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## Editor's Corner

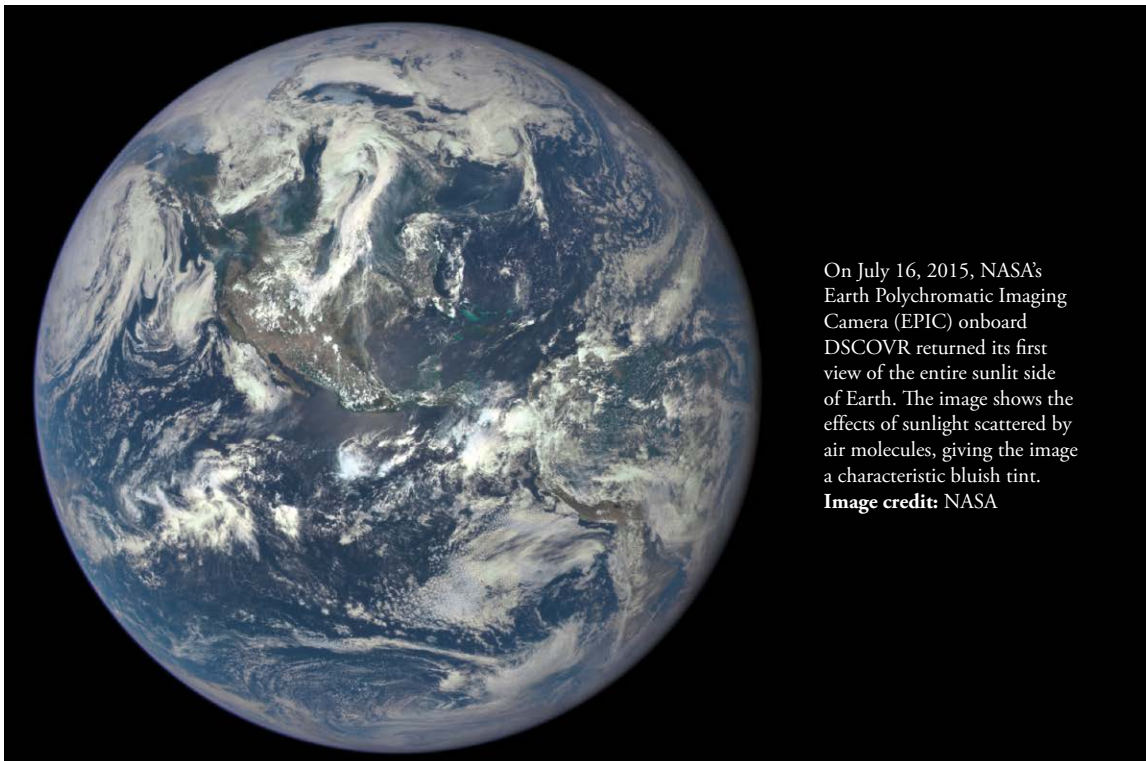
*Steve Platnick*

*EOS Senior Project Scientist*

We are happy to report that the Deep Space Climate Observatory (DSCOVR<sup>1</sup>) spacecraft was successfully inserted into its orbit at the first Earth-Sun Lagrange point (L1)—about 1.5 million kilometers (930,000 miles) from Earth—on June 7, 2015. At this time, all instruments are undergoing test and in-flight calibrations during the commissioning phase. While NOAA has responsibility for the mission's three space weather instruments, DSCOVR includes two NASA Earth-observing instruments: the Earth Polychromatic Imaging Camera (EPIC) and the National Institute of Standards and Technology Advanced Radiometer (NISTAR). EPIC has obtained an initial series of Earth images in all 10 narrow band filter positions (wavelength range from 317 to 780 nm). Tests currently are being performed to determine optimum exposure times. The first lunar calibration test was performed on July 2, 2015, corresponding to a full moon as seen from Earth. EPIC's observations provide a unique perspective for science, with products being developed to provide ozone, sulfur dioxide, aerosol, cloud height and vegetation properties. In addition to the science products, a full disk true color "Blue Marble" image from sunrise to sunset will be produced about every two hours. EPIC and NISTAR data will be available from NASA's Langley Research Center's Atmospheric Sciences Data Center archive after the raw data have been calibrated and officially released by the project. Congratulations to the entire DSCOVR team and best wishes for this ground-breaking mission.

<sup>1</sup> The DSCOVR mission is a partnership between NASA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Air Force.

continued on page 2



On July 16, 2015, NASA's Earth Polychromatic Imaging Camera (EPIC) onboard DSCOVR returned its first view of the entire sunlit side of Earth. The image shows the effects of sunlight scattered by air molecules, giving the image a characteristic bluish tint.  
**Image credit:** NASA

the earth observer

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**Reminder:** To view newsletter images in color, visit [eosps0.nasa.gov/earth-observer-archive](http://eosps0.nasa.gov/earth-observer-archive).

In recent issues of *The Earth Observer*, we have been following the progress of five new missions that launched within a year—between February 2014 and January 2015: the GPM Core Observatory, OCO-2, ISS-CATS, ISS-RapidScat, and SMAP. The first four missions continue to operate well as of this writing. However, on July 7, at about 2:16 PM PDT, the SMAP radar halted its transmissions. All other components of the spacecraft continue to operate normally—including the radiometer instrument that continues to collect science data. An anomaly team has been convened at NASA JPL and is reviewing observatory and instrument telemetry and science data.

In the meantime, *beta* versions of the SMAP Level-1 instrument data (i.e., microwave brightness temperature and radar backscatter) will be released to NASA's Distributed Active Archive Centers (DAACs) and will be publicly available on August 3, 2015. *Beta* versions of the SMAP higher-level products (i.e., soil moisture and freeze/thaw state) will be released to the public at the beginning of November.

It is unfortunate to have to report that the SAC-D observatory that carried NASA's Aquarius instrument experienced a significant hardware failure and ceased operation on June 8, 2015. Aquarius/SAC-D is a partnership between CONAE [the Argentine space agency], which provided the spacecraft bus (SAC-D) as well as

several instruments, and NASA, which provided the primary instrument, Aquarius. On June 7, failure of the Remote Terminal Unit (RTU) that provided power to the spacecraft attitude control system caused a loss of control and communication with the spacecraft. Aquarius itself was functioning well and, in fact, operated without significant issues since being turned on August 25, 2011.

Aquarius was a pathfinder mission demonstrating that scientifically significant measurements of sea surface salinity could be made from space—see top image on the next page. Ocean salinity data are important for improving our understanding of ocean dynamics and the global water cycle. Successfully completing its primary three-year mission in November 2014, Aquarius achieved all of its science requirements. In addition to the science, among the pioneering aspects of Aquarius was the design of the radiometer, the inclusion of a radar to correct for surface roughness, a polarimetric radiometer channel to measure Faraday rotation, and rapid sampling to mitigate the effects of radio frequency interference (RFI).

