it sheds its heat. By the time it gets to Greenland, it's so cold and dense that it sinks a couple of miles down into the ocean depths. There it turns and flows back south. This open loop of shallow and deep currents is known to oceanographers as the Atlantic Meridional Overturning Circulation (AMOC)—part of the "conveyor belt" of ocean currents circulating water, heat, and nutrients around the globe and affecting climate.

Because the AMOC moves so much heat, any change in it is likely to be an important indicator of how our planet is responding to warming caused by increasing greenhouse gases. In the last decade, a few isolated measurements have suggested that the AMOC is slowing down and moving less water. Many researchers are expecting the current to weaken as a consequence of global warming, but natural variations may also be involved. To better understand what is going on, scientists would like to have consistent observations over time that cover the entire Atlantic.

"This [new] satellite approach allows us to improve projections of future changes and—quite literally—get to the bottom of what drives ocean current changes," said **Felix Landerer** [NASA/Jet Propulsion Laboratory (JPL)—*Team Leader*].

Landerer and his colleagues used data from NASA's twin Gravity Recovery and Climate Experiment (GRACE) satellites. Launched in 2002, GRACE provides a monthly record of tiny changes in Earth's gravitational field, caused by changes in the amount of mass below the satellites. The mass of Earth's land surfaces doesn't change much over the course of a month; but the mass of water on or near Earth's surface does, for example, as ice sheets melt and water is pumped from underground aquifers. GRACE has proved invaluable in tracking these changes.

At the bottom of the atmosphere—on Earth's surface—changes in air pressure (a measure of the mass of the air) tell us about flowing air, or wind. At the bottom of the ocean, changes in pressure tell us about flowing water, or currents. Landerer and his team developed a way to isolate, in the GRACE gravity data, the signal of tiny pressure differences at the ocean bottom that are caused by changes in the deep ocean currents.

"We've wanted to observe this phenomenon with GRACE since we launched 13 years ago, but it took us this long to figure out how to squeeze the information out of the data stream," said **Michael Watkins** [University of Texas at Austin—*Director of the Center for Space Research*], former GRACE Project Scientist and a co-author of the study.

The squeezing process required some very advanced data processing, but not as many data points as one might think. "In principle, you'd think you'd have to measure every 10 yds (~9 m) or so across the ocean to know the whole flow," Landerer explained. "But in fact, if you can measure the farthest eastern and western points very accurately, that's all you need [to figure out] how much water is flowing north and south in the entire Atlantic at that section. That theory has long been known and is exploited in buoy networks, but this is the first time we've been able to do it successfully from space."

The new measurements agreed well with estimates from a network of ocean buoys that span the Atlantic Ocean near 26° N latitude. The agreement gives the researchers confidence that the technique can be expanded to provide estimates throughout the Atlantic. In fact, the GRACE measurements showed that a significant weakening in the overturning circulation, which the buoys recorded in the winter of 2009-10, extended several thousand miles north and south of the buoys' latitude.

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[1] A paper in the journal *Geophysical Research Letters* describing the new technique and first results is available online in prepublication form at *onlinelibrary.wiley.com/doi/10.1002/2015GL065730/abstract?campaign=wolacceptedarticle*.

New NASA Satellite Maps Show Human Fingerprint on Global Air Quality

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

Using new, high-resolution global satellite maps of air quality indicators, NASA scientists tracked air pollution trends over the last decade in various regions and 195 cities around the globe[1].

"These changes in air quality patterns aren't random," said **Bryan Duncan** [NASA's Goddard Space Flight Center], who led the research. "When governments step in and say we're going to build something here or we're going to regulate this pollutant, you see the impact in the data."

Duncan and his team examined observations made from 2005 to 2014 by the Dutch-Finnish Ozone Monitoring Instrument (OMI) onboard NASA's Aura satellite. One of the atmospheric gases that OMI detects is nitrogen dioxide (NO_2), a yellow-brown gas that is a common emission from cars, power plants, and industrial activity. NO_2 can quickly transform into ground-level ozone, a major respiratory pollutant in urban smog. NO_2 hotspots, used as an indicator of general air quality, occur over most major cities in developed and developing nations.