Aquarius leaves almost four years of high quality data that will continue to provide new science for years to come. For example, Aquarius has already begun to provide data about the dynamics of the salinity field and insight into interannual changes including coupling to

events such as El Niño, freshwater plumes from large rivers, and even hurricanes. Aquarius data were also integral to the Salinity Processes in the Upper Ocean Regional Study (SPURS), a yearlong international field study of the oceanographic processes that sustain the maximum surface salinities in the central subtropical North Atlantic and influence global ocean circulation. Beyond ocean salinity, data from Aquarius have been used to produce global maps of soil moisture and RFI—see bottom images below.

“The Aquarius sensor collected three years and nine months of valuable data,” said **Gary Lagerloef** [Earth & Space Research—*Aquarius Principal Investigator*]. “It was truly a pioneering effort to determine how accurately we could measure ocean salinity from space and for the first time study large and small-scale interactions of the global water cycle.”

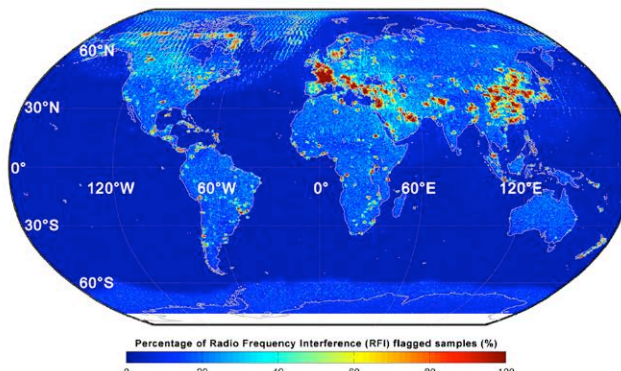
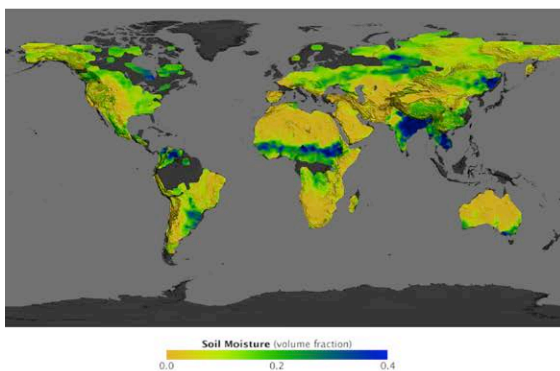
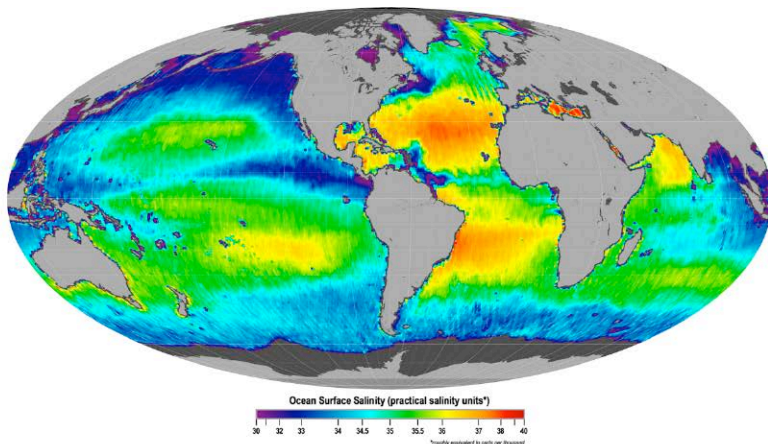
To learn more about Aquarius, visit [www.nasa.gov/press-release/international-spacecraft-carrying-nasa-s-aquarius-instrument-ends-operations](http://www.nasa.gov/press-release/international-spacecraft-carrying-nasa-s-aquarius-instrument-ends-operations) and also [www.aquarius.umaine.edu](http://www.aquarius.umaine.edu).

Finally, it is with great sadness that we inform you about the loss of Angelita “Angie” Castro Kelly, the first woman to become a NASA Mission Operations Manager, who passed away in June 2015. Among many accomplishments, Angie is known for her active role in

guiding the Afternoon Constellation, or A-Train, from concept to reality. To learn more about Angie’s career, turn to page 16. ■

**Undefined Acronyms Used in the Editorial and Article Titles**

ISS-CATS	International Space Station Cloud–Aerosol Transport System
CONAE	Comisión Nacional de Actividades Espaciales
GPM	Global Precipitation Measurement
ISS-RapidScat	International Space Station– Rapid Scatterometer
NOAA	National Oceanic and Atmospheric Administration
OCO-2	Second Orbiting Carbon Observatory
SAC-D	Satelite de Aplicaciones Cientificas-D
SMAP	Soil Moisture Active/Passive



This montage shows some sample data from Aquarius including: a global map of sea surface salinity, which was Aquarius’ prime mission [*top*]; a global map of soil moisture [*bottom left*]; and a global map of radio frequency interference (RFI) at L-band [*bottom right*]. Additional examples of these and other products are available at [www.aquarius.umaine.edu](http://www.aquarius.umaine.edu). **Image credit:** Aquarius Science and Project Team

## NASA Sets the PACE for Advanced Studies of Earth's Changing Climate

P. Jeremy Werdell, NASA's Goddard Space Flight Center, [jeremy.werdell@nasa.gov](mailto:jeremy.werdell@nasa.gov)

Emmanuel Boss, University of Maine, [emmanuel.boss@maine.edu](mailto:emmanuel.boss@maine.edu)

Lorraine Remer, University of Maryland, Baltimore County, [remel@umbc.edu](mailto:remel@umbc.edu)

Brian Cairns, Goddard Institute for Space Studies, [brian.cairns@nasa.gov](mailto:brian.cairns@nasa.gov)

*PACE provides a strategic climate continuity mission that will collect many global measurements essential for understanding marine and terrestrial biology, biogeochemistry, ecology, and cloud and aerosol dynamics.*

### Introduction

Spend any amount of time observing Earth's oceans and one thing becomes readily apparent: Ocean water is anything but clear; its color varies immensely, depending on exactly where one is looking (e.g., coastal waters are very different than the open ocean) and what happens to be dissolved or suspended in the water beneath its surface at that location. Such variations provide the basis for ocean color science. Many particulate and dissolved constituents of the near-surface water column absorb and scatter light differently in the ultraviolet (UV) and visible (VIS) regions of the electromagnetic spectrum. So at its most fundamental level, ocean color science is about relating the spectral variations in the UV-VIS marine light field (i.e., differences in the ocean's color) to the concentrations of the various constituents residing in the sunlit, near-surface water column—see *How Ocean Color Measurements Are Made* on the next page.

To continue a multidecade record of ocean color measurements, NASA recently approved the Pre-Aerosols, Clouds, and ocean Ecosystems (PACE) mission to enter *Pre-Phase A*—mission preformulation and conceptual studies. First presented in the 2010 NASA plan, *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space*<sup>1</sup>, PACE provides a strategic climate continuity mission that will collect many global measurements essential for understanding marine and terrestrial biology, biogeochemistry, ecology, and cloud and aerosol dynamics.

PACE, the primary sensor for which is currently called the Ocean Color Instrument (OCI), is an ocean color mission but, as its name implies, it will also be used to study important aspects of atmospheric science. Since the mission's primary focus is ocean color, this article begins with some background on that topic. The origins of the mission, its objectives and scientific questions, its organizational structure, and benefits to society are also addressed.

In the coming months, [pace.gsfc.nasa.gov](http://pace.gsfc.nasa.gov) will be developed and populated with news, updates, educational materials, and oceanic and atmospheric information for interested community members.

### Contributions to Ocean Color

In addition to dissolved and inorganic material such as salts, ocean water contains a variety of microscopic living organisms, each with their own unique impact on the optical properties of water. In fact, one of the most important components found in ocean water are phytoplankton. These microscopic marine algae form the base of the marine food chain and produce over half of the oxygen we breathe. Phytoplankton also play an important role in converting inorganic carbon in carbon dioxide (CO<sub>2</sub>) to organic compounds, fueling global ocean ecosystems and driving the oceanic biogeochemical cycles through grazing (i.e., they provide a food source for zooplankton) and through their degradation products and the *microbial loop*—where bacteria reintroduce dissolved organic carbon (DOC) and nutrients to the trophic system, effectively recycling both back into the food chain. Phytoplankton are therefore a critical part of the ocean's biological carbon pump, whereby atmospheric CO<sub>2</sub> gets sequestered to the deep ocean, and are responsible for roughly half of Earth's net *primary production*—the difference

<sup>1</sup> To view the report, visit [science.nasa.gov/medialibrary/2010/07/01/Climate\\_Architecture\\_Final.pdf](http://science.nasa.gov/medialibrary/2010/07/01/Climate_Architecture_Final.pdf).

between the rate of plant production of useful chemical energy and the rate of their use of that energy in respiration. However, phytoplankton growth is highly sensitive to variations in ocean and atmospheric physical properties, such as upper-ocean stratification and light availability within this mixed layer. Phytoplankton also vary greatly in their size, function, response to ecosystem changes or stresses, and nutritional value for species higher in the food web. Hence, measurements of phytoplankton community composition and their distributions remains essential for understanding global carbon cycles and how living marine resources are responding to Earth's changing climate. All these inorganic and organic substances combine to form the actual optical properties of the ocean, which ultimately give it its color.

### Ocean Color: An Important Climate Data Record

A key step toward helping scientists understand how the Earth has responded to its changing climate over time—and how it may respond in the future—is through the establishment of high-quality, long-term, global time series of various geophysical parameters. Given the nature of the phenomena and the timescales needed to distinguish trends, such measurements will require combining data from several missions. These climate-quality time series are called climate data records (CDRs<sup>2</sup>), and are being generated for a variety of geophysical parameters, including ocean color.

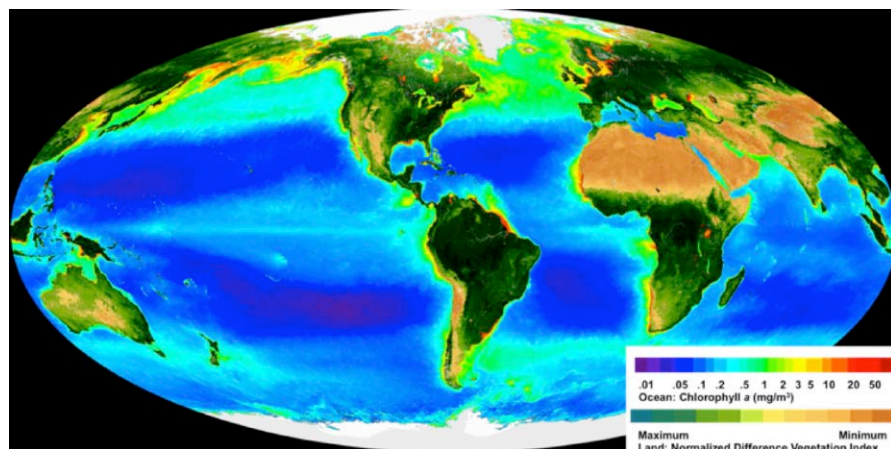
Beginning with the launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS<sup>3</sup>) in 1997, NASA has generated a continuous record of global ocean color measurements—although the proof-of-concept ocean color satellite observations date back to 1978—see *OCI Builds on NASA's Ocean Color Heritage* on page 7. This time series of remotely sensed quantities provides a valuable data record for studying long-term changes in ocean ecosystems. Observations of spectral marine inherent optical properties (IOPs), the spectral absorption and scattering properties of seawater, and the particulate and dissolved constituents it contains, can be used to infer the contents of the upper ocean, including phytoplankton community composition—see **Figure 1**. This information is critical for advancing our understanding of biogeochemical oceanic processes

<sup>2</sup> The U.S. National Research Council (NRC) defines a CDR as a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.

<sup>3</sup> SeaWiFS flew onboard the Orbview spacecraft, and operated until 2010.

### How Ocean Color Measurements Are Made

In simplified terms, here's how an ocean color measurement works: An instrument in space, such as the PACE Ocean Color Instrument (OCI) described on page 8, measures the spectral radiance exiting the top of the atmosphere. Of the total amount of radiance seen by the satellite instrument, only a small portion is actually coming from the ocean; by far the dominant portion comes from the atmosphere, and this "noise" effectively hides the desired signal. To retrieve the portion of the signal exiting the water, scientists and programmers apply atmospheric correction algorithms that remove the radiance contribution from the atmosphere; what remains is the small portion passing through the ocean surface—the component of interest for ocean color measurements. That radiance is then converted to spectral remote-sensing reflectances, which are essentially the ratio of the light coming from the ocean normalized to the light from the sun entering the ocean. Once these reflectances are known, then bio-optical algorithms are used to produce estimates of geophysical and optical properties, such as the near-surface concentration of the phytoplankton pigment chlorophyll-*a* and spectral marine inherent optical properties (IOPs).



**Figure 1.** Global image of the Earth's biosphere as seen by SeaWiFS. For the ocean, the colors indicate the abundances of chlorophyll-*a*, with purple-blue showing low abundances and green-yellow-red showing high abundance. For land, the colors show the normalized difference vegetation index (NDVI), with brown and green indicating arid and lush regions, respectively. **Image credit:** GSFC Ocean Biology Processing Group

*The PACE science objectives...are the result of decades of experience with requirements developed by the ocean color and cloud and aerosol communities. The advanced capabilities of the PACE OCI over heritage instruments will extend the current time series of high quality CDRs.*

—e.g., carbon exchanges and fluxes, phytoplankton community dynamics, and ecosystem responses to disturbances.