The science team analyzed year-to-year trends in NO_2 levels around the world. To look for possible explanations for the trends, the researchers compared the satellite record to information about emissions controls regulations, national gross domestic product, and urban growth.

"With the new high-resolution data, we are now able to zoom down to study pollution changes within cities, including from some individual sources, like large power plants," said Duncan.

Previous work using satellites at lower resolution missed variations over short distances. This new space-based view offers consistent information on pollution for cities or countries that may have limited ground-based air monitoring stations. The resulting trend maps tell a unique story for each region.

The U.S. and Europe are among the largest emitters of NO_2. Both regions also showed the most dramatic reductions between 2005 and 2014. NO_2 has decreased between 20 and 50% in the United States (see **Figure 1**), and by as much as 50% in Western Europe. Researchers concluded that the reductions are largely due to the effects of environmental regulations that require technological improvements to reduce pollution emissions from cars and power plants.

China, the world's growing manufacturing hub, saw an increase between 20 and 50% in NO_2, much of it occurring over the North China Plain—see **Figure 2**. Three

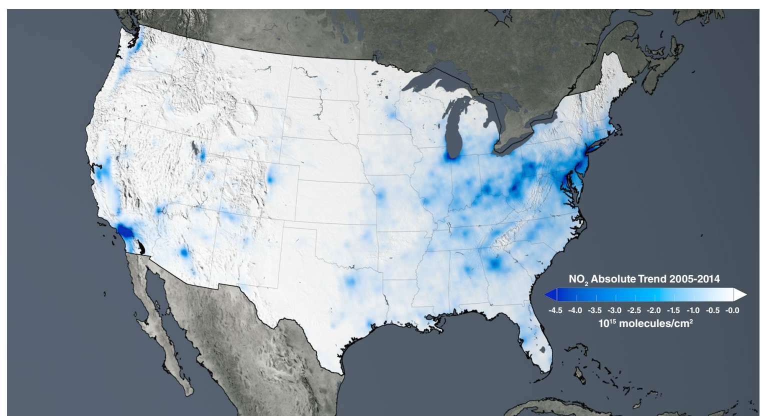

Figure 1. The trend map of the U.S. shows the large decreases in NO_2 concentrations tied to environmental regulations implemented from 2005 to 2014. **Image credit:** NASA

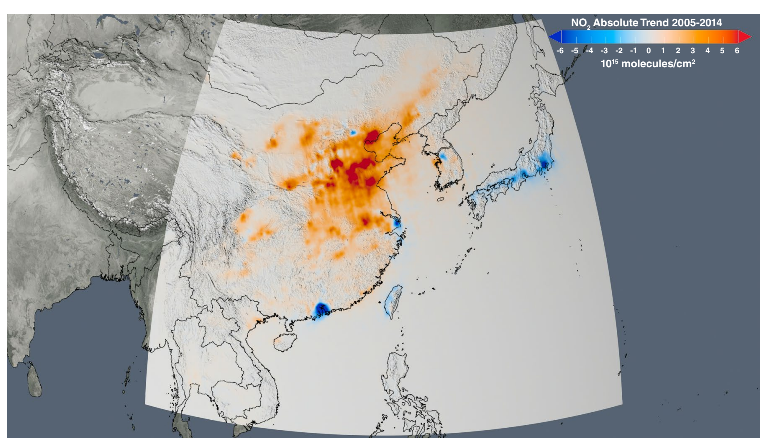

Figure 2. The trend map of East Asia shows the change in NO_2 concentrations related to a mix of economic growth and environmental controls across China, South Korea, and Japan from 2005 to 2014. **Image credit:** NASA

[1] The findings were presented December 14, 2015, at the American Geophysical Union meeting in San Francisco, CA and published in the *Journal of Geophysical Research*.