### **PACE Science Targets**

The PACE science objectives have been described in the *PACE Science Definition Team Report*<sup>4</sup>. They are the result of decades of experience with requirements developed by the ocean color and cloud and aerosol communities. The advanced capabilities of the PACE OCI over heritage instruments will extend the current time series of high-quality CDRs and answer the science questions listed here, grouped by topic:

### **PACE Science Questions**

#### *Global ocean ecosystems and climate*

- What are the standing stocks and compositions of ocean ecosystems? How and why are they changing?
- How and why are ocean biogeochemical cycles changing? How do they influence the Earth system?
- What are the material exchanges between land and ocean? How do they influence coastal ecosystems and biogeochemistry? How are they changing?
- How do aerosols influence ocean ecosystems and biogeochemical cycles? How do ocean biological and photochemical processes affect the atmosphere?
- How do physical ocean processes affect ocean ecosystems and biogeochemistry? How do ocean biological processes influence ocean physics?
- What is the distribution of both harmful and beneficial algal blooms and how is their appearance and demise related to environmental forcings? How are these events changing?
- How do changes in critical ocean ecosystem services affect human health and welfare? How do human activities affect ocean ecosystems and the services they provide? What science-based management strategies need to be implemented to sustain our health and well being?

#### *Coastal ocean ecosystems*

- What are the distributions of habitats and ecosystems and the variability of biogeochemical parameters at moderate scales and what is the impact on coastal (e.g., estuarine, tidal wetlands, lakes) biodiversity and other coastal ecosystem services?
- What is the connectivity between coastal, shelf, and offshore environments?
- How does the export of terrestrial material affect the composition of phytoplankton communities in coastal waters, and how do these in turn affect the cycling of organic matter?
- How do moderate scale processes (e.g., sedimentation, photodegradation, respiration) affect the cycling of terrigenous organic material in the coastal environment?

#### *Aerosols and clouds*

- What are the long-term changes in aerosol and cloud properties and how are these properties correlated with inter-annual climate oscillations?
- What are the magnitudes and trends of direct aerosol radiative forcing (DARF) and the anthropogenic component of DARF?
- How do aerosols influence ocean ecosystems and biogeochemical cycles?

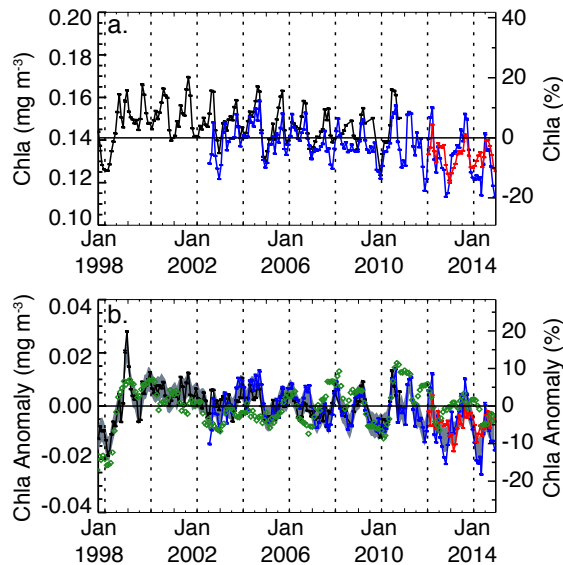
<sup>4</sup> To view the report, visit [decadal.gsfc.nasa.gov/PACE/PACE\\_SDT\\_Report\\_final.pdf](http://decadal.gsfc.nasa.gov/PACE/PACE_SDT_Report_final.pdf).

## OCI Builds on NASA's Ocean Color Heritage

The PACE Ocean Color Instrument (OCI) builds on a firm foundation of ocean color observations at NASA that includes a 17-year continuous record of satellite ocean color observations, and many more years of experience (see graphs below). The Coastal Zone Color Scanner (CZCS), launched in 1978 onboard Nimbus-7, was the first instrument that measured ocean color from space. Intended to be a “proof-of-concept” mission, CZCS did that—and much more. CZCS observations ceased in 1986, but research continued for many years thereafter that laid the groundwork for the missions that followed\*.

While some climate data records (CDRs) (e.g., ozone) are continuous from the Nimbus era to the present, such is not the case with ocean color. There was an 11-year gap between the end of CZCS observations and the next NASA ocean color mission\*\*: the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), launched in 1997 onboard the SeaStar (later renamed Orbview-2) satellite. Despite a challenging start—SeaStar was initially deployed upside down!—SeaWiFS proved itself resilient and went on to provide quality global ocean-color observations for over a decade.

Ocean color measurements continued into the NASA Earth Observing System (EOS) era. Two of the flagship EOS missions carried the Moderate Resolution Imaging Spectroradiometer (MODIS): Terra, launched in 1999, and Aqua, launched in 2002. More recently, the Visible Infrared Imaging Radiometer Suite (VIIRS), launched in 2012 onboard the Suomi National Polar-orbiting Partnership (NPP), also obtains ocean-color measurements. VIIRS will also fly on upcoming Joint Polar Satellite System missions, the first of which (JPSS-1) is scheduled for launch in late 2016.



These graphs illustrate the seventeen-year, multimission record of chlorophyll-*a* averaged globally for the latitudinal band 40° S to 40° N for SeaWiFS (black), MODIS onboard Aqua (blue), and VIIRS (red). The top graph plots the independent record from each mission, with the multi-mission mean chlorophyll-*a* concentration for the region (horizontal black line). The bottom graph plots monthly anomalies after subtraction of the monthly climatological mean (SeaWiFS relative to the SeaWiFS climatology, and MODIS and VIIRS relative to their respective climatologies), with the average difference between SeaWiFS and MODIS-Aqua over the common mission lifetime (grey). The multivariate El Niño Southern Oscillation index is inverted and scaled (green diamonds) to match the range of the chlorophyll-*a* anomalies. **Image credit:** Bryan Franz, NASA's Goddard Space Flight Center

\* To learn more about the ocean-color instruments that followed, click on the Missions & Sensors tab on the left menu bar at [oceancolor.gsfc.nasa.gov](http://oceancolor.gsfc.nasa.gov).

\*\*This story is told in Chapter 5 of *The Color of the Atmosphere with the Ocean Below: A History of NASA's Ocean Color Missions*, by Jim Acker. The book provides a summary of the development of NASA's ocean color missions with many references to “source” material.

### PACE Mission Requirements

Responding to mission objectives and finding ways to answer the scientific questions is what drives mission requirements. NASA will incorporate many of the features and “lessons learned” from heritage spectrometers flown by NASA as well as those flown by international partners<sup>5</sup> into the OCI instrument design. A lesson learned from the

<sup>5</sup> Examples would include the European Space Agency's Medium Resolution Imaging Spectrometer (MERIS) instrument that flew onboard Envisat and the Japanese Aerospace Exploration Agency's Ocean Color and Temperature Scanner (OCTS), and Global Imager (GLI) instruments that flew onboard the Advanced Earth Observation Satellite (ADEOS) and ADEOS II, respectively.

*While some climate data records (CDRs) (e.g., ozone) are continuous from the Nimbus era to the present, such is not the case with ocean color.*

*While PACE is predominantly an “ocean color” mission, it will also have secondary objectives—and possibly a secondary instrument. An additional overarching goal for the mission is to help determine the roles of the ocean and atmosphere in global biogeochemical cycling and how perturbations to Earth’s energy balance both affect and are affected by rising atmospheric CO<sub>2</sub> levels and Earth’s changing climate.*

SeaWiFS era, for example, is the benefit of an ocean color instrument that can view the full Moon each month from its Earth view port. The reflectance of the Moon can be accurately modeled, providing an invaluable temporal calibration source for the ocean color instrument. As of this early stage in the project, the key minimum threshold mission and OCI instrument characteristics and capabilities are:

- Earth surface spatial resolution at nadir of 1 km<sup>2</sup> (-0.4 mi<sup>2</sup>) for all science bands.
- Sun-synchronous polar orbit with an equatorial crossing time near local noon (1100-1300).
- Two-day global coverage of science measurements to a solar zenith angle of 75° and sensor view zenith angles not exceeding 60°—with mitigation of sun glint.
- A spectral range from 350 to 800 nm at 5-nm resolution, plus near-infrared bands at 865 and 940 nm and four or more shortwave infrared bands spanning 1240, 1378, 1640, 1880, 2130, and/or 2250 nm.
- Downlink and storage of the complete 5-nm resolution data from spacecraft to ground.
- Monthly characterization of instrument detector and optical component changes using lunar observations through the Earth-viewing port that illuminate all science detector elements.

#### *Organizational Requirements and Responsibilities*

PACE is being implemented as a NASA *Class C*<sup>6</sup> mission with a notional launch date in the 2022–2023 timeframe and minimum mission duration of three years, with orbit maintenance capabilities for 10 years. PACE is designated as a design-to-cost mission, meaning that it has a fixed budget cap of \$805 million. Under this funding framework, science returns from the mission will need to be optimized through a series of trade and feasibility studies that encompass the OCI, a potential polarimeter (see PACE: Measuring More than Ocean Color below), the spacecraft and launch vehicle, the ground and science data processing segments, pre- and post-launch, science and calibration/validation programs, and all other components of system integration and mission management.

Full responsibility for the PACE mission was directed to NASA’s Goddard Space Flight Center (GSFC) in December 2014. GSFC will design and build the OCI, as well as maintain responsibility for project management, safety and mission assurance, mission operations and ground systems, launch vehicle/spacecraft/instrument payload integration and testing, and OCI calibration, validation, and science data processing.

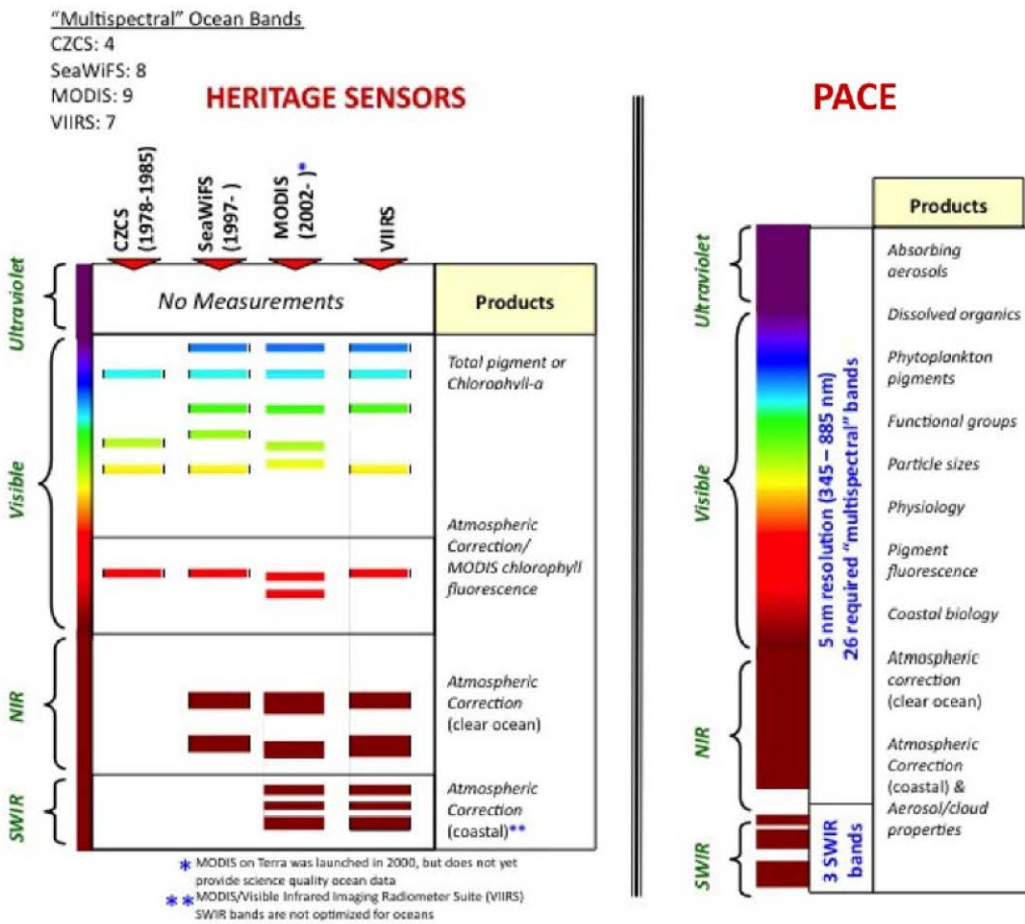
#### **PACE: Measuring More than Ocean Color**

While PACE is predominantly an “ocean color” mission, it will also have secondary objectives—and possibly a secondary instrument. An additional overarching goal for the mission is to help determine the roles of the ocean and atmosphere in global biogeochemical cycling and how perturbations to Earth’s energy balance both affect and are affected by rising atmospheric CO<sub>2</sub> levels and Earth’s changing climate.

The PACE mission will contribute to the continuation of atmospheric CDRs as well as those for ocean color. The OCI will allow continuation of “heritage” aerosol measurements made using the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua and the Ozone Monitoring Instrument (OMI) onboard Aura. It will also provide additional

<sup>6</sup>To learn more about the classifications used to categorize NASA missions, see *Appendix B* of “NASA Procedural Requirements (NPR) 8705.4,” which can be found at [nodis3.gsfc.nasa.gov/npg\\_img/N\\_PR\\_8705\\_0004\\_IN\\_PR\\_8705\\_0004\\_.pdf](https://nodis3.gsfc.nasa.gov/npg_img/N_PR_8705_0004_IN_PR_8705_0004_.pdf).