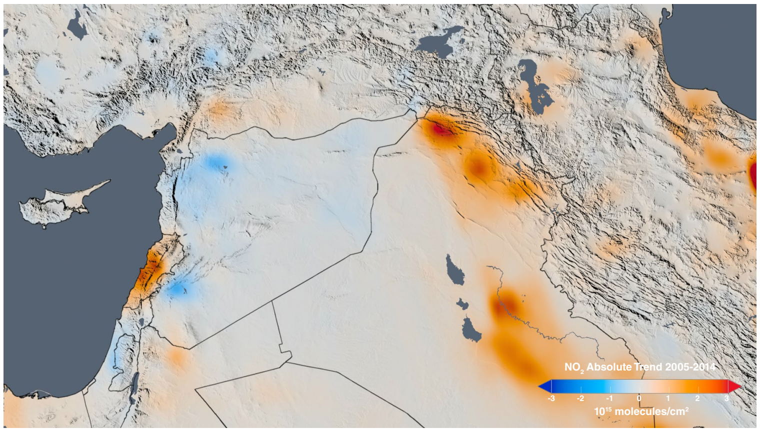

Figure 3. The trend map of the Middle East shows the change in NO_2 concentrations from 2005 to 2014. The decreases in Syria are tied to the economic disruption caused by their civil war. **Image credit:** NASA

major Chinese metropolitan areas—Beijing, Shanghai, and the Pearl River Delta—saw NO_2 reductions of as much as 40%.

The South African region encompassing Johannesburg and Pretoria has the highest NO_2 levels in the Southern Hemisphere, but the high-resolution trend map shows a complex situation playing out between the two cities and neighboring power plants and industrial areas. "We had seen seemingly contradictory trends over this area of industrial South Africa in previous studies," said **Anne Thompson** [NASA's Goddard Space Flight Center—*Chief Scientist for Atmospheric Chemistry*], co-author of the study. "Until we had this new space view, it was a mystery."

The Johannesburg-Pretoria metro area saw decreases after 2008, when new cars were required to have better emissions controls. The heavily industrialized area just east of the cities, however, shows both decreases and increases. The decreases may be associated with fewer emissions from eight large power plants east of the cities since the decrease occurs over their locations. However, emissions increases, from various other mining and industrial activities, occur to the south and further east.

In the Middle East, increased NO_2 levels in Iraq, Kuwait, and Iran since 2005 likely correspond to economic growth in those countries. However, in Syria, NO_2 levels decreased since 2011, most likely because of the civil war, which has interrupted economic activity and displaced millions of people—see **Figure 3**.

To view and download high-resolution air quality maps, visit *svs.gsfc.nasa.gov/12094*. For more on NASA's research into NO_2, and air quality data for 195 cities, visit *airquality.gsfc.nasa.gov*. ■

NASA Finds New Way to Track Ocean Currents from Space

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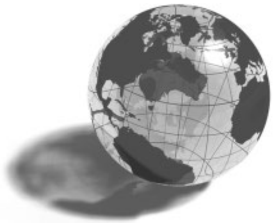
The ocean buoy network, known as RAPID, is operated by the Rapid Climate Change group at the U.K.'s National Oceanography Centre, Southampton, together with the University of Miami and the Atlantic Oceanographic and Meteorological Laboratory of the National Oceanic and Atmospheric Administration.

Gerard McCarthy [RAPID], who was not involved with the study, said, "The results highlight synergies between [direct measurements] like [those from] RAPID and remote sensing—all the more important given the rapid and surprising changes occurring in the North Atlantic at the present time." **Eric Lindstrom** [NASA Headquarters—*Physical Oceanography Program Manager*] pointed out, "It's awesome that GRACE can see variations of deep water transport, [but] this signal might never have been detected or verified without the RAPID array. We will continue to need both *in situ* and space-based systems to monitor the subtle but significant variations of the ocean circulation." ■



NASA Earth Science in the News

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

Temperatures Spike Almost 50 Degrees at the North Pole, January 1, *Fox News*; A heat wave of sorts at the North Pole the week of December 27, 2015, might have had Santa trading in his sleigh for swim trunks. Temperatures were as much as 50 degrees above average on Wednesday, December 30, 2015—almost reaching 32 °F in portions of the Arctic Circle that average -20 °F at this time of year. The briefly balmy conditions alone are unlikely to cause any lasting damage in the Arctic. However, scientists say it exemplifies the challenges facing a region that has been seeing record losses of ice due to rising temperatures around the globe. In December the National Oceanic and Atmospheric Administration (NOAA) reported that November Arctic sea ice was 360,000 mi^2 (~932,400 km^2), or 8.3% below the 1981-2010 average. This was the sixth smallest November extent since data recordings began in 1979, according to analysis by the National Snow and Ice Data Center using data from NOAA and NASA.