**Figure 2.** Comparison of PACE spectral coverage with heritage U.S. ocean color sensors. The PACE instrument will provide continuous high-spectral-resolution observations (5 nm) from the UV to NIR (350 – 800 nm), plus several short-wave infrared (SWIR) bands to support cloud and aerosol science and ocean color atmospheric correction. **Image credit:** PACE Science Definition Team Report (see Footnote 4 for access information)

characterization of aerosol particles because its spectral range will include short-wave infrared wavelengths—see **Figure 2**. This will enable continuation of MODIS-like and OMI-like characterization of aerosol properties, and MODIS-like measurements of water vapor and retrievals of cloud optical properties. These are the key atmospheric components affecting our ability to predict climate change as they contribute the largest uncertainties in our understanding of climate forcings and cloud feedbacks for an increasingly warmer planet. The interactions between these species are key to such understanding, as aerosols, water vapor, and clouds remain intertwined within the hydrologic cycle because most cloud droplets are seeded by small aerosol particles called cloud condensation nuclei. Changes in the amount, type, and distribution of aerosols, therefore, can alter the micro- and macro-physical characteristics of clouds. Furthermore, natural and anthropogenic changes to the aerosol system may affect clouds and precipitation, which can alter where, when, and how much precipitation may fall.

**Possible Enhancements to OCI**

A number of possible enhancements to the base PACE mission have been proposed. While all of these enhancements would make the mission more scientifically robust, they come with possible technical tradeoffs: Enhancements might result in delays in launch schedule; decreasing the mission’s technology readiness level<sup>7</sup> (which implies more risk of failure); increased payload mass leading to increased power requirements;

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<sup>7</sup>Technology readiness levels are a means to classify how “ready” a given system component or instrument is. For more on how the Earth Science Technology Office defines them in the context of NASA missions, see [esto.nasa.gov/technologists\\_trl.html](http://esto.nasa.gov/technologists_trl.html).

*PACE may optionally carry a multi-angle polarimeter as a secondary instrument, which would add significant capabilities to the atmospheric science components of the mission. While still in the exploratory stages, early results suggest that polarimetry has the potential to make significant contributions to the retrieval of atmospheric characteristics and selection of aerosols as part of ocean-color atmospheric correction.*

changes in data rates, data volume, signal-to-noise ratios, spectral resolution, and/or spatial resolution; higher probability of image artifacts (e.g., striping); and more extensive pre- and post-launch calibration efforts. All of these might have an impact on the cost of the mission.

#### *OCI Upgrades*

The possible enhancements to the PACE OCI that are under consideration would push beyond the minimum mission requirements and enable the mission to address some of the more advanced science questions. Possibilities include reducing ground spatial resolution of OCI to 50, 100, or 250 m (~164, 328, or 820 ft, respectively) to enable fine-scale coastal and inland water retrievals; extending the spectral range of the instrument down to 300 nm to better discriminate between color contributions from dissolved organic matter and absorbing aerosols; and, reducing spectral resolution to less than 5 nm and/or enabling spectral subsampling between 1 and 2 nm in particular regions of the spectrum (e.g., over the chlorophyll fluorescence peak to reveal additional information on phytoplankton physiology and health).

#### *Polarimeter Options*

PACE may optionally carry a multiangle polarimeter as a secondary instrument, which would add significant capabilities to the atmospheric science components of the mission. While still in the exploratory stages, early results suggest that polarimetry has the potential to make significant contributions to the retrieval of atmospheric characteristics and selection of aerosols as part of ocean-color atmospheric correction.

With regards to retrieving atmospheric characteristics, a polarimeter allows quantitative retrieval of aerosol scattering optical properties, absorption, size, and particle shape, in addition to the MODIS-OMI heritage of aerosol optical depth, and a less exact measure of size and absorption. For clouds, polarimetry provides a more exact measure of cloud droplet size distributions, including the width of the distribution. Retrievals of cloud top height and ice cloud phase function are also possible with appropriate choices of wavelength bands and angular sampling.

The second area that the addition of a polarimeter would help feed into the mission's primary objective: ocean color. A PACE polarimeter would provide an unprecedented opportunity to develop novel joint ocean-atmosphere retrievals that may improve upon or enhance traditional ocean color atmospheric correction and provide information on ocean biologic and atmospheric components from a simultaneous inversion. Furthermore, polarimetric measurements of the ocean surface may enable estimation of the angular distribution of the underwater light field, which could additionally shed light on the optical properties of near-surface marine particles.

Several polarimeter options exist as of this writing: no polarimeter; a polarimeter development directed to the NASA/Jet Propulsion Laboratory (JPL); and an open-competed (or contributed) polarimeter, with GSFC excluded. Under these options, the Project is exploring several measurement concepts—temporal modulation, spectral modulation, amplitude splitting, and sequential measurement strategies can all be used to provide imaging of both the total and polarized intensity of light. Assuming that a polarimeter is added to PACE, it will certainly constitute a significant enhancement to the base mission—but it will also increase the technical complexity of the mission.

#### **PACE Mission Organization**

Successful implementation of any mission requires close coordination at several organizational levels, and PACE is no different. The main responsibility at the project level is the responsibility of the PACE Project Science Team (listed in sidebar on page 11), with scientific and other responsibilities allocated to the Science Team, the Calibration and Validation Team, and the Science Data Processing Team.

*PACE Science Team*

The first competed PACE Science Team was awarded and assembled in July 2014<sup>8</sup>. This science team will serve three years and is led by **Emmanuel Boss** [University of Maine—*PACE Science Team Lead*] and **Lorraine Remer** [University of Maryland, Baltimore County—*Deputy PACE Science Team Lead*]. Team members received funding to complete a variety of individual science inquiries. Team members have also been working collaboratively in a variety of subgroups to address the science of IOPs and their retrieval from space and of atmospheric characterization as it pertains to PACE, including ocean color atmospheric correction.

The specific goals of the PACE Science Team are to achieve consensus and develop community-endorsed paths forward for the PACE instrument(s) for the full spectrum of IOP and atmospheric measurements, algorithms and retrievals; and to identify gaps in knowledge, research, and technologies that should be filled (such that they could be addressed in future ROSES calls). PACE Science Team members have been conducting new and novel studies and evaluating previous studies to assess the merits associated with various radiometer and polarimeter features. In addition, the PACE Science Team has provided input on radiometer and polarimeter specifications. For example, the Science Team hosted a series of webinars where community experts described new and available technologies, their attributes, and the science they will facilitate.

*PACE Calibration and Validation Team*

Under a separate solicitation, three proposals were funded in the same time frame to develop prototype, advanced hyperspectral radiometer systems to perform vicarious calibration for PACE. This post-launch, on-orbit calibration removes any remaining absolute bias in the instrument (and, atmospheric correction algorithm, in the case of ocean color). Vicarious calibration remains a critical component of every ocean color mission as no satellite radiometer system can be sufficiently well characterized on Earth to provide the accuracy required to derive geophysical products from measured radiances once on orbit.

*PACE Science Data Processing Team*

Building on a legacy of ocean color data processing spanning decades, the Ocean Biology Processing Group within the GSFC Ocean Ecology Laboratory (*oceancolor.gsfc.nasa.gov*) will maintain responsibility for all science data processing of ocean color data products, and their distribution and storage. Similar support for atmospheric science data products from the OCI and potential polarimeter will be determined pending the development of an acquisition strategy for the polarimeter.

**Societal Benefits**

Science for its own sake is not enough to provide the needed support to perform such activities. Particularly in a resource-limited environment, benefits to society at large—most commonly through applications of the data—must be demonstrated, and PACE will amply address this requirement. Specifically, the advanced capabilities of the PACE OCI over heritage instruments will enable improvement in the following categories of science applications:

**Climate:** PACE will allow improved mapping, assessment, and understanding of climate-relevant biogeochemical concentrations and fluxes; enhanced climate model skill and forecasting capabilities; improved support for policy analyses and

*PACE Project Science Team*

**Jeremy Werdell**  
[GSFC—*PACE Project Scientist*]

**Antonio Mannino**  
[GSFC—*PACE Deputy Project Scientist – Oceans*]

**Brian Cairns**  
[Goddard Institute for Space Studies—*PACE Deputy Project Scientist – Atmospheres*]

**Paula Bontempi**  
[NASA Headquarters (HQ)—*PACE Program Scientist*]

**Hal Maring** [NASA HQ—*PACE Deputy Program Scientist – Atmospheres*]

**Woody Turner** [NASA HQ—*PACE Applied Sciences*]

<sup>8</sup> The team resulted from a NASA Research Announcement (NRA), titled *Research Opportunities in Space and Earth Sciences (ROSES)–2013*, implemented by the NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES).

*With the PACE mission now moving forward, NASA anticipates extending its ocean color data record into a third decade with continuous measurements of biogeochemical and cloud and aerosol properties from specialized space-borne radiometers such as OCI.*

assessments; and refined design of planning adaptation and response approaches to impacts of climate change.

*Oceans, coasts, Great Lakes:* PACE will support enhanced fisheries and ecosystem management; improved monitoring of water quality, hypoxic conditions, eutrophication, and oil spills/seeps; refined detection of harmful algal blooms (HABs); improved models of abundances of toxic pollutants, pathogens, and bacteria that affect human and ecosystem health; refined monitoring of sea ice extent and passages; and enhanced mapping of ocean currents with relevance to fuel economy strategies for the shipping industry.

*Ecological forecasting:* PACE will support improved models for forecasting and early warning detection of HABs, identification of endangered species, and assessment of biodiversity; and refined data assimilation into ocean models to improve model skill and forecasting capabilities.

*Water resources:* PACE will allow improved assessment of water quality and management of water resources in lakes, estuaries, coastal areas, and over the open ocean.

*Disasters:* PACE will enable refined detection, tracking, and assessment of the effects of hurricanes, oil spills and seeps, volcanic ash plumes, and fires, and improve evaluation of the impact of these disasters on marine and terrestrial ecosystems and human health.

*Human health and air quality:* PACE will support improved air quality monitoring, forecasting, and management, and refined assessment of climate change impacts on air quality and public health.

### Looking Forward

With the PACE mission now moving forward, NASA anticipates extending its ocean color data record into a third decade with continuous measurements of biogeochemical and cloud and aerosol properties from specialized spaceborne radiometers such as OCI. These data records will enable the continued development of CDRs of oceanic and atmospheric properties that will further our scientific understanding of Earth's responses to its changing climate and the subsequent impacts of these responses on living marine resources. Furthermore, the large-scale views of the biosphere and atmosphere that PACE provides will help reveal the roles of the ocean and atmosphere in global biogeochemical cycling and how Earth's changing energy balance both affect and are affected by rising atmospheric CO<sub>2</sub> levels and changing climate. The PACE mission will also complement two additional missions recommended in the 2007 decadal survey,<sup>9</sup> that will support ocean color, land, and cloud and aerosols science: the GEOstationary Coastal and Air Pollution Events (GEO-CAPE) mission, which will maintain a geostationary orbit that provides continuous views of the Earth's Western Hemisphere, and the Hyperspectral Infrared Imager (HyspIRI) mission, a polar orbiter like PACE, but with very small ground pixel sizes (60 m) and reduced temporal coverage for studying land-ocean ecosystems. For more information about GEO-CAPE and HyspIRI, visit [geo-cape.larc.nasa.gov](http://geo-cape.larc.nasa.gov) and [hyspiri.jpl.nasa.gov](http://hyspiri.jpl.nasa.gov), respectively. ■

<sup>9</sup> To learn more about NASA's decadal survey, visit [science.nasa.gov/earth-science/decadal-surveys](http://science.nasa.gov/earth-science/decadal-surveys).

# DEVELOP Project Uses Satellite Data to Help Control Malaria in Zanzibar

Jerrold Lessel, *International Research Institute for Climate and Society, Columbia University, jlessel@iri.columbia.edu*

Andrew Kruczkiewicz, *International Research Institute for Climate and Society, Columbia University,*

*andrewk@iri.columbia.edu*

## Introduction

According to a 2013 study published by the World Health Organization (WHO<sup>1</sup>), across the globe malaria is considered endemic in 104 countries and territories, with some 3.4 billion people—and children, especially—at risk of the disease.

Given these facts, there is increasing consensus that the practical policy option for dealing with malaria is to pursue a global policy of progressive elimination and aggressive control in high-burden areas, potentially leading to its eventual eradication. Some African countries have chosen this path and are already developing malaria control and elimination strategies along with *aid delivery roadmaps*, plans to effectively target and distribute resources and to prevent malaria from being reintroduced into regions where control strategies have been successful.

New strategies to eradicate malaria require understanding how interventions affect the transmission of the disease across different geographic areas, in varying climates, and where detailed land-surface processes affect vector<sup>2</sup> population dynamics and behavior. Climate variability and change at multiple spatial and temporal scales are among the most important factors in the transmission of malaria. A key problem in collecting appropriate data is that, owing to a lack of much needed resources, and consequently the infrastructure necessary to acquire and process such data, it is often difficult to collect the *in situ* meteorological and ecological data needed to establish links between environmental factors and the spread of vector-borne diseases.

Some of these problems can be overcome by using Earth-observing satellite data to fill these “data voids.” The remainder of this article describes a project conducted under the auspices of NASA’s DEVELOP Program<sup>3</sup> in which data from the International Space

Station (ISS) SERVIR<sup>4</sup> Environmental Research and Visualization system (ISERV) camera are being compared with data from the Landsat 5 satellite to determine which data product produced the best results for classifying land cover on the island of Zanzibar. The results will be applied to help predict the occurrence of and/or track the spread of future malaria outbreaks in this area.

## Study Area: Zanzibar

Zanzibar is located off the coast of Tanzania, in Southeast Africa. The island contains numerous lush forests and mangroves housing a plethora of rare species of flora and fauna. Its picturesque beaches and striking landscapes have propelled tourism to be a major economic driver in the country. Unfortunately, some of those eye-catching landscapes can provide fertile breeding grounds for mosquitoes; therefore, periodic outbreaks of malaria have been problematic for Zanzibar.

Currently, Zanzibar employs several malaria control methods, such as insecticide-treated nets, indoor-residual spraying, and a *combination therapy* based on the use of artemisinin (derived from the sweet wormwood plant) along with some other treatment modality. The combination approach is necessary because malarial parasites in this area appear to be becoming drug-resistant and WHO has explicitly discouraged *monotherapy*—i.e., using artemisinin alone.