NASA Predicts "Weather Chaos" from Strong El Niño, December 30; *The Hill*. A strengthening El Niño is set to wreak "weather chaos" in the U.S. in 2016, warn NASA climate scientists. The current El Niño, a weather pattern characterized by high sea surface temperatures in the central and eastern Pacific Ocean, is growing into one of the strongest on record. As a result, federal agency forecasters expect cold and wet weather in the southern U.S. and warm and dry weather over northern portions of the country. Officials haven't nailed down the exact weather conditions El Niño will bring, but NASA compared the 2015–2016 event to the last stout El Niño in 1997–98 (see **Figure**)—a "wild ride" that brought mild weather and low snowfall to traditionally wintery areas of the country and severe rainstorms to the Southwest. "In early 2015 atmospheric conditions changed, and El Niño steadily expanded in the central and eastern Pacific," **Josh Willis** [NASA/Jet Propulsion Laboratory—*Scientist*] said in a statement. "Although the sea surface height signal in 1997 was more intense and peaked in November of that year, in 2015 the area of high sea levels is larger. This could mean we have not yet seen the peak of this El Niño."

***As Planet Warms, the World's Lakes are Heating Up Even Faster**, December 29; *The Washington Post*. Lakes around the world are growing rapidly warmer. According to a new scientific study co-funded by NASA and the National Science Foundation, potential consequences range from depleted fisheries to harmful algae blooms that kill fish and contaminate water supplies for cities large and small. Warmer freshwater lakes are yet another sign of global climate change,