## Important Satellite Data: Landsat and ISERV

Since a key factor in predicting where malaria outbreaks are likely to happen is knowledge of the land surface, land imagery from satellite remote sensing can be a valuable tool. In this study, a series of images taken by the ISERV camera system were used in concert with a single image from the Thematic Mapper (TM) onboard Landsat 5 to identify which product better classified land cover for Zanzibar, where malaria transmission is still present.

## Landsat Image

The Landsat image chosen for the classification was a Landsat 5 image from July 1, 2009, obtained from

<sup>1</sup>The WHO *World malaria report 2013* is available for download at [www.who.int/malaria/publications/world\\_malaria\\_report\\_2013/report/en](http://www.who.int/malaria/publications/world_malaria_report_2013/report/en).

<sup>2</sup>A *vector* is any agent that carries and transmits pathogens to another organism.

<sup>3</sup>The NASA DEVELOP National Program fosters an interdisciplinary research environment where applied science research projects are conducted under the guidance of NASA and partner science advisors. For more information, visit [develop.larc.nasa.gov/about.html](http://develop.larc.nasa.gov/about.html).

<sup>4</sup>SERVIR is a joint NASA and U.S. Agency for International Development 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 an acronym meaning “to serve” in Spanish.

the 2010 Global Land Survey—shown on the left in **Figure 1**. This particular image was chosen because it was the only image from Landsat 5, 7, or 8 that did not have cloud cover over the island. Unfortunately, because the image was obtained from Landsat 5, panchromatic sharpening could not be used (since the panchromatic band was not available until Landsat 7) to enhance the resolution of the image for classification purposes. Despite this limitation, however, the resolution of the Landsat image was an eminently useful 30 m (~98 ft).

#### *ISERV Images*

The ISERV images chosen for the classification comparison were acquired from NASA's Global Hydrology Resource Center<sup>5</sup>. Unlike the Landsat image, the ISERV images were only able to cover the northern portion of the island due to the camera's smaller viewing area, but they had a higher spatial resolution of approximately 3 m (~10 ft). Despite the reduced aerial coverage, the area covered in the ISERV images contained various land cover types, so it was still a viable candidate for the comparative analysis. As explained in the next section, the image on the right in Figure 1 shows the area covered by all of the mosaicked ISERV images that were used in this study.

#### Classifying and Reclassifying the Data

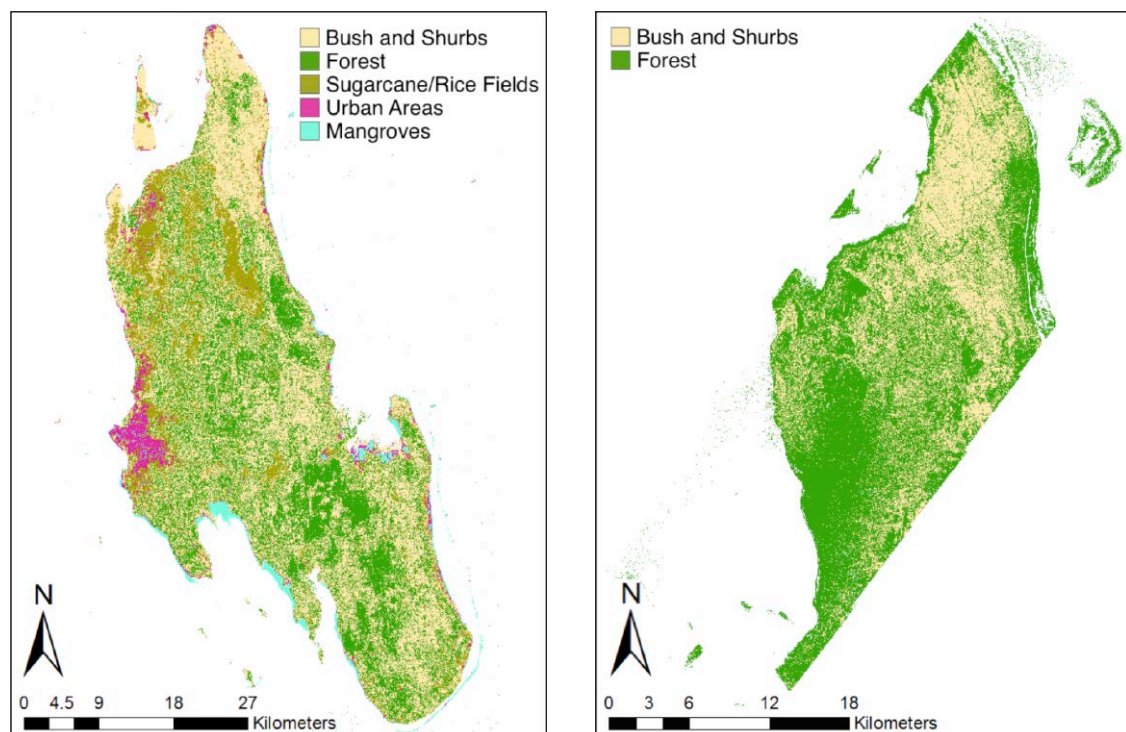
The land-cover determination for the Landsat data was done using an *Iso-Cluster analysis*—an unsupervised

<sup>5</sup> For more on the Center, visit [earthdata.nasa.gov/about/daacs/global-hydrology-resource-center-ghrc-daac](http://earthdata.nasa.gov/about/daacs/global-hydrology-resource-center-ghrc-daac).

classification tool in the *ArcMap* geographic information system (GIS). To complete the classification, the ISERV scenes were mosaicked in *ENVI*, a commercial platform for advanced image processing and geospatial analysis. After that, another unsupervised classification was performed, this time, to classify the mosaicked scene. Both the Landsat image and the mosaicked ISERV images were classified with many different parameters such as the number of classes, minimum class size, and differing sample intervals for the classes. The ideal classifications were selected by visually comparing the results of the classifications with a ground-truth map and *in situ* photos.

After the various classifications were performed on the images, the maps with the classifications that were most similar to the ground-truth map were chosen and then reclassified based on the ground-truth map. Certain land cover types (e.g., forest) in the reclassified images were originally spread over numerous classes and were subsequently combined to match the ground truth map as best as was practicable.

As shown in Figure 1, the Landsat 5 image outperformed the ISERV images in differentiating between the various land cover classes. The Landsat classification was able to adequately classify brush and shrub areas, forest, urban areas, mangrove swamps, and sugarcane and rice fields. One of the limitations found when using the Landsat 5 classification was that it would sometimes incorporate high-reflectance areas (such as coastlines) into the same class as urban areas.



**Figure 1.** Finalized classification maps using an *Iso-cluster* unsupervised classification analysis on a Landsat 5 Thematic Mapper image [left] and on a set of mosaicked ISERV images [right]. Note the scales of these maps are different; the ISERV images only covered the northern portion of the island but had much greater spatial resolution than Landsat 5. **Image credit:** Jerrod Lessel