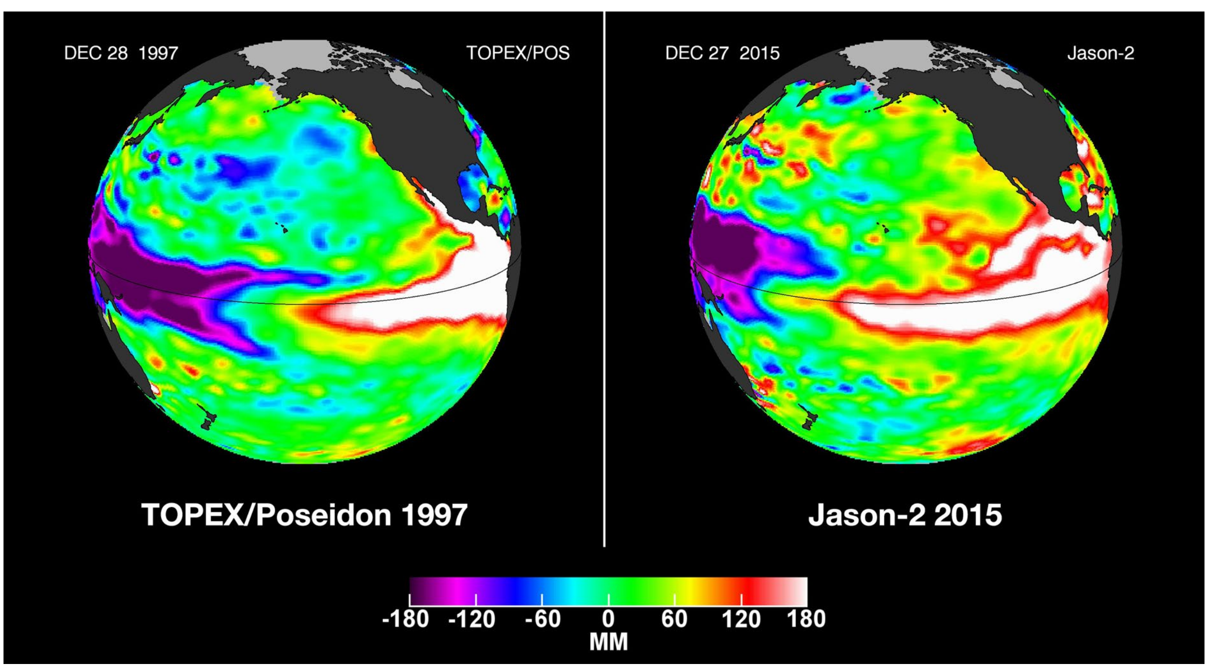


Figure. Satellite image of Pacific sea surface heights from Jason-2 [*right*] differs slightly from one 18 years ago from TOPEX/Poseidon [*left*]. While SSH was more intense in December 1997, the area of high sea levels was considerably broader in December 2015. **Image credit:** NASA and their temperatures are increasing at a faster rate compared to the warming seen in the ocean and atmosphere, as reported in the peer-reviewed journal *Geographical Research Letters*. The study is based on decades of measurements from 235 lakes that contain more than half the world's fresh water supply. On average, temperatures are rising by about six-tenths of a degree Fahrenheit per decade, a rapid increase by geological timescales.

Methane Emissions in Arctic Cold Season Higher than Expected, December 21; *phys.org*. The amount of methane gas escaping from the ground during the long cold period in the Arctic each year and entering Earth's atmosphere is likely much higher than estimated by current climate change models, concludes a major new study led by San Diego State University (SDSU). A team comprising researchers from SDSU, Open University, University of Sheffield, NASA/Jet Propulsion Laboratory, Harvard University, NOAA, and the University of Montana found that far more methane is escaping from Arctic tundra during the cold months (generally from September through May)—when the soil surface is frozen—as well as from upland tundra, than prevailing assumptions and climate modelers previously believed. In fact, they found that at least half of the annual methane emissions occur in the cold months, and that drier, upland tundra can be a larger emitter of methane than wet tundra. The finding challenges critical assumptions in current global climate models. The results are published in the *Proceedings of the National Academy of Sciences*.

November, Autumn, and Year-to-Date were All Hottest on Record for Earth, December 17; *The Washington Post*. November 2015 was the warmest such month on record for the planet, say NOAA scientists. But November's record-breaking temperature is far from the most remarkable result in 2015—which was an incredible year for Earth, toppling temperature records left and right. November's average temperature across land and ocean was an exceptional 1.75 °C (3.15 °F) above the twentieth century average, exceeding the previous record set in 2013 by 0.27 °C (0.49 °F). The November temperature departure—1.75 °C—was the second highest of any month in NOAA's 136-year period of record. The highest was just set one month before in October, at 1.79 °C (3.22 °F). On Tuesday, NASA also announced that November was 1.9 °C (3.4 °F) above its base period from 1951 to 1980. It was the second month that exceeded the significant 1-degree Celsius threshold in NASA's records; the first was October.

*See news story in this issue.

*Interested in getting your research out to the general public, educators, and the scientific community? Please contact **Samson Reiny** on NASA's Earth Science News Team at **samson.k.reiny@nasa.gov** and let him know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of **The Earth Observer**.* ■

Undefined Acronyms Used in the Editorial and Article Titles

AAAS	American Association for the Advancement of Science
ASDC	Atmospheric Sciences Data Center
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CNES	Centre Nationale d'Études Spatiale [French Space Agency]
DAAC	Distributed Active Archive Center
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
GSFC	NASA's Goddard Space Flight Center
GMAO	Global Modeling and Assimilation Office
JPL	NASA/Jet Propulsion Laboratory
LaRC	NASA's Langley Research Center
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
OSTM	Ocean Surface Topography Experiment
SORCE	Solar Radiation and Climate Experiment
TOPEX	Ocean Topography Experiment

NASA Science Mission Directorate – Science Education and Public Outreach Update

Theresa Schwerin, Institute for Global Environmental Strategies, theresa_schwerin@strategies.org
Andrew Clark, Institute for Global Environmental Strategies, andrew_clark@strategies.org

NASA Postdoctoral Fellowships

Audience: Postdoctoral students (doctoral degree attained by the time the appointment begins).

Application Deadline: March 1, 2016

The NASA Postdoctoral Program (NPP) offers scientists and engineers unique opportunities to engage in NASA research in Earth science, heliophysics, astrophysics, planetary science, astrobiology, space bioscience, aeronautics and engineering, human exploration and operations, and space technology.

Awards: Annual stipends start at $53,500, with supplements for specific degree fields and high cost-of-living areas. There is an annual travel budget of $8000, a relocation allowance, and financial supplement for health insurance purchased through the program. Approximately 90 fellowships are awarded annually.

Eligibility: U.S. citizens, lawful permanent residents, or foreign nationals eligible for J-1 status as a research scholar may apply. Applicants must have completed a PhD or equivalent degree before beginning the fellowship, but may apply while completing the degree requirements. Fellowships are available to recent or senior-level PhD recipients.

To obtain more information and to apply for this exciting opportunity, visit *nasa.orau.org/postdoc*.

"Where Over the World Is Astronaut Scott Kelly?" Trivia Contest

During his year-long stay on the International Space Station, astronaut **Scott Kelly** wants to test your knowledge of the world through a geography trivia game on Twitter. Traveling more than 220 mi (354 km) above Earth, and at 17,500 mph (28,163 km/hr), he circumnavigates the globe more than a dozen times a day. This gives Kelly many opportunities to see and photograph interesting geographical locations on Earth. In fact, part of his job while in space is to capture images of Earth for scientific observations.

Follow *@StationCDRKelly* on *Twitter*, where each Wednesday Kelly will tweet a picture and ask the public to identify the place depicted in the photo. The first person to identify the place correctly will win an autographed copy of the picture. Kelly plans to continue posting weekly contest photos until he returns from the space station in March 2016.

For more information, visit *www.nasa.gov/feature/where-over-the-world-is-astronaut-scott-kelly*.

To learn more about the One-Year Mission, visit *www.nasa.gov/content/one-year-crew*.

NASA Goddard Institute for Space Studies Seek Students for Climate Research Initiative

Audience: High School and Undergraduate Students

Application Deadline: March 1, 2016

The NASA Goddard Institute for Space Studies (GISS) Climate Change Research Initiative (CCRI) is a summer 2016 internship opportunity for high school and undergraduate students. Winners will work directly with NASA scientists on a NASA climate-change research project.

The research team—consisting of the selected students, graduate students, and high school science, technology, engineering, and math (STEM) educators—will be led by GISS scientists in activities related to their work.

To complete their component of the research project during the summer session, the high school intern will work for 40 hours per week for six weeks; the undergraduate student will work 40 hours per week for eight weeks. Interns will write a research paper and create a PowerPoint presentation and a scientific poster to be presented at GISS and the City University of New York (CUNY) Cooperative Remote Sensing Science and Technology Center (CREST) Summer STEM Symposium. For more information and to apply, visit *www.giss.nasa.gov/edu/ccri/ccri_intern.pdf*. ■

EOS Science Calendar

March 1–3, 2016
CALIPSO/CloudSat Science Team Meeting, Newport News, VA.
stm.dpc.cira.colostate.edu

March 22–24, 2016
AIRS Science Team Meeting, Pasadena, CA
airs.jpl.nasa.gov/events

April 18–19, 2016
LCLUC Science Team Meeting, Bethesda, MD.
lcluc.umd.edu/meetings.php

April 26–28, 2016
CERES Science Team Meeting, Hampton, VA.
ceres.larc.nasa.gov

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

Global Change Calendar

February 21–26, 2016
2016 Ocean Sciences Meeting, New Orleans, LA.
osm.agu.org/2016

April 17–22, 2016
European Geosciences Union General Assembly, Vienna, Austria.
www.egu2016.eu

April 20–21, 2016
MuSLI Science Team Meeting, Bethesda, MD.
lcluc.umd.edu/meetings.php

May 6–7, 2016
Second EARSeL SIG LU/LC and NASA LCLUC Joint Workshop, Prague, Czech Republic.
lcluc.umd.edu/Documents/Announcements/Leaflet_workshop.pdf

May 22–26, 2016
Japan Geoscience Union Meeting, Makuhari Messe, Japan.
www.jpgu.org/meeting_e2016/greeting.html

July 31–August 5, 2016
AOGS 13th Annual Meeting, Beijing, China.
www.asiaoceania.org/aogs2016/public.asp?page=home.htm

October 25–28, 2016
GSA Annual Meeting, Denver, CO.
www.geosociety.org/meetings/2016

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Articles, contributions to the meeting calendar, and suggestions are welcomed. Contributions to the calendars should contain location, person to contact, telephone number, and e-mail address. Newsletter content is due on the weekday closest to the 15th of the month preceding the publication—e.g., December 15 for the January–February issue; February 15 for March–April, and so on.

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